BISTABLE LIQUID CRYSTAL DISPLAY DEVICE

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ABSTRACT

A display device including two parallel transparent plates (10, 12) having transparent electrodes on the inner surfaces thereof and containing a liquid crystal material (20). The device includes means defining a monostable anchoring for each plate (10, 12), means (40) controllable to break at least one of the anchorings, and means for thereafter inducing volume bistability.
FIG. 40

FIG. 41

FIG. 42
FIG. 46

FIG. 47

FIG. 48a FIG. 48b FIG. 48c FIG. 48d FIG. 48e
Intensity of the optical response

Surface effect

Volume effect

FIG. 53B

FIG. 53A

FIG. 52B

FIG. 52A

FIG. 54
BISTABLE LIQUID CRYSTAL DISPLAY DEVICE
[0001] The present invention relates to the field of liquid-crystal-based display devices.
[0002] More precisely, the present invention relates to the field of display devices having a bistable effect.
[0003] Liquid-crystal-based display devices have already given rise to a vast literature.
[0004] Mention may be made for example, in a non-limiting manner, of the following documents:

[0017] (13) J. Appl. Phys. 52 (2) “Surface pinning of disclinations and the stability of bistable nematic storage displays” by J. Cheng et al.;
[0020] (16) J. Appl. Phys. 56 (2) “Physical mechanisms of DC switching in a liquid-crystal bistable boundary layer display” by R. N. Thurston et al.;
[0022] (18) J. Appl. Phys. 52 (4) “New bistable liquid-crystal twist cell” by D. W. Berreman et al.;
[0024] (20) Asia Display 95 “A bistable Twisted Nematic (BTN) LCD Driven by a Passive-Matrix Addressing” by T. Tanaka et al.;

[0026] The abovementioned documents essentially concern studies relating to the breaking of bistable anchoring, to anchoring energies and to changes of state induced by the propagation of defects.

[0027] The object of the present invention is to improve liquid-crystal display devices in order to make it possible to obtain a novel bistable effect.

[0028] This object is achieved according to the present invention by virtue of a display device comprising two parallel transparent plates provided with transparent electrodes on their internal surfaces and containing a liquid-crystal material, characterized in that the device comprises:

[0029] means defining a monostable anchoring on each plate;
[0030] means capable of breaking, on command, at least one of these anchorings; and
[0031] means capable of inducing, after this breaking, a bistable volume effect in the absence of an electric field.

[0032] These two volume textures, which maintain a stable state in the absence of an external electric field, must be compatible with the monostable anchorings on the plates.

[0033] According to one particular embodiment;

[0034] the plates define different anchoring thresholds (these anchorings may be, for example, planar or homeotropic);
[0035] the thickness of the device between the two plates is sufficiently small to allow hydrodynamic coupling between the internal surfaces of these plates; and
[0036] means are provided which are capable of applying, between the electrodes of the two plates, alternately a write electric field pulse above a threshold capable of breaking the anchorings on the two plates in order to define, after interruption of this electric field, a twisted first stable state resulting...
from hydrodynamic coupling between the two plates, and a second electric field below the said threshold capable of breaking a single anchoring or having a falling edge which varies slowly in order to decouple the tilts on the two plates, so as to define a homogeneous second stable state.

[0037] Other characteristics, objects and advantages of the present invention will appear on reading the detailed description which will follow, and with regard to the appended drawings given by way of non-limiting example, in which:

[0038] FIGS. 1a and 1b diagrammatically illustrate two nematic liquid-crystal textures obtained with planar anchorings;

[0039] FIG. 2 illustrates the forced alignment of liquid-crystal molecules with a positive dielectric anisotropy in an applied electric field;

[0040] FIG. 3 illustrates the curve relating the angle of the molecules at the surface of the electrodes with respect to a normal to the plates and the applied electric field;

[0041] FIG. 4 illustrates the curve relating the field threshold for breaking the anchorings to the duration of the applied field pulse;

[0042] FIGS. 5a, 5b, 5c and 5d diagrammatically illustrate four textures obtained in succession when the applied electric field is progressively decreased;

[0043] FIGS. 6a, 6b, 6c and 6d illustrate the textures obtained when, in contrast, the electric field is suddenly cut off;

[0044] FIG. 7 shows diagrammatically a mass current obtained close to a plate when the electric field is switched off;

[0045] FIG. 8 diagrammatically represents a localised flow shear adjacent to a plate and spreading out as far as the other plate upon cutting off the drive electric field;

[0046] FIG. 9 illustrates the effect of hydrodynamic coupling between the two plates;

[0047] FIG. 10 illustrates a bend structure obtained by virtue of the hydrodynamic coupling;

[0048] FIG. 11 illustrates a twist structure obtained after relaxation of the bend structure in FIG. 10;

[0049] FIG. 12 illustrates the tilt of molecules on a second plate due to the effect of hydrodynamic coupling;

[0050] FIGS. 13, 14 and 15 show diagrammatically the azimuthal orientation of the molecules and the azimuthal moment obtained due to the effect of the hydrodynamic coupling for various relative orientations between the easy anchoring directions;

[0051] FIG. 16 shows diagrammatically the structure obtained when a single anchoring is broken;

[0052] FIG. 17 shows diagrammatically two superposed plates possessing easy orientation directions rotated with respect to each other;

[0053] FIG. 18 diagrammatically illustrates a cell in accordance with the present invention;

[0054] FIG. 19 diagrammatically represents a matrix-configured screen in accordance with the present invention;

[0055] FIGS. 20, 21 and 22 diagrammatically represent three types of electrical drive signals;

[0056] FIGS. 23 and 24 represent curves of switching voltage versus duration of the electric field, respectively for pure 5 CB and for doped 5 CB;

[0057] FIGS. 25, 26 and 27 diagrammatically illustrate three possible orientations of the nematic director, in the vicinity of a surface;

[0058] FIGS. 28, 29 and 30 diagrammatically illustrate three possible textures for homeotropic anchorings;

[0059] FIGS. 31 and 32 diagrammatically illustrate two possible textures for oblique anchorings;

[0060] FIG. 33 diagrammatically illustrates the switching caused by an oblique field applied by interdigitated electrodes;

[0061] FIG. 34 shows diagrammatically another alternative form of means making it possible to apply an oblique switching field, these being based on the resistance of the electrodes, and FIG. 35 represents the equivalent diagram of these electrodes;

[0062] FIG. 36 diagrammatically illustrates the switching caused by a hydrodynamic effect obtained by virtue of an auxiliary drive electrode;

[0063] FIG. 37 diagrammatically represents four stages of a device in accordance with the invention, comprising an oblique anchoring master plate;

[0064] FIG. 38 diagrammatically illustrates the angle of the surface molecules as a function of the static drive electric field;

[0065] FIG. 39 illustrates the same angle as a function of time, after stopping of the drive field in the absence of coupling between the two surfaces;

[0066] FIG. 40 represents an example of a drive electric field for erasing this device;

[0067] FIG. 41 diagrammatically represents three stages of the same device, ending in erasure by virtue of the drive electric field illustrated in FIG. 40;

[0068] FIG. 42 represents another example of a drive electric field for erasure;

[0069] FIG. 43 represents four stages of the same device, leading to erasure by virtue of the drive electric field illustrated in FIG. 42;

[0070] FIG. 44 represents a diagram of the voltage U2 as a function of time T2 and illustrates writing/erasure states as a consequence;

[0071] FIG. 45 represents five steps of a device in accordance with the invention, comprising an oblique anchoring slave plate and leading to writing;

[0072] FIG. 46 represents the variation in the angle of the surface molecules as a function of the static drive electric field;

[0073] FIG. 47 represents the orientation of the surface molecules;
FIG. 48 represents five steps of the same oblique-anchoring slave-plate device, leading to erasure;

FIG. 49 represents the angle of the surface molecules as a function of the electric field;

FIG. 50 represents the spontaneous erasure time as a function of the thickness of the cell;

FIG. 51 illustrates the optical behaviour of transparent confinement plates 10, 12 of a display cell: for example, readily produced anchoring called monostable “planar” anchorings, the two textures illustrated in FIGS. 1a and 1b may be obtained. In the texture illustrated in FIG. 1a, the liquid-crystal molecules 20 are all parallel to each other in the volume, and at the surface on the plates 10, 12. On the other hand, in the texture illustrated in FIG. 1b, the liquid-crystal molecules 20 exhibit a 180° twist structure, that is to say that the molecules, while still remaining parallel to the plates 10, 12, rotate progressively through 180° from one plate 10 to the other 12.

These two textures in FIGS. 1a and 1b have different optical properties and could, in theory, be used to define two states, white and black, for transmission of polarized light, by maintaining the anchoring conditions on the plates 10, 12. It is not possible to pass by continuous deformation from one texture to the other (they are “topologically” different); it is only possible to do so by creating defects which represent a high energy barrier compared to thermal agitation: even if the energy of the two textures a and b is very different, in the absence of defects these states may be regarded as being stable forever. The same is true if the defects become immobile, by adhering to the surfaces. The simplest way of providing bistability of the two different twist textures is well known to those skilled in the art: it consists in cholesterising the nematic liquid crystal with respect to a spontaneous twist intermediate between those of the two textures.

The multiplicity of textures corresponding to defined monostable anchorings is a general property of nematic or cholesteric liquid crystals. Those skilled in the art know how to choose, from these textures, two with similar energies but with different optical properties.

The present invention aims to cause transition between these two textures, in order to make it possible to produce stable pixels and therefore bistable liquid-crystal displays.

The description will remain for the moment with planar anchorings. It is known (see document [1]) that it is possible to “break” the surface anchorings by using an electric field E normal to the plates (see FIG. 2) and a nematic liquid crystal with positive dielectric anisotropy, ε-<1>, which forces alignment along the field. The critical field to break the anchoring is defined by the condition:

\[ \varepsilon_E = 1 \]

where \( \varepsilon_E \) is given by \( K/\varepsilon_E = (\varepsilon_1/4\pi)E^2 \), K is the elastic curvature constant (~10^-11 cgs) and 1 is the extrapolation length defining the zenithal anchoring energy. This energy is written:

\[ W_{Ez}=K/(16\pi \cos \theta_0) \]

where \( \theta_0 \) is the angle of the surface molecules.

In the case of “strong” anchorings (1–1000 Å), \( E_s=5 \text{ V/µm} \) and for “weak” anchorings (1–1 µm), \( E_s=0.5 \text{ V/µm} \). For E increasing and approaching \( E_s \), the surface angle \( \theta_0 \) goes rapidly from 90° to 0. Above \( E_s \), the angle \( \theta_0 \) remains zero and the surface is said to be “broken”. The curve relating \( \theta_0 \) to E is illustrated in FIG. 3. When the field E is applied in the form of a pulse of length T, the threshold increases when T decreases (see document [3]), but since the surface dynamics are rapid it is possible to break the surface anchoring with voltages which remain moderate: for example, about 30 V, for times T=10 µs, with the 5 CB liquid crystal at room temperature (ε-~10). The curve relating the threshold \( E_s \) to the duration T of the pulse is illustrated in FIG. 4.

When both surface anchorings are broken the texture of the cell is uniform (as illustrated in FIG. 2) and there is no memory of the initial state since the molecules 20 seen end-on cannot keep any twist.

The effect used within the context of the invention to initiate the textures is a dynamic effect. It relies on the following studies and observations.

Let us first assume that the two anchorings of the plates 10 and 12 have been broken, as explained above; if the electric field is decreased slowly, at every instant the system will choose its lowest-energy state in order to define a slowly varying texture.

Starting from the homotropic orientation illustrated in FIG. 2, in an electric field, these textures will always go, in a zero field, towards the non-twisted state illustrated in FIG. 5a, with a planar orientation, passing through an intermediate situation illustrated in FIGS. 5b and 5c in which the molecules on the two surfaces of the plates 10, 12 rotate in the same direction, while remaining parallel. This arises from an elastic interaction between the plates 10, 12 which minimizes the curvature and the curvature energy of the system.

On the other hand, if the electric field is cut off suddenly, the effect obtained is very different, as illustrated in FIG. 6.

The dynamic effects are controlled by two characteristic times: the volume characteristic time \( T_V \), V and the surface characteristic time \( T_s \).

\( T_s \) is universally given by the curvature elasticity over the thickness d of the specimen as:

\[ 1/T_s=K/d^2 \eta, \text{ where } \eta \text{ is a viscosity (}\eta=0.1 \text{ or } 1 \text{ poise).} \]

\( T_s \) is given by the same formula, in which d is replaced by the surface extrapolation length l, namely \( 1/T_s=K/l^2 \eta \).

Since \( l=\delta \), \( T_s \) is very much less than \( T_s \); typically, for \( d=\mu \) and \( l=1,000 \text{ Å} \), \( T_s=1 \text{ ms} \) and \( T_s=10 \mu \text{ s} \).

When the field E is released, the molecules on the two surfaces rotate rapidly during their times \( T_s \), while the volume molecules remain virtually immobile. On this timescale, the elastic coupling between the plates 10 and 12 is negligible, but there is hydrodynamic coupling. Associated with the rotation of the molecules is a mass current (see document [22]). This current exists close to each plate, over
a thickness of ~1. Its velocity \( V \) is approximately \( V = l/T \). Such a current is shown diagrammatically in FIG. 7.

[0067] Let us assume that the plate 12 has a threshold \( E_{\text{th}} \) greater than that \( E_{\text{th}} \) of the plate 10. In this case, the molecules 20 adjacent to the plate 12 tend to revert to the planar state before the molecules adjacent to the plate 10. Moreover, the return of the surface molecules adjacent to the plate 12 from the \( \theta_0 = 0 \) orientation to the stable \( \theta_0 = 90^\circ \) orientation (called the planar orientation) produces a localised flow shear \( V \) over 1, as shown diagrammatically in FIG. 8.

[0097] This shear diffuses over the thickness \( d \) of the cell in a time given classically by the relaxation of the vortices (Navier-Stokes equation in hydrodynamics) by:

\[
\eta \tau = \eta V d / \rho, \quad \text{where} \quad \rho = \text{the density} (\rho \sim 1), \text{give}
\]

a uniform final texture. The velocity gradient shear \( \eta d \) gives, within the volume, a moment density \( \eta \tau d \) to the molecules. The sum of these volume moments is a surface moment, \( \eta \eta V d \) which will rotate the surface molecules in the \( \theta_0 \) direction, as illustrated in FIG. 12.

[0099] In order to obtain the tilt which creates a twist structure as illustrated in FIG. 11, the surface moment thus obtained must therefore be greater than the anchoring moment which rotates in the \( \theta_0 \) direction (FIG. 12).

[0100] This condition is:

\[
(K) \theta_0 = \eta V d / \rho, \quad \text{Replacing} \quad V = 1/T, \quad \text{with} \quad V = K \eta \theta_0, \quad \text{gives} \quad 0 < \eta d.
\]

[0102] \( \theta_0 \) is of the order of the variation in angle over the time \( T_\theta \) and hence of the order of \( T_\theta / T = (K / \eta^2) \) (d/f). The condition becomes: \( d \eta / \eta^2 (K / \eta^2) \); with \( \eta \sim 0.1 \) poise, this gives \( d \leq 20 \) Å. If \( d \leq 1000 \) Å, \( d \) must be less than \( 2 \) μm. However, since \( d > 2 \) μm is a typical thickness of the specimens, this condition is sometimes a little difficult to achieve. It would be necessary to use weak anchoring, with a longer response time.

[0103] Within the context of the invention, it will be considered that, preferably, the thickness \( d \) of the cell must be less than \( 5 \) μm.

[0104] Within the context of the invention, a method of hydrodynamically coupling the anchoring is therefore proposed which is more effective and which operates for strong anchoring.

[0105] Hitherto, only the \( \theta_0 \) zenithal anchoring, which is generally stronger, has been taken into account. However, there is also a preferred azimuthal direction on the plates which adopt “planar” orientations in a defined direction. Calling \( \rho \) the azimuthal angle of the molecules with respect to this direction, the surface energy should be:

\[
W_{\rho} = \rho \eta V d / \rho, \quad \text{where} \quad \rho = \text{the density} (\rho \sim 1), \text{give}
\]

[0106] where \( L \) is the extrapolation length defining the azimuthal anchoring energy \( K \).

[0107] In general, the azimuthal term has an amplitude an order of magnitude smaller than the zenithal term (see document [13]): \( L \) is an order of magnitude greater than 1. Looking at the lower plate 10 from above, it may be assumed that the surface molecules have been inclined by an angle \( \theta_0 \) after the time \( T_\theta \), as illustrated in FIG. 13.

[0108] If the planar direction on the plate 10 is \( P \), the molecules may assume the two possible states \( P1 \) and \( P2 \) on it. In order to force the molecules to drop down to the \( P2 \) state, which will give a half-turn, and not the \( P1 \) state, it is sufficient to move the end \( m \) of the molecule on the other side of \( y' \), the mid-perpendicular of \( P1, P2 \) (FIG. 13). To do this, instead of changing \( \theta_0 \) by moving \( m \) along \( P1, P2 \), it is more effective to rotate \( m \) at constant \( \theta_0 \) around the circle C (FIG. 13). To do this, it suffices to rotate the easy anchoring direction of the upper plate 10 through an angle \( \alpha \) with respect to \( P1, P2 \). The velocity \( V \) is in the direction \( \alpha \) and produces a final alignment \( f \). Since the moment exerted by the transient velocity gradient is now balanced by the single reaction of the azimuthal anchoring energy, the condition for the moments may be written here, for small \( \theta_0 \), as:

\[
K \eta \theta_0 = \rho \eta V d / \rho, \quad \text{where} \quad \rho = \text{the density} (\rho \sim 1), \text{give}
\]

[0109] The condition to be fulfilled is now: \( \theta_0 < L / d \). Since \( L \) is an order of magnitude greater than 1, the coupling condition is easy to fulfill. Thus, finally:

\[
\theta_0 = (L / d) \eta V d / \rho.
\]

[0110] There exists an optimum rotation angle \( \alpha \) of the two plates. If \( \alpha \) is very small, a tilt very close to \( P2 \) (through \( 180^\circ - \alpha \)) will occur, but it will be difficult to exert the initial azimuthal rotation moment: the system will prefer to change \( \theta_0 \) with less effectiveness, as illustrated in FIG. 14. On the other hand, if \( \alpha \) is close to \( 90^\circ \) the strongest possible azimuthal moment will be obtained, as illustrated in FIG. 15, but the rotation obtained will be only \( 90^\circ \), and ineffective for providing the tilt since this rotation places the system just on the line of equal energy between \( P1 \) and \( P2 \). There exists an optimum value, which may be around \( 45^\circ \), or around \( 135^\circ \), if the anchorings have a polarity defined in the plane, as is the case for evaporated SiO or for a unidirectional rubber polymer.

[0111] In order to erase a "half-turn" twist, as shown diagrammatically in FIG. 16b, it is sufficient to "break" only a single surface anchoring, if carried out quickly, or to decrease the applied field slowly in order to decouple over time the two surface tilts, assumed to have different thresholds. In every case, surface treatments will be chosen which will give different anchoring thresholds on the two plates 10, 12.

[0112] The principle of effecting the half-turn twist relies on the following phenomenon. When only one of the two surfaces is broken, as shown diagrammatically in FIG. 16, or when the two anchorings are released in succession at a time interval \( T \), there is no longer a hydrodynamic coupling effect: the elastic couplings dominate and the vertical orientation of one surface cannot maintain the twist, which disappears. The half-turn twist is therefore erased.

[0113] On the basis of the above observations, the inventors propose to produce a display (in fact a pixel) with the aid of two plates 10, 12 treated in order to give planar anchorings A1 and A2 (or anchorings with a planar component) which are different. These anchorings coupled to a nematic with \( \varepsilon > 0 \) have breaking thresholds E1 and E2 respectively. They are placed at \( \alpha = 45^\circ \) to each other, as shown diagrammatically in FIG. 17, or at an angle \( \alpha \) which is different from \( 0^\circ, 90^\circ, 180^\circ \) or \( 270^\circ \) but which optimizes the rotational hydrodynamic coupling.

[0114] This angle \( \alpha \) is also chosen to give good contrast between the initial texture, which is now twisted through the
angle \(\alpha\), and the so-called “\(\frac{1}{2}\)-turn” final texture, which is now twisted through an angle \(180^\circ - \alpha\). In order to write, an electric field pulse above the two thresholds, \(E=\text{E1}\) and \(E=\text{E2}\), is applied. By abruptly cutting off the field, the \(180^\circ - \alpha\) state is still obtained, due to the effect of the hydrodynamic coupling, irrespective of the initial state, \(\alpha\) or \(180^\circ - \alpha\). In order to erase, a pulse \(E\) between \(\text{E1}\) and \(\text{E2}\) is applied, rapidly cutting off the pulse, or a pulse which has a level above the two thresholds \(\text{E1}\) and \(\text{E2}\), but the amplitude of which is decreased slowly, is applied, in order to decouple the tilts on the two plates \(10, 12\); the \(\alpha\) state is always obtained, whatever the initial state, \(\alpha\) or \(180^\circ - \alpha\).

[0115] The supply means designed to apply such drive pulses are shown diagrammatically by the reference 40 in FIG. 18.

[0116] The optical contrast between the two states of such a pixel depends on the thickness of the specimen and on the orientation of the polarizers 30 and analysers 32 used (see FIG. 18).

[0117] This optimization problem is known to specialists (see document 23). In practical terms, for each liquid crystal and each cell, instabilities of another type, for example the Freedericks instability, \(\nu\) of about 1 volt, typically, for example, \(\nu \leq 1\) volt, will be chosen in order to do this. The threshold higher will therefore have to be well-defined and uniform. The value of the lower threshold is less constraining. It cannot be too low in order for the system to remain rapid. In practical terms, anchorings will therefore be chosen which give threshold values in volts, in the region of about 1 volt. Since the typical thresholds are of the order of 10 \(\text{V}/\mu\text{m}\) (document 1), for a 2 \(\mu\text{m}\) thick cell, the thresholds must differ by from 5 to 10%.

[0118] In order to produce slightly different anchoring thresholds, and therefore breaking voltages, on the two plates \(10, 12\), it may be advantageous to use the same surface preparation technology (oblique \text{SiO} evaporation or surface- rubbed polymer, for example), but to vary the polarity of the thresholds. It is thus almost possible to cancel out or to amplify an existing small threshold difference. To do this, the flexoelectric effect or the ion transport effect may be used.

[0119] The two anchorings on the two plates \(10, 12\) play interchangeable roles in the proposed mechanism. Giving a difference in threshold between the two anchorings, which is related to the polarity of the applied field, is only meaningful if the cell is initially unsymmetrical, with two different threshold fields, \(\text{E1}\) and \(\text{E2}\), and therefore two different threshold voltages \(V1\) and \(V2\).

[0120] A first way of varying the thresholds is to use the flexoelectric effect which shifts the anchoring forces in proportion to the applied field (see document 24). This effect has a relative magnitude of \(\varepsilon(K)\frac{1}{2}\) a few \(10^{-2}\), that is to say moderate or small.

[0121] A stronger polar effect may be obtained by ion doping. This is because it is observed that the anchoring energy depends on the polarity, as shown by the experiment below.

[0122] A 45° twist cell is taken, with two planar anchorings obtained by the same \text{SiO} evaporation. A cell [0123] When the charged end of a chain adheres to the surface, the chain induces a perpendicular orientation, which decreases the planar anchoring force.

[0124] Those skilled in the art will understand that bringing the thresholds \(\text{E1}, \text{E2}\) closer together favours the writing procedure while moving the thresholds \(\text{E1}\) and \(\text{E2}\) further apart favours the erasure procedure.

[0125] Illustrative Embodiment

[0126] The inventors have produced a display with the pentylenanobiphenyl (5 CB) nematic liquid crystal which has a nematic phase at room temperature and a high dielectric anisotropy \(\varepsilon_{\parallel}-10>0\).

[0127] The display comprises glass plates 10, 12 treated with \(\text{ITO (Indium Tin Oxide)}\) which gives transparent electrodes with a low resistance (30 \(\Omega/\text{square}\)). These are treated by oblique \text{SiO} evaporation with an almost grazing evaporation angle of 75°, and thicknesses of 25 \(\text{Å}\) and 30 \(\text{Å}\), these being known to give a planar anchoring with slightly different anchoring force (document 25). The cell has a thickness of \(d=1.5\ \mu\text{m}\) with a rotation of \(\alpha=45^\circ\). The geometry of the orientations of the cell is shown in FIG. 18.

[0128] This cell makes it possible to obtain, for the 45° texture, a bright yellow colour with a high transmitted intensity. For the 180°-\(\alpha=135^\circ\) state, a low transmitted intensity, with a very dark blue, almost black, colour has been obtained.

[0129] In order to test the model, the inventors applied square pulses, of a fixed length of 300 \(\mu\text{s}\) and of amplitude \(V\) varying from 0 to 40 volts, to the system. The fall time was less than 1 \(\mu\text{s}\). Bright-to-dark (white to black) switching was obtained at \(V=24.5\) volts. Starting from a black state, the inventors always obtained a black state with these same pulses. Next, the inventors applied a pulse of the same polarity to this black state, but with an amplitude of 21.5 volts. A black-to-white transition, corresponding to erasure, was obtained. These same 21.5 volt pulses leave an initial white state unchanged. The final state of the system therefore depends, for the same polarity, only on the amplitude of \(V\). This behaviour is explained by the inventors by the fact that one of the thresholds is slightly less than 24.5 \(V\) and the other less than 21.5 \(V\). System is controlled by just the final decrease of the drive signal, the inventors performed the following experiments.

[0130] In the first place, the inventors used pulses whose front edge is linear in time, as illustrated in FIG. 20.

[0131] More specifically, the inventors chose a plateau time \(T=100\ \mu\text{s}\) and varied the rise time of the front edge \(T\) from 0 to 300 \(\mu\text{s}\). With \(T=0\), the system undergoes the white-to-black transition at \(V=25\ \text{volts}\) (or black to black if the initial state is black). Over the entire range of \(T\) used, the behaviour does not change, the threshold remaining at 25 volts \(\pm 0.5\) volts. This shows that only the amplitude and the fall of the pulse are effective.

[0132] In the second place, the inventors used pulses whose falling edge is linear in time, as illustrated in FIG. 21. For flare times of \(0>T<30\ \mu\text{s}\), the behaviour remains unchanged. Beyond this, for \(30>T<300\ \mu\text{s}\), a black-to-white erasure is obtained on starting from black, and white goes to white on starting from white. For \(T=100\ \mu\text{s}\) and \(T=0\), a threshold \(V=25\ \text{volts}\) is found. This behaviour confirms that
only the slow falling edge of the pulse is effective for erasure. By falling linearly, the triggering of the two thresholds is shifted in time. With the 21 volt and 25 volt values, the shift in time is $[(25-21)/25] \times 30 \mu s = 5 \mu s$.

[0133] This value is the estimated value of the surface tilt time.

[0134] In order to really isolate the two thresholds in the same experiment, the inventors next used a pulse having a double-square shape of amplitudes $V$ and $V'$ and of durations $T$ and $T'$, as illustrated in FIG. 22.

[0135] The inventors chose $T = 1$ ms in order to be sure that the system switches only on the falling edge, without any memory of a prior effect. With $V = 0$, a white-to-black or black-to-white switch was obtained at $V = 22$ volts.

[0136] Next, the inventors chose $V = 30$ volts, in order to be well above the threshold and, by taking $T = 0.5$ ms, they varied $V'$. For 30 volts $> V > 20$ volts, the black writing was preserved. On the other hand, for 20 volts $> V > 7$ volts, the system becomes a binary counter, that is to say that it produces white-to-black or black-to-white switch-overs. For $V'$ between zero and 7 volts, the black writing is again well-defined.

[0137] The inventors next changed the polarity of $V'$, keeping that of $V$. The same result was observed:

[0138] $-30 \text{ volts} < V' < -20 \text{ volts}$: writing in black

[0139] $-20 \text{ volts} < V' < -7 \text{ volts}$: "counter" regime

[0140] $-7 \text{ volts} < V' < 0 \text{ volts}$: writing in black.

[0141] As it stands from their work, the inventors explain the counter regime as an incomplete erasure the system remembers the initial state.

[0142] The important result from this experiment is that, for $V' = -V$, writing is obtained; this is also confirmed for $T = 1$ ms. The inventors have therefore shown that AC driving is possible.

[0143] The inventors measured $V(T)$ for the above specimen. On 5 CB for the curve of $V$, they observed writing (T) as illustrated in FIG. 23. This writing/erasure behaviour at a fixed polarity is satisfactory down to $T = 150 \mu s$. For shorter times, a "counter" regime is observed.

[0144] In order to improve this behaviour, the inventors then used a 5 CB liquid crystal doped with $10^{-5}$ mol of Na$^+$ Tp$^+$, with a thickness of 1.5 $\mu m$. They used positive pulses for writing and negative pulses for erasure. In this case, they obtained a controlled writing and erasure regime down to 10 $\mu s$, at voltages of 30 and 38 volts as illustrated in FIG. 24. At 30 $\mu s$, erasure and writing were obtained for 22 and 26 volts.

[0145] In white light, the inventors obtained a contrast of 20 between the two states.

[0146] Of course, the present invention is not limited to the particular embodiment which has just been described, but extends to any alternative form in accordance with its spirit.

[0147] In particular, the present invention is not limited to the use of nematic liquid crystals. It also extends to the use of liquid crystals of the cholesteric type.

[0148] Furthermore, the switching by hydrodynamic coupling is not limited to the use of planar anchorings on the plates. It may extend to homeotropic or even oblique anchorings.

[0149] Moreover, in a more general way, as explained above, the invention is not limited to the use of switching by hydrodynamic coupling but extends to any monostable-anchoring device, comprising means capable of causing a break in at least one of the anchorings and in subsequently inducing a bistable volume effect.

[0150] Furthermore, the invention applies to a large number of possible textures.

[0151] It is known that the treatments applied to each of the plates 10, 12 of a liquid-crystal cell may be designed to impose a planar anchoring direction (nematic director parallel to the plates, see FIG. 25), a homeotropic anchoring direction (nematic director perpendicular to the plates, see FIG. 26) or an inclined anchoring direction (nematic director which is oblique with respect to the plates, see FIG. 27).

[0152] With both these plates arbitrary, it is possible to define several textures with a single anchoring direction of the molecules on each plate.

[0153] For example, for two planar anchorings it is possible to produce a uniform planar texture, as illustrated in FIG. 16, or structures twisted to the left or to the right with a half-turn, as illustrated in FIG. 16a, or indeed with several half-turns, the nematic director in this case remaining parallel to the plates but rotating progressively around an axis perpendicular to them, or else bend structures, as shown diagrammatically in FIG. 10, for which the nematic director does not remain parallel to the plates but is progressively inclined with respect to them.

[0154] For two homeotropic anchorings, it is possible to obtain a homeotropic uniform texture (FIG. 28) or bend textures with one (FIG. 29) or more half-turns. These bend textures may, in addition, be twisted (FIG. 30).

[0155] In general with two monostable surface anchorings in two arbitrary directions, it is possible to obtain different textures: a simple texture which connects, directly by a simple twist and a simple bend, the two arbitrary anchoring directions, as illustrated in FIG. 31, and textures which differ from this simple texture by adding one or more half-turns on going from one surface to the other, as shown diagrammatically in FIG. 32.

[0156] The nematic director has been shown diagrammatically in the appended FIGS. 28 to 32 as an arrow.

[0157] By comparing FIGS. 28 and 29 or 30, 31 and 32, it may be seen that the corresponding arrows on the two plates are in opposite directions. Physically, since the interaction of the nematic liquid crystal with the surface is not polar, the opposite directions of the two arrows are equivalents with respect to the surface. However, these arrows enable the differences in volume textures, rotated for example through a half-turn between FIGS. 28 and 29, or 30, 31 and 32, to be clearly visualized. The same applies to FIGS. 1a and 1b.

[0158] Moreover, these various textures, corresponding to the same anchoring direction, possess different optical prop-
erties, which allow them to be optically distinguished and to be used as one of the two states of a black-and-white display pixel.

[0159] As indicated previously, the switching between the various textures takes place, having broken the surface anchoring.

[0160] FIG. 3 illustrates the variation in the angle θ of a surface molecule with planar anchoring as a function of an applied electric field E.

[0161] Above Eg, the surface molecules are in a situation in which the elastic energy of the interaction with the surface is maximum. If the field E is cut off, the surface molecules drop back to the initial planar orientation, but they may choose two different paths. In FIG. 3, these two paths correspond to the bifurcation below Eg between positive and negative angles. The two final states, 0 = ±90°, are identical for the surface, as explained above. However, they give different volume textures: the additional 180° rotation corresponds to a texture which is twisted through a half-turn with respect to the initial texture. If the distortion remains in the plane of the figure, a 180° bend texture is obtained (FIG. 10). In general, since twisting is easier than bending, the 180° bend is transformed continuously into a 180° twist in FIG. 1b.

[0162] The function of the switching means capable of inducing a bistable effect, after breaking the anchoring, is to control the bifurcation of the orientation Eg so as to obtain, as required, one or the other of the two corresponding bistable textures.

[0163] More generally, for any bistable texture mentioned above, obtained by varying the angles, elastic constants and the twisting power corresponding to the same anchoring on one plate and to two anchorings differing by a half-turn on the other plate, there exists a dividing line, similar to the bifurcation already described, for the surface energy on the second plate.

[0164] The purpose of the anchoring breaking is to bring the surface molecules into the vicinity of this dividing line by means of a strong electric field.

[0165] In addition, the function of the switching means, through a small external effect, is to control the movement of the system on either side of the dividing line. The two resulting directions are equivalent for the surface but lead to one or the other of the two bistable textures.

[0166] In order to break the surfaces, appropriate means will be chosen: if the field is perpendicular to the plates, it is necessary, in order to break a planar anchoring, for the liquid crystal to have positive dielectric anisotropy so that the molecules are aligned parallel to the field; in order to break a homotropic anchoring, it is necessary for the material to have negative dielectric anisotropy.

[0167] It will be noted that an important and general property of surface breaking is their rapidity: the corresponding relaxation times are in the microsecond range. They are independent of the thickness of the nematic cells.

[0168] Various means will now be described which make it possible to switch between the various possible textures, that is to say making it possible to control the bifurcation of the orientation at Eg.

[0169] Let us assume that a planar anchoring has been broken above its bifurcation point. The surface molecules are perpendicular to the plates. When the field is cut off, the molecules drop back down to one or the other of the two equilibrium states, +90° and −90°. The function of the switching means is to control the final direction of orientation between these two states. The purpose of these means is to apply a small moment to the molecules in order to make them tilt to one side or to the other. This moment may be applied either at the same time as the breaking field or just afterwards, but it must act for as long as the molecules remain close to the dividing line.

[0170] A first way of generating such a moment consists in applying a lateral electric field to the cell.

[0171] Such a lateral field may itself be obtained in several ways.

[0172] According to a first variant, the lateral field may be applied with the aid of interdigitated electrodes 50, 52 on one of the plates 10, facing the plate 12 whose anchoring is broken as shown diagrammatically in FIG. 33. The mean field remains applied between the two plates 10, 12 at the top and bottom. The lateral field gives a small oblique component to the resultant field. Depending on its sign, the oblique fields E1, or E2, are obtained.

[0173] The application of E1 or E2, which are shifted through a small angle about the normal, makes it possible to control drop-down onto the planar states 1 or 2, which are identical for the surface but different for the texture.

[0174] According to a second variant, the lateral field may be applied by means of electrodes provided along the edge of the cell.

[0175] According to a third variant, the lateral field may result from the resistance of the transparent electrodes provided on the plates 10, 12. As illustrated in FIG. 34, one of the electrodes 60 in this case possesses at least one edge 62, preferably two edges 62, which are more conducting than its central part 64. The electrical signal V necessary to break the anchoring is transmitted along the RC circuit formed by the surface resistance R and the capacitance C of the liquid crystal (see FIGS. 34 and 35). At high frequencies, a signal is rapidly attenuated and the pixel appears as an electrode edge, giving an oblique field. At low frequencies there is no attenuation and the field is vertical. This mechanism is described in document FR-A-86 00916. A field inclined in both directions is obtained by using double-lateral-control pixels: the signal V1 or V2 is applied to one or the other of the conducting edges of the semi-transparent electrode of the pixel. V1 gives the right orientation and V2 the left orientation.

[0176] A second way of generating the aforementioned orienting moment consists in exploiting a hydrodynamic effect.

[0177] In this case, at the time of returning to equilibrium, a small shear v is generated between the plate with broken anchoring and the nematic.

[0178] This may be achieved by a mechanical displacement of all or part of the plate, due to the effect of a piezoelectric system for example, or else due to the effect of sound waves.
The nematic is sensitive to the velocity gradient close to the plate and drops, depending on the direction of \( v \) (or \( v_x \) or \( v_y \)), on one side or on the other side of the bifurcation.

The shear \( v \) may also be produced by a flow between the two plates, this being produced by any source whatsoever, for example by simply pressing on the screen perpendicular to the plates.

The system then constitutes a pressure detector. It may be used to write on a screen, by converting the pressure into an electrical property associated with one of the two bistable textures.

Another variant consists in exploiting the shear current caused by the tilting of certain molecules. This effect is the reverse of the previous effect, in which a shear controls a tilt.

To do this, it is possible to use, for example, a linear drive electrode \( e \) alongside a square pixel (FIG. 36).

At \( e \) the anchoring is, for example, oblique while at \( P \) it is planar.

Due to the effect of a field applied to the pixel, the anchoring \( P \) is broken.

If a drive field \( E \) is applied to the lateral electrode, at the time when the field \( E \) is cut off, the flow \( v \) associated with the reorientation of \( c \) due to the effect of \( E \) switches the orientation of the pixel \( P \) into state 1.

If on the other hand the field \( E \) is applied at the same time as \( E \) and if it is also cut off at the same time, the flow caused by \( E \) is in the opposite direction, \(-v\), and the pixel switches into state 2.

Another variant which exploits hydrodynamic coupling and consists in breaking two face-to-face anchoring has been described previously.

Of course, the invention is not limited to the bifurcation control examples described previously in the case of planar geometry which, after breaking, become homeotropic.

Indeed, as mentioned, the invention also applies to controlling the bifurcations in geometries which are homeotropic or inclined in the off state.

Furthermore, the tilting may be performed in two dimensions, by involving not only the zenithal surface angle \( \theta \) but also the azimuthal angle \( \sigma \), as described previously in the case of hydrodynamic coupling. Rotation of \( \theta \) equal to \(-90^\circ\) to \(+90^\circ\) may also be interpreted as a simple \( 180^\circ \) rotation of \( \phi \). This is important for the couplings with the lateral electric fields or the lateral hydrodynamic flows, which have a well-defined azimuthal direction.

It will furthermore be noted that the switching may be performed over the entire surface of a pixel at the same time, in order to form a back-and-white display, or over a variable part of this pixel, in order to form a grey-tone display.

Driving only a variable part of a pixel may be achieved either by a non-uniform breaking field on the latter or by non-uniform means for controlling the bifurcation.

Finally, it will be noted that, in some configurations, the anchoring breaking means and the means capable of inducing a bistable volume effect, which were described previously, may be used with multistable, for example bistable, anchorings and not just monostable anchorings.

Up to now, it has essentially been demonstrated in the preceding description that the breaking of a planar anchoring makes it possible to control a transition between two bistable volume textures. This is, in this case, complete breaking—in an electric field the molecules on the surface orient precisely along the field, passing through the point of bifurcation. The breaking of oblique anchorings, also mentioned in the preceding description, is different. This is a partial breaking: the molecules move towards the direction of the field, without ever reaching it and without passing through the point of bifurcation.

Within the scope of the invention, the use of this partial breaking of the oblique anchorings will now be explained in detail.

The oblique anchoring plate may fulfill two different roles:

1) Either an emitter role (“master plate”)—in this case the oblique anchoring plate serves to drive the to its initial orientation (see FIG. 39). The angle \( \theta \) increases exponentially as \( \theta_{\text{max}} \exp(-t/T) \), from the high initial value \( \theta_{\text{in}} \), and afterwards saturates to the value imposed by the oblique anchoring. On the other hand, the planar plate 12 is in unstable equilibrium at \( t=0 \) and tilts slowly: \( \theta_{\text{52}} \) also increases exponentially, but from a very low angle \( \theta_{\text{52}} \), which is determined by fluctuations.

The shear produced by each of the plates 10, 12 is proportional to the derivative of the angle with respect to time. It is much greater for the oblique plate 10 (of the order of \( \theta_{\text{10}}/T \gg \theta_{\text{52}}/T \)). The latter plate thus becomes a master plate; its shear current after diffusion through the specimen 20 drives the planar slave plate 12 beyond the point of bifurcation (FIG. 37e). A bend half-turn is therefore produced in the specimen 20, which transforms into a twist half-turn (FIG. 37d).

Alternatively, in order to erase the half-turn, it is necessary to prevent the hydrodynamic coupling between the two plates 10, 12. One way of doing this is to decrease the voltage across the threshold \( U_{\text{C2}} \) gradually, as illustrated in FIG. 40.

During the first part of the pulse (i.e. from \( t=0 \) to \( T \)), the anchoring on the planar plate 12 is broken and irrespective of the initial texture the almost homeotropic texture in FIG. 37b or 41a is obtained. The slow fall \( (T>>T) \) through the threshold renders the hydrodynamic effect induced by the master plate 10 barely effective. The slave plate 12 is now driven by the weak elastic static coupling (FIG. 41b), which always favours the uniform final texture (FIG. 41c).

Another way of achieving the same effect—that is to say of erasing the previously obtained half-turn in the specimen 20—is to use a two-step rectangular electrical signal (FIG. 42). Once again, the initial texture is erased during the first part of the pulse (FIG. 43a) (from 0 to \( T \), in FIG. 42). At \( t=T \), the voltage abruptly falls to \( U \) slightly
above the threshold $U_{\text{c}}$. The master plate 10 produces a strong transient hydrodynamic current (FIG. 43b), which gradually disappears. The anchoring remains perpendicular in the broken position. The elastic effect, which in this geometry is permanent, overcomes it and at the end of the pulse the slave plate 12 has already chosen an inventors have observed writing of half-turns. Lengthening $\tau_3$ without changing the voltage $U$, they always obtained a uniform final texture.

[0204] These observations confirm the model explained above and show that the use of an oblique anchoring master plate 10 is a highly effective means for writing and erasing the half-turns. Similar results were also obtained with cells having a pretwist between 0° and 90°, these being obtained by rotating one of the plates with respect to the other (as already explained, this geometry facilitates the hydrodynamic coupling).

[0205] We will now tackle the case of an oblique anchoring slave plate.

[0206] To understand the utility of an oblique anchoring slave plate 12, we will analyse the anchoring breaking in a cell in which the molecules on both plates 10, 12 have oblique anchoring (FIG. 45): the angle of inclination $\theta_2$ is greater on the master plate 10 and much smaller on the slave plate 12.

[0207] We start with the “uniform” (twist-free) texture in FIG. 45a. In an electric field perpendicular to the plates 10, 12, the molecules on the two surfaces 10, 12 move towards the vertical, without ever reaching it (FIG. 45b and 46): for both surfaces, the point of bifurcation is on the other side of the vertical (FIG. 47). In FIG. 47, $\Gamma_1$ depicts the hydrodynamic moment, $\Gamma_2$ the elastic moment and $\eta$ the direction of the anchoring energy maximum (bifurcation).

[0208] Let us now assume that the field is strong enough to orient the molecules on both surfaces 10, 12 (FIG. 45b) so as to be almost vertical ($\theta_1=\theta_2=0$). When the field is cut off, a large elastic surface moment $\Gamma_\eta=m(\kappa l_\alpha)\eta_x$ acts on the master plate 10. $l_\alpha$ represents the anchoring force on the plate 10. The molecules on this plate 10 tilt towards their initial position, emitting a high shear current. The hydrodynamic moment $\Gamma_\eta$ transmitted to the slave plate 12 is of the order of $K_\eta d$ and it tries to tilt the molecules through the vertical (FIG. 45c). An elastic surface moment $\Gamma_\eta$, of the order of $K_{\eta\alpha} l_\alpha$, opposes this. $l_\alpha$ represents the anchoring force on the plate 12. The condition for writing half-turns in this geometry is therefore obtained: $K_\eta d > K_{\eta\alpha} l_\alpha$, or $\alpha_{\eta\alpha} l_\alpha > d$, that is to say that the oblique slave plate 12 can be driven effectively if its anchoring is weak and its field-free inclination $\theta_2$ is very close to 90° (almost planar). If this is the case, the bend half-turn in FIG. 45d and, finally, the twist half-turn in FIG. 45e are obtained.

[0209] For erasure, an electric field is once again applied to the twist half-turn texture (FIG. 48a). In a field, it transforms to a bend half-turn (FIG. 48b), which allows the molecules to orient along the field almost throughout the specimen. However, close to the slave plate 12, a thin region of almost planar orientation remains. This region is topologically blocked in the texture: its existence depends on the relative orientation of the two anchoring and on the initial volume texture. A high (elastic and electric) energy is stored in the planar region and the resultant moment pulls on the molecules at the surface towards the plate 12 and no longer towards the vertical: in this way, the planar region is “expelled” from the specimen and the energy decreases (FIG. 48b and 48c).

[0210] The behaviour of the surface angle $\theta_2$ as a function of the field is diagrammatically shown in FIG. 49, assuming that, with no field, $\theta_2$ is large and negative ($\theta_2$=90° and $\theta_2$=0°). The point A in FIG. 49a. In a field, $\theta_2$ decreases (path ABC in FIG. 49) and the molecules move towards the $\theta_2$=90° direction, which corresponds to the anchoring energy maximum and therefore to the zero anchoring moment. At the critical value $\theta_2$, the anchoring moment can no longer balance the electric moment and the surface becomes unstable: $\theta_2$ switches to the path CD (FIG. 49) and the molecules are now on the other side of the vertical (FIG. 48d). If the field is now decreased gradually (in order to eliminate the hydrodynamic coupling), $\theta_2$ follows the path DE (FIG. 49) and the final state of the system is the non-twisted texture in FIG. 48e the half-turn is erased.

[0211] This erasure mechanism, discovered by the inventors, uses a breaking of the oblique anchoring on the slave plate 12 which is induced by the elastic interaction with the oblique master plate 10 and the initial texture. An initial texture may be erased by this mechanism only if it includes a planar region in the volume. On the other hand, in order to write such a texture, it is necessary to use other means, for example the hydrodynamic effect: the elastic breaking of the anchoring of the slave plate 12 is a transient and irreversible phenomenon, passage along the path CD (FIG. 49) being a one-way process.

[0212] On the other hand, if the field is cut off before exceeding the point C, $\theta_2$ returns to A and the texture remains twisted after cutting off a field. This is because, if the field is too low to exceed the point C, rewriting occurs.

[0213] In order to demonstrate the utility of the oblique slave plates 12, the inventors prepared several thin specimens (d=1.5 μm) with the oblique master plate 10 (evaporated SiO and an angle of inclination of the molecules with respect to this surface of approximately 35°) ($\theta_2$=90°=35°-55°). The slave plates were prepared with different rubbed polymers ($\eta_x$, angle of inclination of between 2° and 10°).

[0214] In order to facilitate the writing of half-turns by means of the hydrodynamic coupling, a pretwist angle $\phi$ (between 0° and 90°) was imposed by rotating one of the plates with respect to the other. As already explained, this pretwist helps the hydrodynamic effect. The writing of half-turns was observed for $\phi$ close to 80° and with a voltage of 40-50 V. This difficulty in writing is due to the fact that the polymeric anchorings have a very high anchoring energy.

[0215] On the other hand, for all geometries, the inventors observed erasure, by elastic transient breaking, of those initial structures which include a planar region in the volume. The oblique slave plates can therefore be used to write and erase bistable volume textures on condition of having a low anchoring energy and a low inclination.

[0216] The two volume textures used in the devices described above are bistable: in the absence of an external field they cannot undergo a transition to another, lower-energy texture except by surface breaking or by defects.
Therefore, in the absence of an external field and of any defects, each of the textures is stable for an infinitely long time by virtue of the topological incompatibility of the two textures.

However, in practice the two textures may have very different energies, especially in the case of nematic liquid crystals. This may create defects which move with greater or lesser rapidity, spontaneously erasing the high-energy texture and writing the other. This property may be undesirable in some applications, if a long memory time is required of the device.

The time for spontaneous erasure caused by movement of the defects depends on several parameters: thickness of the cell, dimensions of the pixel, chiral dopant, geometry (greater or lesser pretwist), etc. Some of these parameters may be adjusted in order to lengthen or shorten the spontaneous erasure time. For example, FIG. 50 shows the dependence of the spontaneous erasure time \( \tau_e \) on the thickness of the cell (2x2 mm\(^2\) pixel, undoped 5 CB nematic with a half-twist texture, which transforms into a uniform texture with no pretwist). It may be seen that the time \( \tau_e \) changes with thickness over a wide range (from 0.1 to 1 second) and may be adjusted depending on the application. The spontaneous erasure time \( \tau_e \) may also be controlled by the pretwist \( \alpha \) of the cell. At \( \alpha=90^\circ \) for example, the energies of the two textures become equal and \( \tau_e \) tends toward infinity.

However, the thickness and the pretwist are also important parameters in the case of field-induced surface transitions. It is therefore preferable to control \( \tau_e \) by other means, in particular by the spontaneous twist induced in the nematic by adding a low concentration of cholestERIC.

The inventors prepared several specimens with nematic-cholesteric mixtures in order to control the spontaneous erasure time \( \tau_e \). FIG. 51 shows the optical behaviour of such a specimen when the half-twist (180° twist) texture is written and when it is erased (uniform texture, with no twist). The energies of the two textures were made almost equal by adding a few percent of cholesteric. As a result, the time \( \tau_e \) was extended to several hours, it is infinitely long compared to the scale of the figure.

The possibility of extending the spontaneous erasure time of the bistable textures by equalizing their energies has been described above. This makes it possible to use one of the main advantages of the bistability: after cutting off the field, the final texture is preserved indefinitely, or at least for a time \( \tau_e \) which is very long compared to the refresh time of the device \( \tau_r \), specific for each application. For some applications, \( \tau_e \) is very long or ill-defined. For example, be chosen (FIG. 52) one of which (FIG. 52A) has a field-free elastic energy which is much greater than the other (FIG. 52B). As a non-limiting example corresponding to an oblique anchoring on the plate \( 10 \) and a planar anchoring on the plate \( 12 \), the low-energy texture B in FIG. 52B is the twist-free slightly splayed texture and the texture A in FIG. 52A is the half-twist texture.

In the absence of an external electric field, the texture A is metastable: in a characteristic time \( \tau_m \) it transforms into B by nucleation and propagation of defects. The time \( \tau_m \) is adjusted to \( \tau_m-\tau_r \), the refresh frequency, by controlling, for example, the density of the defect nucleation centres on the plates or by chiralization of the nematic. In such a way, the texture A, once written, self-erases after \( \tau_s \), that is to say at the end of the image. In order to break the anchoring, only a single mechanism is now required, that which writes the texture A. For this example, the hydrodynamic coupling already described may be used.

A second non-limiting example of a metastable-mode device is shown in FIG. 53. This time, opposite oblique anchoring is chosen on the two plates 10, 12 and the texture A may be written by the irreversible transient breaking of the anchoring on the slave plate 12. In a field \( \mathbf{E} \), the anchoring on the plate 12 breaks and \( \theta_{ad} \) jumps to the other side of the bifurcation, as described already. In this specific case, the hydrodynamic coupling and elastic coupling do not oppose each other but, on the other hand, help each other to write the texture A. Writing becomes very effective and rapid, and the threshold \( \mathbf{E} \) decreases.

The metastable anchoring-breaking displays described above have, in particular, the following advantages.

The metastable display preserves all the advantages of surface bistability, except the infinite memory, which in this case is limited to the time \( \tau_e \). The write time \( \tau_e \) is very short, typically \( 10 \mu s \) for \( U=20 \) volts.

A first advantage of the metastable display compared with the conventional nematic displays is its abrupt threshold.

In a conventional display, a change in texture (and therefore an optical response) is produced by applying a strong short pulse. The optical response just after the pulse is plotted in FIG. 54 (curve a) as a function of the applied voltage. At \( U<U_a \), the threshold voltage, no change in texture occurs. At \( U>U_a \) an optical response, the amplitude of which increases with voltage, is obtained. The threshold is greatly spread out, of the to the gradual change-over in the textures, which pass, during and after the drive voltage, through a whole continuum of intermediate states. This spread greatly limits the multiplexing rate of continuous-response systems.

In the metastable displays in accordance with the present invention, the threshold \( U_a \) is very abrupt (curve b in FIG. 54): there is no longer a progressive \( B \rightarrow A \) change-over, and the display writes in "all or nothing" mode. No intermediate states exist which would impart a gradual nature to the optical response. Those skilled in the art know that such an abrupt threshold makes infinite multiplexing possible. This is a very important advantage compared with classical volume displays.

Another advantage of the invention compared with nematic-liquid-crystal volume displays is the possibility of adjusting the erasure time \( \tau_e \) depending on the application, without changing the duration and the voltage of the drive pulses. It is possible, for example, to control \( \tau_e \) by the cholesteric doping or by the density of defect anchoring centres, independently of the surface breaking threshold. In contrast, in conventional nematic volume displays, a relationship exists between the write time \( \tau_e \), the field-free erasure time \( \tau_e \) and the threshold voltage \( U_a : \tau_e = \tau_e U_a^2 \), or \( U_a = V \) for nematics with a high dielectric anisotropy. For rapid writing (\( \tau_e=10 \mu s \)) and video-rate erasure (\( \tau_e=40 \) ms),
U_o=60 V is obtained for a nematic volume display, compared to only U_o=15 V for the metastable display of the invention (FIG. 55).

[0230] The inventors have produced a cell in the geometry of FIG. 52 which corresponds to the first example mentioned above, with the undoped 5 CB liquid crystal. The master plate 10 is oblique (SiO, grazing evaporation, θ_o=55°) and the slave plate 12 is planar (SiO, θ_o=90°). The thickness of the cell is defined by ball spacers (d=1.5 μm) placed on the planar plate 12. The texture A (twist half-turn) is written using short rectangular pulses. The very low write threshold in this cell (FIG. 55) confirms the effectiveness of the hydrodynamic control brought about by the oblique master plate 10. The spontaneous erasure occurs by nucleation of defects on the spacer balls, the density of which was chosen to be quite high in order to obtain a reasonably short erasure time τ_e≈300 ms (FIG. 56).

[0231] In a second cell, which corresponds to the second example mentioned above, the inventors have tested the writing, using elastic breaking, in the geometry of FIG. 53. This cell, filled with pure 5 CB, is thicker (d=3.5 μm) in order to demonstrate that the elastic effect does not depend critically on the thickness. The master plate 10 has a highly oblique anchoring (SiO, grazing evaporation, θ_o≈55°), while the slave plate 12, prepared by deposition of a thin film of PVA on the evaporated SiO, is slightly oblique (θ_o=86°). Once again, the write threshold for the half-turn state is very low (E_w=11 V/μm for τ_e≈10 μs), demonstrating the effectiveness of the elastic mechanism for anchoring breaking. For this thick cell, τ_e≈3 ms is measured.

[0232] The methods of excitation in an alternating field, in accordance with the present invention, will now be explained in detail.

[0233] For practical reasons, liquid-crystal displays must preferably be driven by “alarming” signals such that the mean value of the applied voltage is as low as possible. This makes it possible to avoid the irreversible electrochemical effects which would limit the lifetime of the display. The inventors have demonstrated experimentally the equivalence of “polar” and “alarming” signals for causing surface breaking. This arises physically because of the fact that the volume moments transmitted to the surfaces are mainly of a dielectric origin (−E) and does not depend on the sign of the electric field.

[0234] By way of example, the inventors have shown the equivalence, in the case of writing, of a “polar” signal having an amplitude V_o=13 V and a duration τ=40 μs, as illustrated in FIG. 57, with a square “alarming” signal having an amplitude very close to V_o=13.4 and the same duration, as illustrated in FIG. 58.

[0235] The same equivalence is observed for the erasure signals: a polar voltage V_o=5 V and τ=240 μs gives erasure while an alternating voltage of approximately V_α=5.3 gives the same erasure.

[0236] The inventors have observed a small difference between two “alarming” signals of opposite phase, as illustrated in FIGS. 59 and 60. This difference arises from a small flexoelectric contribution to surface anchoring breaking. They observe, for example, that the signal in FIG. 59, having V_o=5.8 and τ=240 μs, writes the half-turn and that the signal V_o, having the same amplitude and same duration, in FIG. 60 causes erasure. This may make it possible in practice to use only the phase of alternating signals to cause surface breaking, as explained previously, by using the sign of polar signals.


1. Display device comprising two parallel transparent plates (10, 12) provided with electrodes on their internal surfaces and containing a liquid-crystal material (20), characterized in that it comprises:

- means defining a monostable anchoring on each plate (10, 12);
- means (40) breaking, on command, at least one of these anchorings; and
- means inducing, after this breaking, a bistable volume effect.

2. Device according to claim 1, characterized in that the anchoring breaking means (40) are suitable for breaking the anchorings on both the plates (10, 12).

3. Device according to either of claims 1 and 2, characterized in that the monostable anchorings are planar.

4. Device according to either of claims 1 and 2, characterized in that the monostable anchorings are homeotropic.

5. Device according to either of claims 1 and 2, characterized in that at least one of the monostable anchorings is oblique with respect to the plates (10, 12).

6. Device according to either of claims 1 and 2, characterized in that one of the anchorings is homeotropic and the other planar.

7. Device according to either of claims 1 and 2, characterized in that one of the anchorings is planar and the other oblique.

8. Device according to either of claims 1 and 2, characterized in that one of the anchorings is homeotropic and the other oblique.

9. Device according to one of claims 1 to 8, characterized in that the anchoring breaking means comprise means capable of applying an electric field.

10. Device according to claim 9, characterized in that the anchoring breaking means comprise means capable of applying an electric field perpendicular to the plates (10, 12).

11. Device according to claim 10, characterized in that the anchoring is planar and the liquid crystal possesses a positive dielectric anisotropy.

12. Device according to claim 10, characterized in that the anchoring is homeotropic and the liquid crystal possesses a negative dielectric anisotropy.
13. Device according to one of claims 1 to 12, characterized in that the anchoring breaking means are suitable for placing the liquid crystal in an unstable situation in which the elastic energy of interaction of the liquid-crystal surface molecules with the surface of the plates (10, 12) is maximum.

14. Device according to one of claims 1 to 13, characterized in that the means inducing a bistable volume effect comprise means capable of applying a lateral electric field to the device.

15. Device according to claim 14, characterized in that the means inducing a bistable volume effect comprise interdigitated electrodes (50, 52) on one of the plates (10), facing the plate (12), the anchoring of which is broken, and means capable of applying a drive voltage to at least one of these electrodes, this being chosen alternately.

16. Device according to claim 14, characterized in that the means inducing a bistable volume effect comprise at least one electrode (60) possessing at least one edge (62) which is more conducting that its central part (64).

17. Device according to claim 14, characterized in that the means inducing a bistable volume effect comprise electrodes along the edge of the device.

18. Device according to one of claims 1 to 13, characterized in that the means inducing a bistable volume effect comprise means capable of generating a hydrodynamic effect.

19. Device according to claim 18, characterized in that the means inducing a bistable volume effect comprise means capable of producing a mechanical displacement of at least one part of the plate, for example by using a piezoelectric system or by using sound waves.

20. Device according to claim 19, characterized in that the means inducing a bistable volume effect comprise means capable of ensuring a mechanical transverse stress to the plate.

21. Device according to claim 19, characterized in that the means inducing a bistable volume effect comprise means which include an auxiliary electrode (e) placed alongside an electrode (p) defining a pixel.

22. Device according to claim 21, characterized in that the anchoring is oblique on the auxiliary electrode (e) and is provided with means selectively applying a drive field to the auxiliary electrode at the moment when the electric field on the pixel electrode (p) is cut off or a drive field to the auxiliary electrode at the same time as the electric field on the pixel electrode (p).

23. Device according to one of claims 18 or 19, characterized in that the means inducing a bistable volume effect comprise means defining a hydrodynamic coupling between the two plates (10, 12).

24. Device according to one of claims 1 to 24, characterized in that the means for anchoring breaking and for bistable volume switching are suitable for homogeneously driving the entire surface of a pixel.

26. Device according to one of claims 1 to 24, characterized in that at least one of the means for anchoring breaking and for bistable volume switching is suitable for driving a variable part of a pixel.

27. Device according to claim 19 or 24, characterized in that:

the plates (10, 12) define different anchoring thresholds;
the thickness of the device between the two plates (10, 12) is sufficiently small to allow hydrodynamic coupling between the internal surfaces of the plates; and
means (40) are provided which apply, between the electrodes of the two plates alternately, a write electric-field pulse above a threshold capable of breaking the anchorings on the two plates (10, 12) in order to define, after interruption of this electric field, a twisted first stable state resulting from hydrodynamic coupling between the two plates (10, 12) and a second electric field, below the said threshold capable of breaking a single anchoring or having a falling edge which varies very slowly in order to decouple the tilts on the two plates, so as to define a homogeneous second stable state.

28. Device according to claim 27, characterized in that the liquid-crystal material (20) is a nematic liquid crystal.

29. Device according to claim 27, characterized in that the liquid-crystal material (20) is a cholesteric liquid crystal.

30. Device according to one of claims 27 to 29, characterized in that the liquid-crystal material (20) possesses a positive dielectric anisotropy.

31. Device according to one of claims 27 to 30, characterized in that the thickness (d) of the liquid-crystal material is less than 1/\(\theta_0\), in which expression:

\(\theta_0\) denotes the extrapolation length defining the zenithal anchoring energy; and

\(\theta_0\) denotes the angle of the surface molecules.

32. Device according to one of claims 27 to 31, characterized in that the thickness (d) of the liquid-crystal material satisfies the relationship: \(d < (\eta / K \rho)^{1/2}\) in which:

1 denotes the extrapolation length defining the zenithal anchoring energy;

\(\eta\) denotes a viscosity;

\(K\) is the elastic curvature constant; and

\(\rho\) is the density.

33. Device according to one of claims 27 to 41, characterized in that the surface treatments on the two plates (10, 12) are suitable for defining anchoring thresholds which differ by from 5 to 10%.

34. Device according to one of claims 27 to 42, characterized in that the anchoring thresholds depend on the polarity of the applied electric field.

35. Device according to one of claims 27 to 43, characterized in that the liquid-crystal material (20) is doped by ions which make it possible to modify the tilt thresholds of the molecules on at least one of the plates.

36. Device according to claim 44, characterized in that the ions are chosen from the group comprising sodium tetrathyphalaborate, tetrabutylammonium chloride and cetyltributylammonium bromide.

37. Device according to one of claims 27 to 45, characterized in that the fall time of the write drive voltage is less than 30 \(\mu s\).

38. Device according to one of claims 27 to 46, characterized in that the fall time of the erase drive voltage is greater than 30 \(\mu s\).
48. Device according to one of claims 27 to 47, characterized in that the electrical drive means (40) are suitable for applying an alternating electrical voltage.

49. Device according to one of claims 5 or 7, characterized in that it comprises means applying write electric-field pulses with an amplitude greater than the threshold for breaking the anchoring on the plate (12) opposite the oblique anchoring master plate (10).

50. Device according to claim 49, characterized in that it comprises means applying an erasure electric field whose amplitude decreases gradually in order to get over, by default, the threshold for breaking the anchoring on the plate (12) opposite the oblique anchoring master plate (10).

51. Device according to claim 49, characterized in that it comprises means applying an erasure electric field consisting of two successive steps: a first step markedly above the threshold for breaking the anchoring on the plate (12) opposite the oblique anchoring master plate (10) and the second step just slightly above this anchoring breaking threshold in order to limit the hydrodynamic effect during the cutoff of this second step.

52. Device according to claim 1, characterized in that the anchorings are oblique on the two plates (10, 12).

53. Device according to claim 52, characterized in that the angle of inclination of the anchoring is large on a master plate (10) and lower for a slave plate (12).

54. Device according to either of claims 52 and 53, characterized in that it comprises means applying write electric-field pulses with an amplitude greater than the threshold for breaking the anchoring on both the plates (10, 12).

55. Device according to one of claims 52 to 54, characterized in that it comprises means applying an erasure electric field with an amplitude greater than the threshold for breaking the anchoring on the oblique anchoring slave plate (12).

56. Device according to one of claims 49 to 55, characterized in that the anchorings on the two plates (10, 12) have a pretwist in the off-state, favouring the hydrodynamic effect.

57. Device according to one of claims 1 to 56, characterized in that the liquid crystal comprises a nematic/cholesteric mixture.

58. Device according to claim 57, characterized in that the anchorings on the two plates (10, 12) are twisted through 90°.

59. Device according to either of claims 57 and 58, characterized in that the liquid crystal comprises a nematic/cholesteric mixture.

60. Device according to one of claims 1 to 59, characterized in that, for a metastable operation, the anchorings on the plates (10, 12) define two textures in the absence of a field, one having an elastic energy much greater than the other.

61. Device according to claim 60, characterized in that the two textures correspond to an oblique anchoring on one plate, (10), and a planar anchoring on the other, (12).

62. Device according to claim 60, characterized in that the two textures correspond to oblique anchorings on each of the plates.

63. Device according to one of claims 60 to 62, characterized in that the two textures correspond to a splayed non-twisted texture and the other to a half-turn twist texture.

64. Device according to one of claims 60 to 63, characterized in that it comprises ball spacers between the plates (10, 12) favouring the nucleation of defects.

65. Device according to claim 53, characterized in that the texture of the LCD molecules includes a volume planar zone, and in that the device includes means capable of applying electric-field pulses with an amplitude greater than the irreversible breaking threshold in order to convert the stable texture having a volume planar zone into another stable texture.

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