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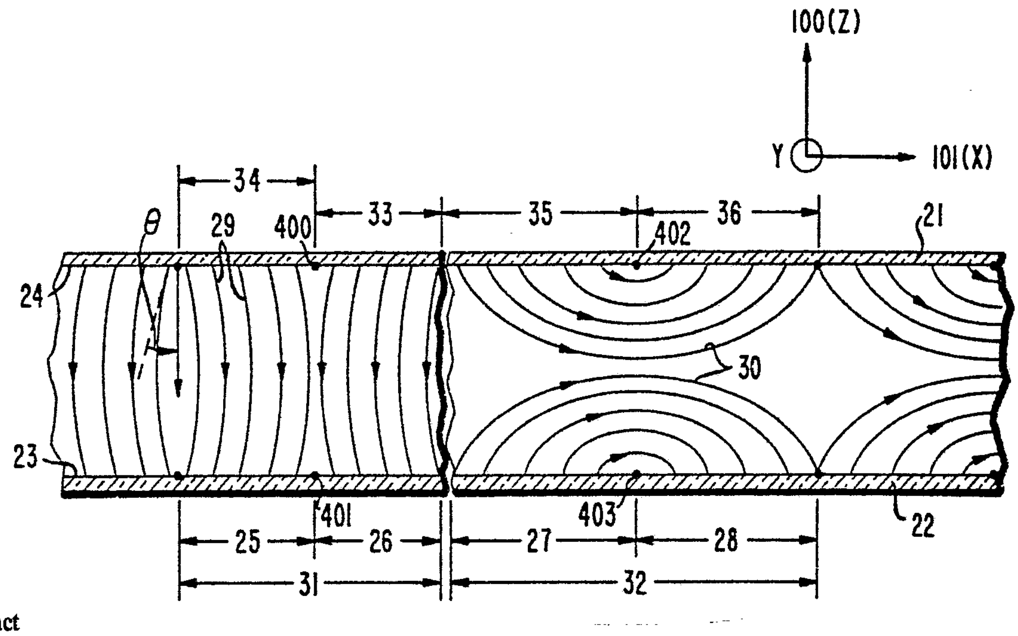

(57) Abstract

A liquid crystal cell (1010) having memory is provided by disposing a liquid crystal material having nematic directors between two substrates (910, 950) which are fabricated to contain an array of singular points (e. g., 921). The cell may further include means for detaching singularities such as appropriate electrode arrangements (FIG. 12, 60-63). These substrate configurations provide multistable configurations of the director alignments because disclinations must be moved, either through the bulk of the liquid crystal material or on the substrate surfaces, to switch between the stable configurations. The switching of the device between stable configurations may be accomplished by the application of electrical fields to the liquid crystal material. The stable configurations may be optically differentiated by the incorporation of pleochroic dyes into the liquid crystal material or by the use of crossed polarizers (FIG. 29, 303, 304).

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MECHANICALLY MULTISTABLE LIQUID CRYSTAL CELL

Background of the Invention

This invention pertains to the field of liquid crystal displays, and more particularly to a liquid crystal cell that can be utilized in displays.

Present nematic liquid crystal displays are primarily field-effect devices which lack memory, and thereby suffer from stringent multiplexing limitations imposed by refresh requirements. A persistent electro-optic response in such nematic type displays requiring no sustaining voltage is desirable.

Summary of the Invention

Devices fabricated in accordance with the present invention comprise a liquid crystal material disposed between two substrate materials, the liquid crystal material having orientational directors. Mechanically stable liquid crystal configurations in a cell, that is, stable states not requiring the addition of energy to maintain the states, are achieved by using substrates whose surfaces contain an array of singular points or, in the alternative, by combining substrates with means for generating singularities. A singular point may be broadly defined for the purposes of the present invention as a point on the substrate at which a director alignment ambiguity exists. The presence of the singular points requires that the switching from one mechanically stable configuration to another requires the movement of disclinations either through the bulk of the liquid crystal or on the substrate surfaces. (The singular points also serve as sources from which these disclinations are generated.) Since the energy of the intermediate configurations, i.e., those configurations where disclinations are moving, is larger than that of the stable configurations, the need to move disclinations for switching provides an energy barrier between the configurations and results in stability. To provide, within a single body of liquid crystal material, adjacent portions which can be in different stable configurations (so as to produce, e.g., an optical display), isolation means comprising special boundary conditions are provided between the adjacent portions.

Brief Description of the Drawing

FIG. 1 shows, in graphical form, an energy diagram which illustrates the concept of bistability;

FIG. 2 shows, in diagrammatic form, a liquid crystal cell;

FIG. 3 shows, in diagrammatic form, the surface of a substrate with regions of director alignment giving rise to lines of singular points at the boundaries between said regions;

FIG. 4 shows, in diagrammatic form, the definition of positive and negative director alignment;

FIG. 5 shows, in diagrammatic form, the surface of a substrate with regions of director alignment having straight line boundaries;

FIG. 6 shows, in diagrammatic form, untwisted and twisted director alignment configurations;

FIG. 7 shows a diagrammatic cross section of one embodiment of the present invention;

FIG. 8 shows in diagrammatic form a top view of a cell element as appropriate for use in the embodiment shown in FIG. 7;

FIG. 9 shows, in diagrammatic form, the top view of several cells shown in FIG. 8 taken together;

FIGS. 10 and 11 show a diagrammatic cross section of a modification of the FIG. 7 embodiment;

FIGS. 12, 13, and 14 show diagrammatic cross sections of different embodiments of the invention;

FIGS. 15-18 show, in diagrammatic form, a model of the transition from a "vertical" stable configuration to a "horizontal" stable configuration for the embodiment shown in FIG. 12;

FIGS. 19-22 show, in diagrammatic form, a model of the transition from a "horizontal" stable configuration to a "vertical" stable configuration for the embodiment shown in FIG. 12;

FIGS. 23-27 show, in diagrammatic form, a model of the transition from a "vertical" stable configuration to a "horizontal" stable configuration for the embodiment shown in FIG. 7;

FIG. 28 shows, in diagrammatic form, a cross section of the FIG. 12 embodiment wherein the field lines for switching from the "horizontal" to the "vertical" stable configuration are displayed;

FIG. 29 shows in diagrammatic form a section of the FIG. 7 embodiment including crossed polarizers;

FIGS. 30, 31, and 32 show, diagrammatically, electrode arrangements for various embodiments of the invention;

FIGS. 33-35 show, in diagrammatic form, a cross section of FIG. 32;

FIGS. 36 and 37 show, in diagrammatic form, the transition between stable configurations in different embodiments;

FIG. 38 shows, in diagrammatic form, the relationship between the "horizontal" and "vertical" stable configurations in conjunction with a cell boundary having tilted director alignments;

FIG. 39 shows experimental results of disclination velocity and approximate switching time between stable configurations for the embodiment shown in FIG. 12;

FIG. 40 shows the relative optical transmission of the embodiment shown in FIG. 7;

FIG. 41 shows the transit time for the switching of the embodiment shown in FIG. 7;

FIGS. 42-43 show a diagrammatic cross section of the field lines produced by an electrode arrangement suitable for switching between stable configurations for the embodiment shown in FIG. 12; and

FIG. 44 shows, in schematic diagram form, a wave form and an electrode arrangement for switching between stable configurations for the FIG. 12 embodiment.

Detailed Description

Devices fabricated in accordance with the present invention comprise a liquid crystal material disposed between two substrate materials. These devices exhibit mechanically stable configurations of alignment of the directors of the liquid crystal material.

We have discovered how to form liquid crystal cells in these devices which have mechanically stable configurations of alignment of the orientational directors (e.g., the liquid cystal molecules) of the liquid crystal material. For the moment it is best to envision the liquid crystal cell to be a volume of liquid crystal material within the device which is bounded on the top by the surface of one of the two substrates and on the bottom by the surface of the other one of the two substrates. The sides of the volume comprise surrounding liquid crystal material. Hereinbelow we will describe how these individual cells are combined in devices but our invention, which specifically addresses the structure which provides for mechanically stable configurations, is best understood by considering the liquid crystal cell described hereinabove. Basically the aspect of the invention which provides the stable configurations addresses specific treatments of the substrate surfaces which bound the liquid crystal cell.

Configurations of director alignment which are mechanically stable with respect to each other can be described mathematically by the existence of two different solutions of the equilibrium equation for the same physical boundary conditions. For example, a mechanically bistable liquid crystal cell is one in which the liquid crystal directors can assume either of two different ordered stable configurations of equal or nearly equal energy.

(Degeneracy in the sense of equivalent energy is, however, not a prerequisite to bistability.)

Our analysis of this problem has led us to the conclusion that one class of mechanically stable configurations is that in which movement of disclinations (a discontinuity in the direction of the orientational directors) through the bulk of the liquid crystal material or possibly on the surface of the substrates is necessary in order to switch from one stable configuration to another. The movement of the disclinations causes the director alignment of one stable configuration to evolve into the director alignment of another stable configuration. The inducement of such movement requires the addition of energy to the system with the result that the configurations separating the stable configurations have a higher elastic energy content than either of the two stable configurations. This fact provides the energy barrier which causes the initial and final configurations to be stable with respect to each other. This relationship is illustrated in FIG. 1. Our invention provides these disclinations either by providing boundary conditions on the substrate surfaces which provide topological singular points thereon, which singular points serve as sources of disclinations, or by providing means for generating disclinations such as by specific electrode arrangements which provide inhomogeneous electric fields. A singular point is to be defined, for our purposes, as a point on the surface enclosing the liquid crystal cell at which a director alignment ambiguity exists. This ambiguity means that the director alignment at the particular point is not uniquely determinable from the given boundary conditions.

In its most general form we may state that this first aspect of the present invention encompasses all liquid crystal cells having a liquid crystal material mainly in the nematic mesophase whose boundary either contains at least two singular points or means for generating disclinations at at least two points.

Definitions

FIG. 2 shows substrates (e.g., transparent glass plates) 910 and 950 having a liquid crystal material disposed therebetween. Volume 1010 shows, in most general form, an individual liquid crystal cell which is bounded on top by section 951 made up of regions 901-906 on the surface of substrate 910, on the bottom by section 1001 made up of regions 1021-1026 on the surface of substrate 950, and on the sides by the surrounding volume of liquid crystal material. Clearly then, in our terminology a device comprises many liquid cells. FIG. 3 shows a portion of the surface of substrate 910 which is disposed adjacent to the liquid crystal material. Regions 901-906 as well as regions 1021-1026 of the substrate surfaces are configured or treated so that specific boundary conditions for director alignment in the liquid crystal material cell are provided.

When substrate 910 is planar we can define a normal to substrate 910 which points into the liquid crystal material. In FIG. 4 arrow 911 denotes a normal, $\hat{n}$, to substrate 910 which points into the liquid crystal material. Arrows 912 and 914 denote the direction of orientation, $\hat{d}$, of a director in the liquid crystal material. We define angle 913 to be positive with respect to normal 911 when $\hat{n} \times \hat{d}$ points into the plane of the paper containing FIG. 4 and angle 915 to be negative with respect to normal 911 when $\hat{n} \times \hat{d}$ points out of the plane of the paper containing FIG. 4.

As is shown in FIG. 5, typical regions on the substrate surfaces have regular patterns so that boundaries 920-924, which comprise a line of singular points, are straight lines which are parallel to and equidistant from each other.

We now define twisted and untwisted configurations. For purposes of this discussion we consider a liquid crystal cell where the top substrate surface has been treated so that directors at the surface are aligned to be parallel to each other at an angle θ at the surface, where θ is measured from the surface normal, and the bottom substrate surface has been treated so that directors at the surface are aligned parallel to each other at an angle -θ at the surface. The illustrative figures used in discussing this point will all have reference to a view of the cell obtained by slicing the cell with a plane perpendicular to the substrates. We will define the plane to contain the Z-X axis of a three dimensional coordinate system. We will view the slice of the liquid crystal cell by looking into the positive Y direction. The arrows in the region of the cell between the substrate surfaces represent the direction of orientation of the directors. When a director is oriented out of the above-defined Z-X plane we have shortened its length.

FIG. 6 shows a schematic representation of three director alignment configurations, 1100, 1101, 1102, that satisfy the above-defined boundary conditions. Note that arrows 1090,1092 immediately adjacent to the surface of the top substrate and arrows 1093, 1095 immediately adjacent to the surface of the bottom substrate are aligned parallel to each other respectively. These arrows are shown as full length to denote the fact that they lie in the Z-X plane shown in FIG. 6.

Configuration 1101 is denoted as a two-dimensional configuration or an untwisted configuration. Its noteworthy feature is that all the directors lie in the Z-X plane and do not twist out of it.

Configurations 1100 and 1102 are denoted as three-dimensional configurations or twisted configurations. The noteworthy feature is that the directors are not all aligned in the Z-X plane. Configuration 1100 is referred to as a right twist configuration and configuration 1102 is referred to as a left twist configuration. It should be clear that, for illustrative purposes, we are considering a twist of 180 degrees.

Each of the configurations 1100, 1101, and 1102 corresponds to a director "vertical" configuration, even though the directors of configurations 1100 and 1102 appear somewhat horizontal. The "horizontal" configuration for twisted configurations is described hereinafter. We have discovered that the formation of the twisted or untwisted configurations is a function of liquid crystal material parameters such as the moduli of elasticity, magnitude of director alignment angles at substrate surfaces and the relative alignment of the substrate surfaces with respect to each other. However, the structure of the devices and the method in which they operate is most straightforwardly understood if we deal with the two-dimensional or untwisted mode. We will of course note, as we go along, any pertinent differentiations in either fabrication or in operation.

Structures

FIGS. 7, 12, 13 and 14 show the pattern of liquid crystal directors for four embodiments of liquid crystal cells having at least two stable configurations. How the pattern of directors is generated is discussed in a separate section hereinafter. In each of the embodiments the stable configurations will be referred to as either a "vertical" configuration, i.e., where a substantial portion of the directors are aligned along a direction which is substantially parallel to arrow 100, i.e., the Z direction, in FIG. 7 or a "horizontal" configuration, i.e., where a substantial portion of the directors are aligned along a direction which is substantially parallel to arrow 101, i.e., the X direction, in FIG. 7. These two configurations are both stable and optically differentiable with respect to one another.

In the structures described below we would like to note that although the substrate planes are shown to be substantially parallel for ease of illustration this is not a critical requirement of the present invention.

Alternating-Tilt Geometry

Figure 7 shows a cross section of a liquid crystal cell which has been cut in a vertical plane, i.e., a plane defined by arrows 100 and 101 corresponding to the Z and X axes respectively. The liquid crystal cell comprises substrates 21 and 22 and a nematic liquid crystal material between the substrates.

Surfaces 23 and 24 of substrates 21 and 22 have been fabricated as described hereinafter such that nematic directors at a substrate surface are preferentially aligned at a tilt angle $|\theta|$ to a normal to the surface which points into the liquid crystal material. Regions 25, 26, 27 and 28 on surface 23 of substrate 22 are areas having alternating patterns of tilt directions of $+\theta$ and $-\theta$. There is no specific requirement that the tilt angle have the same magnitude in alternate regions. θ should, however, be approximately within the range of angles between 22.5 degrees and 67.5 degrees, 45 degrees, however, being the preferred angle. The reason for this is, with a tilt angle of 45 degrees, the "vertical" and "horizontal" stable configurations are nearly at equal energy levels.

FIG. 8 shows a portion of the surface 24 of the substrate 21. Arrows 310 and 311 show projections of the directors onto the substrate surface in the regions 34 and 33.

FIG. 8 also shows three different cells 360, 365, and 366. Each cell comprises a number of different regions, e.g., the regions 33 and 34 plus the immediately adjacent regions. Each region is defined by a boundry line, e.g., line 400, on the substrate surfaces, and each cell is isolated from other cells by a surrounding isolation region, e.g., regions 315 and 370. The purpose of the isolation regions is to permit individual and independent addressing of each cell. How the isolation regions function is described hereinafter.

Each cell can comprise different numbers of regions in various arrays, and the cells can similarly be disposed in various arrays to produce the desired, e.g., optical, effect. FIGS. 8 and 9 show examples of different region and cell patterns. In FIG. 9, each cell C comprises a pair of regions R_1 and R_2, each cell being isolated by a common isolation region I.

Referring, again, to FIG. 7, the arrows on director lines 29 show the directions that directors take in a "vertical" stable configuration. The arrows on director lines 30 show the directions that directors take in a "horizontal" stable configuration. Thus, in order to switch from the "vertical" stable configuration, shown in section 31, to the "horizontal" stable configuration, shown in section 32, the director lines 29 must be rearranged to form lines similar to lines 30. This movement of the director lines is caused by the movement of disclinations. How this is accomplished is described hereinafter.

FIG. 7 displays the "alternating-tilt geometry" embodiment with the substrates lined up over each other in a specific manner. The alignment shown is not critical. The substrate surfaces may be translated with respect to each other along the direction of arrow 101 and still provide bistable operation. FIG. 10 shows, in diagrammatic form, a cross section of an "alternating-tilt geometry" embodiment in a "vertical" stable configuration where the substrates have been translated relative to each other from the positions shown in FIG. 7. FIG. 11 shows, in diagrammatic form, a cross section of the "alternating-tilt geometry" embodiment of FIG. 10 in a "horizontal" stable configuration.

Points 400-403 in FIG. 7 are singular points, i.e., points at which a director alignment ambiguity exists. Note that in the embodiment shown in FIG. 7 the singular points are aligned over each other in such a manner that the director alignments about the singular points 400 and 402 on the top substrate surface 21 are the mirror image of the director alignments about the singular points 401 and 403 on the bottom substrate surface 22. Points 404 and 405 in FIG. 11 are singular points. However, in contrast with the embodiment shown in FIG. 7, the director alignments about the singular point 404 in FIG. 11 are not the mirror image of the director alignment about singular point 405. Thus, in FIG. 7, regions 25, 27, 33 and 36 of positive tilt angle are aligned over regions 34, 35, 26 and 28, respectively, of negative tilt angle, whereas in FIGS. 10 and 11, regions of positive tilt angle are aligned over regions of positive tilt angle.

Single-Tilt Geometry

In embodiment 55, shown in FIG. 12, surfaces 56 and 57 of substrates 58 and 59 have been fabricated such that all the directors at each substrate surface are preferentially uniformly aligned at a tilt angle Φ with respect to a normal to each surface. The tilt angle of directors on surface 57 of substrate 59 is $+\Phi$ while the tilt angle of directors on surface 56 of substrate 58 is $-\Phi$. The tilt angles for both surfaces need not be exactly equal. Because all the directors are uniformly tilted with respect to each substrate, no singular points are thereby created, and other means must be provided for generating such points. In this embodiment, as shown, such means comprise electrodes 60, 61, 62 and 63, etc. These electrodes provide surface discontinuities at which disclinations are formed. These disclinations are formed at the surface or in the bulk of the liquid crystal material in the vicinity of the surface. The surface discontinuities can take other forms, such as ridges, or the like, on the substrate surfaces (see for example, FIG. 13). However, the electrodes are convenient because they also serve as a means for providing stress centers for detaching and pinning these disclinations. (Note that in other embodiments there is no need to utilize the electrodes to generate singular points, and electrodes, for a different purpose, described hereinafter, may indeed be buried in the substrate surface.)

The arrows on director lines 64 show the directions that directors take in an untwisted "vertical" stable configuration. The arrows on director lines 65 show the directions that directors take in a untwisted "horizontal" stable configuration. Thus, in order to switch from the "vertical" stable configuration, shown in section 66, to a "horizontal" stable configuration, shown in section 67, the directors in the vicinity of section 66 on surface 57 must be turned around.

In this embodiment, as in the FIG. 7 embodiment, switching between stable configurations is accomplished by the movement of disclinations. Such disclinations are produced by local stresses within the liquid crystal material induced by topological singular points at the substrate surfaces.e.g., notches within the electrodes or sharp corners of the electrodes. The disclinations are moved by inhomogeneous electric field stresses set up by the electrodes.

The particular structure shown in FIG. 12 has been arranged so that the plane of the directors is the Z-X plane for both the top and bottom substrates. Another way of stating this is to consider, on each substrate, the line, referred to as a "substrate alignment line", formed by the intersection of the substrate plane, for planar substrates, and a plane parallel to the director alignments at the substrate surface. In FIG. 12, the substrate alignment line of the two substrates are parallel to each other.

Twisted configurations, shown in FIG. 6, are also formed in this embodiment. The twisted "vertical" stable configuration, i.e., configurations 1100 and 1102 (configuration 1101 being untwisted), has a substantial portion of the director alignments in the bulk of the liquid crystal material in the vertical direction and for this reason is similar to the untwisted configuration.

However, as can be seen from FIG. 6 the directors undergo a 180 degree twist in going from the top substrate surface to the bottom substrate surface. It is important to note, however, that transition between the "vertical" and "horizontal" twist configurations requires the movement of disclinations and it is this requirement, provided by the boundary conditions, which produces the bistability.

We can see, however, that the twisted configurations and the untwisted configurations are not separated by a disclination. In fact, we note that the right twist configuration, 1100 in FIG. 6, and the left twist configuration, 1102 in FIG. 6, are separated by an untwisted configuration 1101.

We have concluded that it is possible to fabricate a liquid crystal cell having a twisted or untwisted "vertical" stable configuration by properly adjusting the tilt angle of director alignment at the substrate surfaces and the ratio of elastic moduli of the liquid crystal material. For example, for small tilt angles from the normal to a substrate surface we expect to find untwisted configurations whereas for large tilt angles from the normal we expect to find twisted configurations. This can be understood heuristically because if the angle of tilt (from the normal) is large it is easier, i.e., requires less energy, for the director to rotate around 180 degrees to change its direction so as to point into the other substrate, see directors 1093 and 1090 in FIG. 6, than it would be for it to bend over a large angle in the vertical direction, see directors 1094 and 1091 in FIG. 6. Conversely, if the angle of tilt is small, it is easier, i.e. requires less energy, to bend in the vertical direction than to rotate around 180 degrees. Clearly, this illustrates that the elastic moduli of the liquid crystal material are pertinent because they determine whether it requires less energy to rotate or bend.

From the above discussion it is clear that for a given liquid crystal material there is a critical angle which divides those cells which have an untwisted from those which have twisted configurations. The precise value of this angle cannot be specified because it depends on the actual conditions of the cell, such as thermal conditions, which may affect the elastic moduli and the orientation of the substrates themselves.

In the discussion so far we have been referring to FIG. 12 where the substrate alignment lines are parallel. Clearly if the alignment lines are substantially nonparallel the configurations will, of necessity, be twisted configurations. Of course if the substrate alignment lines are slightly nonparallel (perfect parallellism being quite difficult to achieve on a production basis), this tends to give a bias toward forming a twist state. This means that the critical angle which separates untwisted from twisted configurations has a smaller value. Thus, to ensure untwisted configurations, the tilt alignments at the surface are preferrably quite small.

Saw-Tooth Geometry

In embodiment 1 shown in FIG. 13 the surface of substrates 2 and 3 form a saw tooth pattern. The surfaces 4 and 5 have been treated with known surfactants so that the nematic directors are preferentially aligned substantially perpendicular to the surface. The arrows on director lines 6 show the directions that directors take in an untwisted "vertical" stable configuration. The arrows on director lines 7 show the directions that directors take in an untwisted "horizontal" stable configuration. Thus, in order to switch from the "vertical" stable configuration, shown in section 10, to the "horizontal" stable configuration, shown in section 11, the directors in the vicinity of region 12 on surface 4 and of region 13 on surface 5 must be redirected. As previously noted, the surface discontinuities of the substrate surfaces provide the singular points necessary for switching between stable configurations.

Alternating Parallel-Perpendicular Geometry

In embodiment 35 shown in FIG. 14 the surfaces 36 and 37 of substrates 38 and 39 have been fabricated such that the nematic directors are preferentially aligned alternatively parallel or perpendicular to the substrate surfaces. Regions 40-43 on surface 37 of substrate 39 are areas having alternating directions of parallel and perpendicular alignment. A similar pattern is impressed on surface 36 of substrate 38. The junctures of the adjoining regions provide the singular points. The arrows on director lines 47 show the directions that directors take in an untwisted "vertical" stable configuration in a region, like region 42, where the directors are preferentially aligned perpendicular to the surfaces. The arrows on director lines 48 show the directions that orientational directors take in a twisted "vertical" stable configuration in a region, like region 43, where the directors are preferentially aligned parallel to the surface. The director alignments shown in FIG. 14 are merely a model of the true physical picture because one can envision equivalent director alignments for the stable configurations provided by these boundary conditions.

Physical Mechanism Producing Stability

The following discussion outlines a model of our understanding of the manner in which the above-disclosed embodiments produce multistable configurations. We are disclosing this model with the cautionary statement that the true physical manifestation may involve a combination of intermediate configurations: some involving disclination movement on the surface of the substrate and some involving complex disclination formation and movement in the bulk of the liquid crystal material.

In the following discussion we are referring only to untwisted configurations because they are more amenable to understanding in the form of two dimensional figures. However, note that the discussion of the underlying physical manifestations is the same for both twisted and untwisted configurations.

In general, the switching from one stable configuration to the other involves the generation of disclinations and the movement of the disclinations in such manner as to properly reconfigure the director pattern from one configuration to the other.

FIGS. 15-18 show the transition, in a "single-tilt" geometry of the type shown in FIG. 12, of director alignments for switching from a "vertical" stable configuration to a "horizontal" stable configuration under the influence of a transverse electric field whose direction is shown by arrow 200. The transverse electric field is generated by applying appropriate voltages to electrodes 201-204 as will be further described hereinbelow. In this embodiment of the invention, the sharp corners of the electrodes shown in cross section in FIG. 15 are utilized to provide local regions of maximum stress in the liquid crystal material at which disclinations are generated. The spaced apart electrodes on each substrate do not generate uniform transverse fields and the resultant irregular field lines set up nonuniform stresses in the bulk of the liquid crystal material. Other means can be used to generate the necessary nonuniform electric field. These field-induced elastic stresses are eased by the detachment and subsequent movement of strength one-half disclinations such as 209 in FIG. 17. FIGS. 16 and 17 also show the propagation of the disclination between the electrodes to relieve the field-induced stresses. The disclinations are "reattached" when the disclination from one electrode has propagated (FIG. 17) to the neighboring electrode. FIG. 18 shows the cell in the "horizontal" stable configuration.

FIGS.19-22 show the transition of director alignments for switching of the "single-tilt geometry" embodiment of FIG. 12 from a "horizontal" stable configuration to a "vertical" stable configuration under the influence of a vertical electric field whose direction is shown by arrow 211.

FIGS. 23-27 show the transition of director alignments for switching of the "alternating-tilt geometry" embodiment of FIG. 7 from a "horizontal" stable configuration to a "vertical" stable configuration under the influence of a vertical electric field applied from a pattern (not illustrated) of spaced apart electrodes. Note that in this geometry the alternating tilt pattern provides singular points on the substrate. It is from these singular points that disclinations are moved to relieve the stresses created by the electric fields.

The transition from the "horizontal" stable configuration shown in FIG. 23 proceeds by detachment and movement of disclinations as indicated by arrows 113 and 114 in FIG. 25. Although FIG. 25 shows the movement of the disclinations to be on the substrate surfaces, the transition between the stable states could possibly occur by the movement of disclinations through the bulk of the liquid crystal material or by a combination of disclination movement through the bulk and on the surface. This description is of an idealized model of the switching mechanism, and the disclinations which are described as being attached at the substrate surfaces may, in practical devices, actually exist in the liquid crystal material in close proximity to the singular points. However, it is the existence of the singular points which provides for the existence of the disclinations and hence for the stability of the "vertical" and "horizontal" stable configurations with respect to each other.

Mechanisms to Initiate Switching

The switching of the liquid crystal cell between the twisted or untwisted "horizontal" and "vertical" stable configurations may be accomplished by the application of electric of magnetic fields to the liquid crystal material.

Switching between stable configurations requires the ability to apply to the liquid crystal material electric fields having directions which are perpendicular or horizontal to the substrate surfaces. Electric fields which are perpendicular to the substrate surfaces are achieved by imposing voltage differences across electrodes disposed on opposite substrates (it is preferred to apply the same voltage to the electrodes on the same substrate). Electric fields which are substantially horizontal to the substrate surfaces are achieved by imposing voltage differences across electrodes disposed on the same substrate. Specific electrode configurations will be discussed further hereinbelow.

Although switching between stable configurations in these devices may be accomplished by the application of magnetic fields, an electric field of 10 volts/cm has the same effect on the liquid crystal material as a magnetic field of 1000 gauss, hence the use of electric fields for switching is generally preferred.

Note that the use of electrodes in conjunction with the "single-tilt geometry" embodiment (FIG. 12) has a drawback compared to the use of electrodes with the "alternating-tilt geometry" embodiment (FIG. 7). Ideal switching requires that the local direction of the electric field applied to produce switching be so disposed as to be parallel to the final director configuration lines. If the field lines are roughly parallel to the initial director alignment then there is little torque operating to promote switching. FIG. 28 shows electric field lines 700 generated to switch the "single-tilt geometry" embodiment from a "horizontal" stable configuration to the "vertical" stable configuration, and the director lines 702 of the "vertical" stable configuration. Note that in the area enclosed by the dotted line 710, the field lines 700 are roughly perpendicular to the director alignments, whereas the field lines 700 are nearly parallel to the director alignments in the area enclosed by dotted line 715. Thus, the electric field lines produced by this arrangement of electrodes are not parallel to the final director alignments within substantial portions (e.g. 710) of the active area of the cell. This affects the ability and the time required to switch from the "horizontal" to the "vertical" stable configuration, especially with large boundary tilt angles. This problem is reduced in devices having smaller tilt angles, and does not occur in the "alternating-tilt geometry" embodiment.

Switching may be also accomplished with an electric field if a liquid crystal material is used having a "two-frequency" dielectric relaxation behavior, i.e., $\Delta\varepsilon > 0$ for $f < f_c$, and $\Delta\varepsilon < 0$ for $f > f_c$ where f is the frequency of the applied electric field. Thus, when $\Delta\varepsilon > 0$, the directors in the liquid crystal material line up parallel to the applied electric field and when $\Delta\varepsilon < 0$, the directors line up perpendicular to the applied electric field. Thus, the "vertical" stable configuration can be established by an electric field directed perpendicular to the substrates with $f < f_c$, and the "horizontal" stable configuration can be addressed by a transverse electric field having a component along a normal to the symmetry plane of the stable configuration with $f > f_c$.

Optical Differentiability Between Configurations

For untwisted stable configurations optical differentiation is best achieved by the inclusion of pleochroic dyes in the liquid crystal material. A pleochroic dye has the property that absorption is much stronger when the electric field of incident radiation is parallel to the long axis of the dye molecule than when it is perpendicular to it. This property can be used to enhance the transmission of polarized light propagating through the liquid crystal material when the device is in the "vertical" stable configuration as compared to the "horizontal" stable configuration. The directors in the liquid crystal material have the effect of aligning the pleochroic dye molecules parallel to the director configuration lines.

Consider a display using a single polarizer having a direction of polarization parallel to the horizontal direction as shown by arrow 101 in FIG. 7. The display is absorbing to radiation if the directors are in a "horizontal" stable configuration such as that shown in section 32 in FIG. 7, and the display is transmitting to radiation if the directors are in a "vertical" stable configuration such as that shown in section 31 in FIG. 7.

For twisted configurations the same effect described above with regard to the incorporation of pleochroic dyes into the liquid crystal material is observed. The only difference observable is a qualitative one in that the transmissive state for the twisted configuration appears to be slightly less transmissive of light than that of the untwisted configuration. This is explainable by noting, as was explained hereinabove, that the twisted configuration usually occurs with larger tilt angles of director alignment at the substrate surfaces than the untwisted configurations, so that on the average the directors are more horizontal in the twisted configuration.

Note that as a general feature of these embodiments the curvature of the director lines reduces both the light transmission and absorption because not all the pleochroic molecules are aligned totally along one axis or the other in either of the stable configurations.

FIG. 29 shows one portion, 300, of a liquid crystal cell utilizing crossed polarizers. A cross section of portion 300 in the Z-X plane shows a director alignment for the "horizontal" stable configuration of an "alternating-tilt geometry" embodiment. A first polarizer, 303, is placed on top of portion 300 and a second polarizer, 304, is placed beneath portion 300 (the polarizers, in an actual structure, being disposed on the outside surfaces of the substrate). The direction of polarization of the polarizers is shown by arrows 302 and 305. Light transmitted from below portion 300 is detected by detector 311, positioned above portion 300. In theory, light transmitted along the direction shown by arrow 310 should be totally extinguished during transmission through portion 300 for an ideal "horizontal" or ideal planar "vertical" stable configuration, but may be transmitted through portion 300 for an ideal twisted "vertical" stable configuration under some circumstances.

The twisted "vertical" stable configuration leads to extinction when the Mauguin (waveguide) limit is satisfied. This is satisfied in twisted "vertical" stable configurations having large tilt angles. The configuration becomes transmitting when the Mauguin limit is violated. This violation occurs with low tilt angles.

Cell Fabrication

In the following we describe methods of fabricating cells according to an embodiment of the present invention.

In FIG. 30 we show cell 140 which corresponds to the "alternating-tilt geometry" embodiment shown in FIG. 7. The alternating stripes of tilted boundary alignment at $\pm\theta$ are optimally set at $\theta = 45$ degrees. Glass substrates 160 and 161 have electrodes such as 162 photolithographically produced from In_2O_3 or Cr. Lines 163 illustrate the alignment of directors at the surface of substrates 160 and 161. The alternating tilt regions are produced by evaporating TiO_2 at alternate angles of ± 5 degrees from the substrate surface by electron-beam deposition using appropriate masking techniques to define the different regions. Other obliquely evaporated oxides may also be used. Also as generally known, small tilt angles can be obtained by coating a known homeotropic surfactant onto the deposited oxide layer. The substrates are aligned as shown in FIG. 30. Typical dimensions for the cell are: (1) the distance, 164, between substrates is $\approx$ 10-100 μ and (2) the distance, 165, between electrodes is $\approx$ 10-100 μm. We believe optimal performance is achieved when these two distances are substantially the same, and whether or not the same, when the two distances are small.

The cell 130 shown in FIG. 31 corresponds to the "single-tilt geometry" embodiment shown in FIG. 12. Glass substrates 152 and 153 have In_2O_3 conducting electrodes. These electrodes are photolithographically produced. The single-tilt boundary condition is produced by an oblique electron-beam deposition of TiO_2 or SiO_x at an angle of 5 degrees from the substrate surface. These electrodes provide means, for both twisted or untwisted configurations, for generating disclinations and then detaching and moving them under the influence of electric fields when the cell is switched between "vertical" and "horizontal" stable configurations. Typical dimensions for the cells are: (1) the distance, 150, between substrates is ≃ 10-100 μm and (2) the distance, 151, between electrodes is ≃10-100 μm.

The electrodes in FIGS. 30 and 31 are typically 1-10 μm wide.

In general, the greater the ratio of the electrode spacings 151 or 165 to the substrate spacings 150 or 164, the more homogeneous is the electric field over the bulk of the liquid crystal material, the greater is the electric field required for switching, and the longer is the switching transition time.

We have used various liquid crystal mixtures between the substrates. Some examples are: (1) "E9" obtained from EM Laboratories, Inc., 500 Executive Blvd., Elmsford, N.Y., an associate of E. Merck, Darmstadt, Germany, which is a cyanobiphenyl mixture. (This was doped with 1 percent pleochroic anthraquinone dye "D5", also obtained from EM Laboratories.); (2) cyanobiphenyl mixtures "E7" and "E8" obtained from EM Laboratories; and (3) cyanophenylcyclohexane mixture "ZLI-1083", from EM Laboratories. All the above-mentioned mixtures have a large positive dielectric anisotropy, i.e., $\Delta\varepsilon \sim +10$, ε_{11}: ~ 20, and $\varepsilon_{\perp} \sim 5-10$. The liquid crystal material was introduced into the device by capillary action while the material was in the isotropic phase. The device was held in a magnetic field directed parallel to the TiO_2 deposition directions. The material is allowed to cool to the nematic state and then the device is sealed.

The following mixtures have a two-frequency dielectric anisotropy: (1) Eastman Kodak Organic Chemicals in a diester mixture; one part "EK 11650", one part "EK 15320", two parts "EK 14046 and a 1 percent pleochroic dye; producing a two-frequency mixture with $\Delta\varepsilon > 0$ for $f > 2.5$ kHz, ($\Delta\varepsilon \sim 6$ at 50 Hz) and $\Delta\varepsilon < 0$ for $f > 2.5$ kHz ($\Delta\varepsilon \sim -2.2$ at 10 kHz); and (2) EM Laboratories compound "ZLI-1085" a two-frequency diester mixture with $\Delta\varepsilon = +0.8$ at 100 Hz and $\Delta\varepsilon = -0.9$ at 20 kHz. These diesters will switch in a magnetic or electric field when operated in the same manner as a single frequency material. However, switching is slower for these diesters in the electric field than for the cyanobiphenyl mixtures because $\Delta\varepsilon$ is much smaller, hence are less preferred.

In order to utilize the above-described two-frequency diesters in a two-frequency effect for untwisted configurations an electrode structure such as shown in FIG. 32 is required which applies a vertical field at low frequency and a mixture of vertical and transverse fields having field components perpendicular to the symmetry plane of the untwisted configuration at high frequency. Arrows 510 and 511 show the tilt boundary conditions on substrate 507, arrows 512 and 513 show the tilt boundary conditions on substrate 508, and numerals 501-504 denote the electrodes.

FIGS. 33-35 show a cross section of the electrode structure of FIG. 32 taken in the Z-Y plane. The four electrodes shown can be driven with sine waves or square waves. To obtain the vertical electric field and, thus, the "vertical" stable configuration, we connect electrodes 501 and 504 together and 503 and 502 together and adjust the phases, ϕ, as shown in FIG. 33.

FIG. 34 shows the same electrode structure as shown in FIG. 33, but a mixture of vertical and transverse fields are generated by connecting electrodes 501 and 504 together and 502 and 503 together and adjusting the phases, ϕ , to the values shown in FIG. 34.

For the phase pattern of the fields shown in FIG. 33 we utilize low frequency fields and for the phase pattern of the fields shown in FIG. 34 we utilize high frequency fields. The electric fields produced by the arrangement shown in FIG. 33 provide that the bulk liquid crystal material is in a lower energy state if the directors are perpendicular to the ZY plane, i.e., parallel to the X-axis. This causes a torque to rotate the liquid crystal molecules and hence, the directors, to form the "horizontal" stable configuration.

Another, and probably preferred arrangement, is to apply fields to the electrode configuration as shown in FIG. 35. The phase at electrode 501 is zero, the phase at electrode 504 is $\pi/2$, the phase at electrode 503 is $3\pi/2$, and the phase at electrode 502 is π . At the center of the cell the field is a continuously rotating circularly polarized electric field in the Z-Y plane, whereas at other positions in the cell it is elliptically polarized in the Z-Y plane. This rotation is shown by arrow 550 in FIG. 35. At any given location X, Y, Z the field is constantly changing between E_Y and E_Z. Therefore, the average torque is such as to align the liquid crystal molecules in the X direction perpendicular to the ZY plane. The field must rotate at a rate exceeding the dielectric response time to avoid unwanted molecular motion. That is, the molecules should experience a rms field whose average value in the Z-Y plane is isotropic to prevent the molecules from ever becoming parallel to the Z-Y plane. In addition, the rotating field must encompass as much of the space between substrates as possible. This means that the electrode widths must be small compared to their spacing.

The discussion above assumes that the embodiments have substantial untwisted alignment configurations. However, as a consequence of the fact that the elastic moduli $k_{22} < k_{33}, k_{11}$ in most liquid crystal materials, the directors undergo twist, under some circumstances, in lieu of or in addition to, splay-bend alignments. Therefore, twisted alignment configurations are likely to occur in the aforementioned tilted-boundary condition alignment embodiments.

The specific circumstances under which twisted or untwisted configurations may predominate are governed both by the liquid crystal material properties and by the boundary tilt. In particular, a high tilt from a normal to the substrate surface favors twist deformations and a low tilt favors bend deformations which involve a lower energy content than a large twist deformation. In general, there exists a critical boundary tilt angle θ_c above which twist configurations are stable and below which untwisted configurations are stable, with the two states identical at θ_c. This θ_c depends on the elastic moduli of the particular liquid crystal material. For the $k_1 = k_3 = 2k_2$ approximation that describes many nematic materials, θ_c = 58.7 degrees. For the elastic parameters presently available for E7 mixtures, $\theta_c \doteq$ 58.7 degrees. For the elastic parameters presently available for E7 mixtures, $\theta_c \doteq$ 66 degrees from normal. Thus, tilt angles exceeding 66 degrees will promote stable twist configurations in E7, while angles less than 66 degrees should <u>theoretically</u> favor planar vertical states.

Several important considerations are noted. First, it is important to recognize that the two states - untwisted and twisted vertical states - under discussion are topologically equivalent to each other, but distinct from the untwisted horizontal state. The arrows signifying director lines point alternately into and away from the opposite substrates in the former two, while they always point into (or away from) both substrates in the latter. Secondly, as $\theta > \theta_c$ in either the untwisted or twisted configurations, the twist configurations will become more indistinguishable from a true vertical (untwisted) configuration. This is essential in terms of optical differentiability when pleochroic dyes are incorporated for contrast.

The existence of even a small misalignment of boundary tilt azimuths in the nominally planar structures described hereinabove has a pronounced effect on θ_c and thus, the character of the stable configuration - twisted or untwisted. Specifically, misalignment tends to reduce θ_c, making a twist configuration increasingly probable at a fixed boundary tilt. Indeed, a twisted structure, described hereinbelow, naturally promotes twisted nonplanar configurations and breaks the degeneracy that permits opposite twist domains to exist.

At this point we note that further embodiments of the present invention may be formed by rotating one of the substrates relative to the other about a normal to the substrate planes. This causes the stable configurations to include twists. The stable configurations, however, still retain the property of requiring movement of disclinations through the bulk of the liquid crystal material, along the substrate surfaces, or by a combination of both movements in order to switch.

These embodiments also form "vertical" and "horizontal" stable configurations.

We have found that in some of these twisted substrate embodiments, such as 90 degrees twist, it is preferred to add some liquid crystal material in the cholesteric mesophase to the nematic material in order to properly bias the twist at the substrate boundary.

The manufacture and optical differentiability are similar to that described above with respect to the substantially two-dimensional structures.

Cell Termination

For good stability of the cell, the boundary which consists of liquid crystal material, see FIG. 2, must have the following property: a transition from the director alignment configuration established in the interior of the cell to that configuration corresponding to the director alignment required to meet the termination boundary condition necessitates the detachment of disclinations. It is also important that the boundary condition matching for both of the "vertical" and "horizontal" stable configurations in a bistable device involve the detachment of disclinations. If this were not required, the transition of director alignments from one of the stable configurations in the interior body of the cell to the boundary would be continuous, i.e., without the existence of disclinations, and the transition of director alignments from the other stable configuration in the body of the cell would not be continuous. The result of this asymmetry would be that one stable configuration would gradually destabilize the other configuration. The problem with an asymmetric boundary condition is illustrated in FIG. 36, where 800-804 represent cross sections, parallel to the Z-X plane, of a rectangular cell for an untwisted "single-tilt geometry" embodiment. Plane 800 shows a cross section in the middle of the cell and plane 804 shows a cross section at the boundary of the cell. Note that the transition of the director alignment configuration in the "horizontal" stable configuration at the middle of the cell, shown in plane 800, to the director alignment configuration at the cell boundary, shown in plane 804, does not require formation of disclinations. Plane 805 shows a cross section in the middle of the cell and plane 809 shows a cross section at the boundary of the cell. Note that the transition of the director alignment configuration in the "vertical" stable configuration at the middle of the cell, shown in plane 804, to the director alignment configuration at the cell boundary, shown in plane 809, requires disclinations. Thus, the "horizontal" stable configuration will gradually destabilize the "vertical" stable configuration for a cell boundary condition which produces the horizontal director alignments shown in planes 804 and 809. A similar argument for a vertical director alignment at the cell boundary again shows a non-ideal cell termination condition. Note, however, that we still would have metastable configurations if we used these boundary conditions because we estimate that the time for complete destabilization along a one cm stripe would be on the order of an hour.

FIG. 37 shows an embodiment of a cell termination boundary condition which is preferred over the simple horizontal or vertical director alignments discussed above. Plane 520 shows a cross section of the middle of a rectangular cell in the "vertical" stable configuration for an untwisted "alternating-tilt geometry" embodiment and plane 523 shows a cross section of the middle of the rectangular cell in the "horizontal" stable configuration. (This preferred cell termination boundary condition can be applied equally as well to the "single-tilt geometry" embodiment but we disclose its application to the "alternating-tilt geometry" embodiment for ease of description.) Planes 521 and 522 show cross sections of the rectangular cell at the boundary for the preferred cell termination director alignment condition embodiment. FIG. 37 shows that the transition of the director alignment configuration for a stable configuration in the middle of the cell to the director alignment configuration at the cell boundary consists of disclination-pinned textures for both stable configurations. Thus, this particular tilt boundary alignment condition embodiment is not likely to favor one stable configuration more than the other. In fact, because it favors neither, the stable configurations are unlikely to destabilize one another.

FIG. 38 shows a planar cross section, parallel to the Z-X plane, taken through the middle of a liquid crystal cell for an untwisted "single-tilt geometry" embodiment. Dotted lines 822-825 represent the cell termination boundaries for planes parallel to the Z-Y plane. Planes 820 and 821 show, for the "single-tilt geometry" embodiment, how the preferred cell boundary alignment achieves stability at cell boundaries which are perpendicular to the cell boundaries shown in FIG. 37.

Switching Time

Switching between stable configurations requires a discontinuous change in director alignment and thus necessitates the detachment and movement of disclinations. On a homogeneous surface, such as is illustrated by the "single-tilt geometry" embodiment shown in FIG. 12, this can only occur at the cell boundaries or at local surface defects where the existence of disclinations is most likely to occur. The detached disclination assumes the form of a line separating the regions in the "vertical" and "horizontal" stable configurations. The disclination moves under the influence of a vertical or transverse field. Switching is complete when the disclination has been reattached at an adjacent pinning site.

In FIG. 39 we disclose experimental results for transit times of a wall which encompasses a disclination. The wall is defined, for an untwisted "single tilt geometry" embodiment, to be the volume contained between dotted lines 169 and 170. We measured the wall velocity by using a transverse magnetic field of up to 10K Gauss to switch to the "horizontal" stable configuration and a vertical electric field to switch to the "vertical" stable configuration.

Data taken for the "horizontal" to "vertical" transition for voltages up to 150 volts is shown in FIG. 39 for cells having a thickness d = 50 μm. The driving force for the transition is the difference in effective dielectric tensor or capacitance on either side of the wall, which difference decreases inversely with applied field. We found an approximately constant wall mobility μ of $2.5 \times 10^{-6} cm^2$/volt-sec for fields with coherence length $\leq d$.

Theoretically, the switching time for a cell is approximately equal to the time t_T required for the wall to transit a distance S, so that $t_T = S/ E$ where $E = V_o/d$ is the field strength at voltage V_o. Thus, fast switching requires a small electrode distance S. For example, with $S = d = 25\ \mu m$, t_T is 50 msec at $V_o = 70$ volts peak (50 v rms).

The optical rise time of an "alternating-tilt geometry" cell is quite fast. This fact is shown in FIG. 40. This optical rise time shown in FIG. 40, however, reflects only the response time of molecular rotation and not the movement of disclinations which are required for making the configuration stable. A truer measure of the switching time for a cell is the transmit time t_T of the disclinations. Since $t_T = dS/\mu V$, where d is the distance between the substrates, S is the distance between the electrodes, μ is the high field wall mobility and V is the applied voltage, a transmit time of 0.1 sec should be theoretically possible with $s = d = 25\mu m$ and $V = 40$ volts peak. FIG. 41 illustrates the transmit time for a cyanobiphenyl mixture with $\mu = 2.5 \times 10^{-6} cm^2/V\text{-sec}$ across $25\ \mu m$ wide regions.

<u>Electrode Configuration</u>

In FIG. 42 we show the electric field lines and polarity of electrodes in a condition that will switch a cell from the "vertical" to the "horizontal" stable configuration.

In FIG. 43 we show the electric field lines and polarity of electrodes in a condition which will switch a cell from the "horizontal" to the "vertical" stable configuration.

In FIG. 44 we show electrodes 200-203 with a schematic diagram of a circuit for generating the appropriate polarities shown in FIGS. 42 and 43. It should be clear to those skilled in the art as to how pulse stream 210, shown in FIG. 44, generates the appropriate polarities when applied to the circuit illustrated in FIG. 44. We note that pulse areas 215 switch to the "horizontal" and pulse areas 216 switch to the "vertical" stable configurations.

Claims

1. A liquid crystal cell (1010, FIG. 2) comprising a liquid crystal material having orientational directors disposed between a first substrate (910) surface and a second substrate (950) surface, said liquid crystal material being mainly in the nematic mesophase;

characterized in that

the boundary provided by said first and second substrate surfaces contains at least two singular points (e.g., 920, 921) of orientational alignment.

2. A liquid crystal cell as defined in claim 1 characterized in that said substrate surfaces are in parallel alignment.

3. A liquid crystal cell as defined in claim 2 characterized in that at least two adjacent regions (FIG. 7, 33-34, 25-26) on each of said first and second substrate surfaces have the property that directors disposed at each surface are parallel aligned, and the alignments in adjacent regions alternate from a positive angle to a negative angle with respect to a normal to each substrate surface.

4. A liquid crystal cell as defined in claim 3 characterized in that said regions having directors aligned at a positive angle on said first substrate surface lie substantially above said regions having directors aligned at a negative angle on said second substrate surface (FIG. 7).

5. A liquid crystal cell as defined in claim 3 characterized in that said regions having directors aligned at a positive angle on said first substrate surface lie substantially above said regions having directors aligned at a positive angle on said second substrate surface (FIG. 10).

6. A liquid crystal cell as defined in claim 3 characterized in that said first substrate surface and said second substrate surface have the property that directors disposed at said first and second substrate surfaces are

aligned substantially perpendicular to said surfaces.

7. A liquid crystal cell as defined in claim 3 characterized in that at least two adjacent regions on each said surface have the property that the directors are aligned alternately parallel and perpendicular thereto.

8. A liquid crystal cell comprising a liquid crystal material having orientational directors disposed between a first substrate surface (FIG. 12, 56) and a second substrate surface (57), said liquid crystal material being mainly in the nematic mesophase;

characterized in that

the cell further includes means (63) for detaching disclinations in said liquid crystal material at at least two points.

9. A liquid crystal cell as defined in claim 8 characterized in that said means for detaching disclinations comprises a pattern of electrodes on said surfaces.

FIG. 1

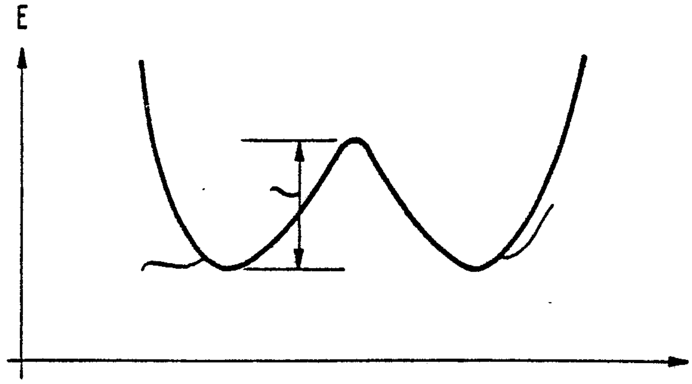


FIG. 2

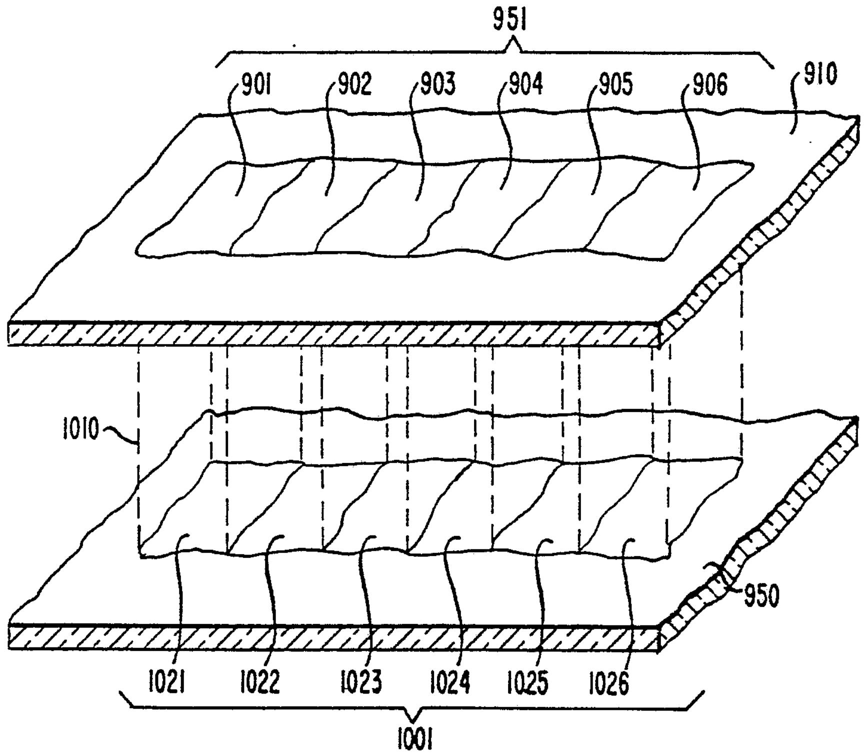


FIG. 3

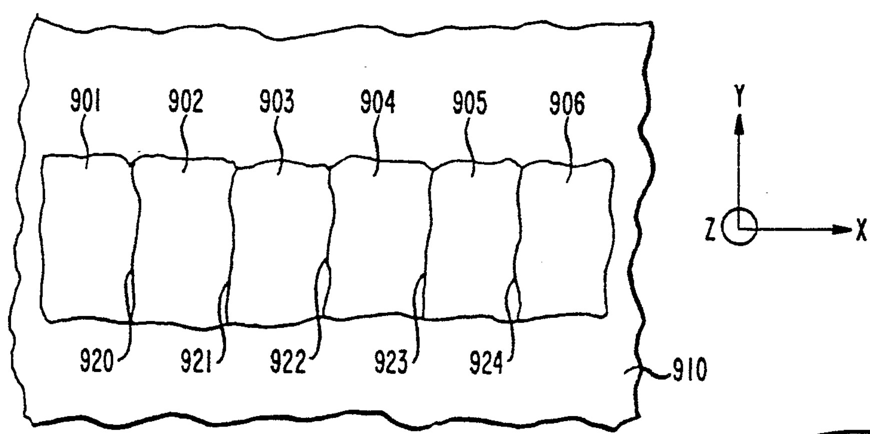


FIG. 4

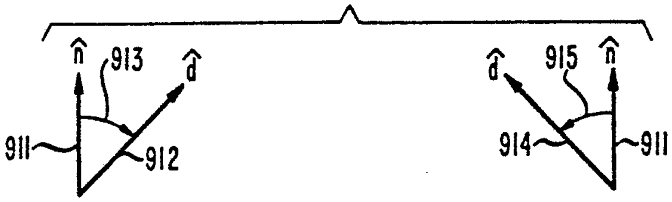


FIG. 5

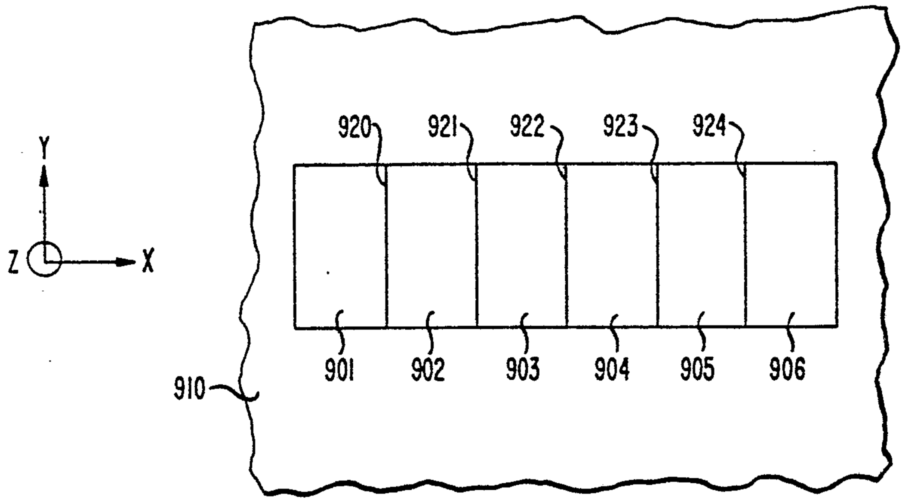


FIG. 6

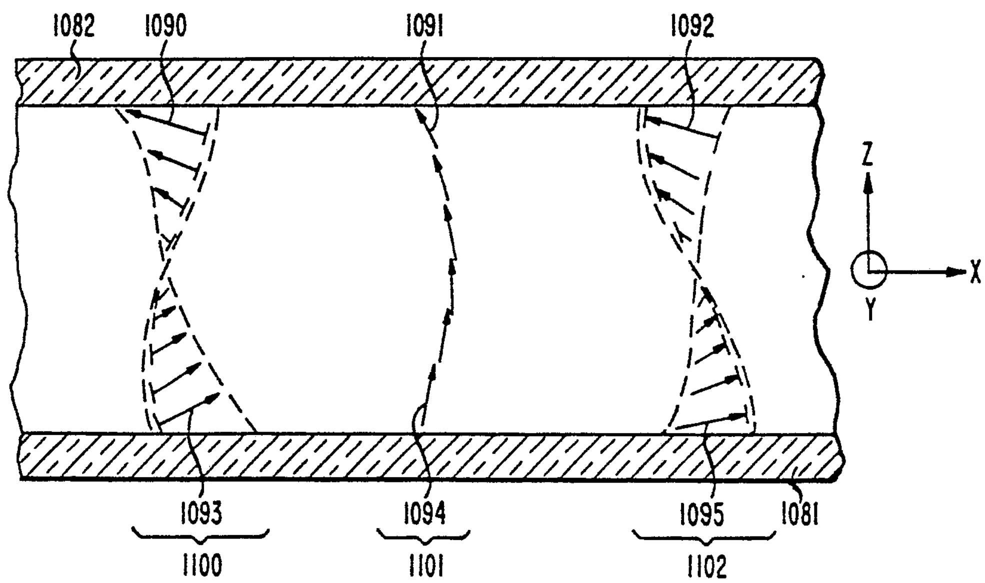
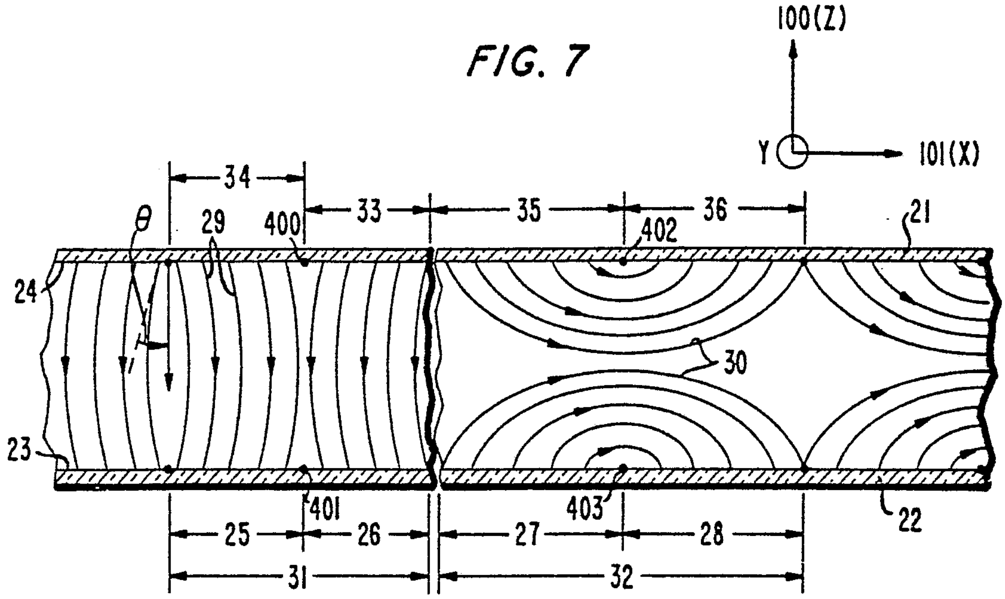


FIG. 7


100(Z)
Y
101(X)
34
33
35
36
θ
29
400
402
21
24
30
23
401
403
22
25
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27
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32

FIG. 8

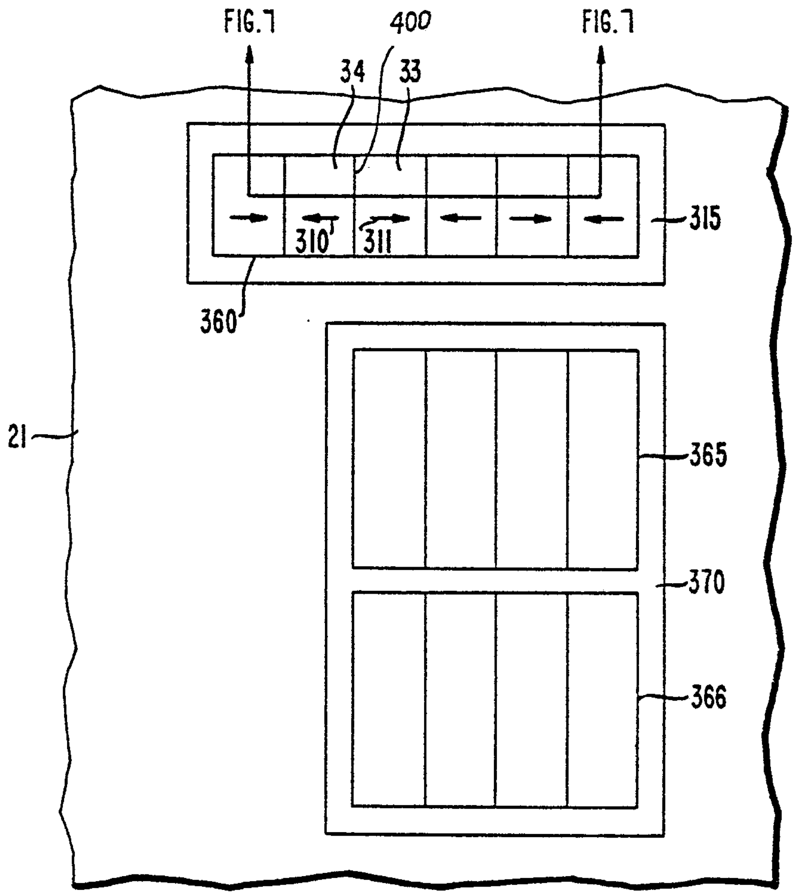


FIG.7
400
FIG.7
34
33
310
311
315
360
21
365
370
366

FIG. 9

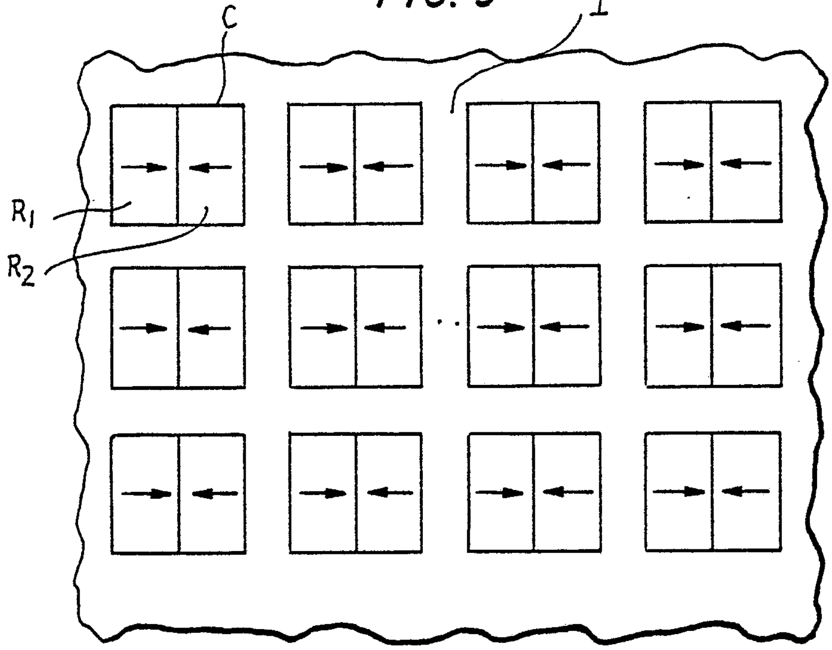


FIG. 10

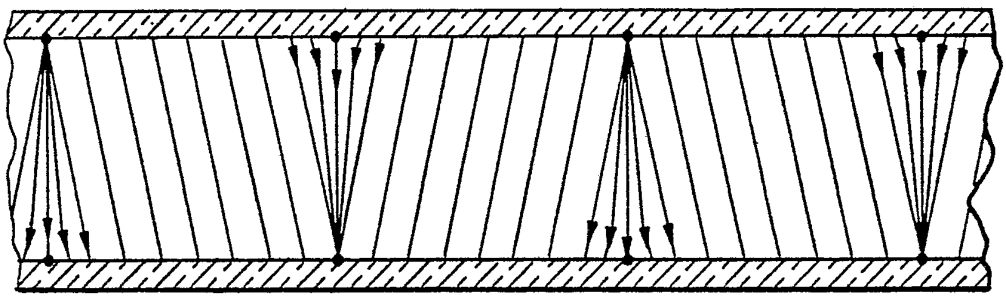


FIG. 11

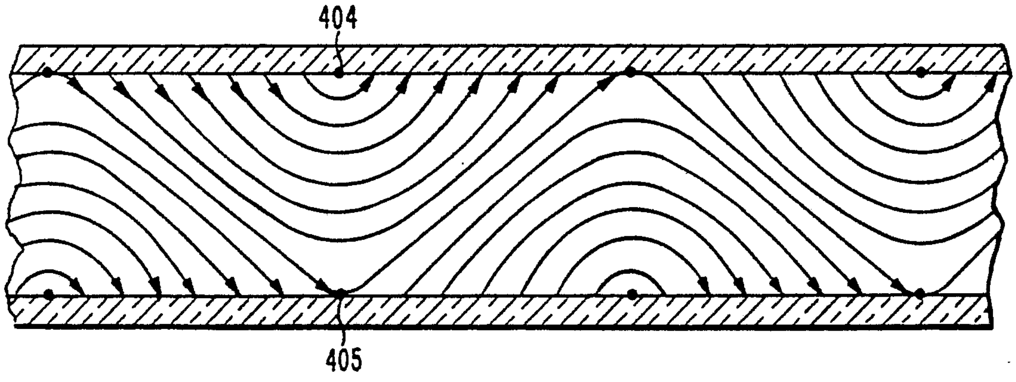


FIG. 12

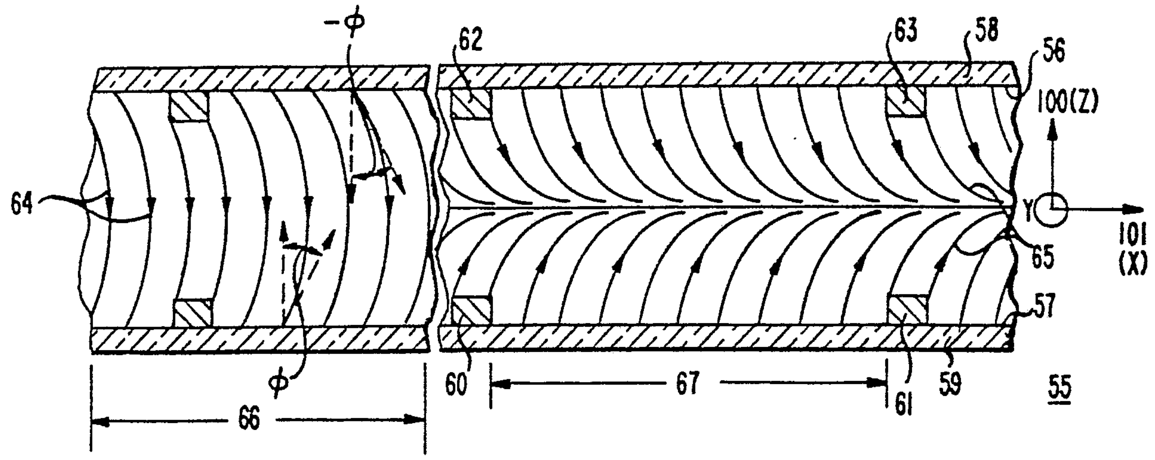


FIG. 13

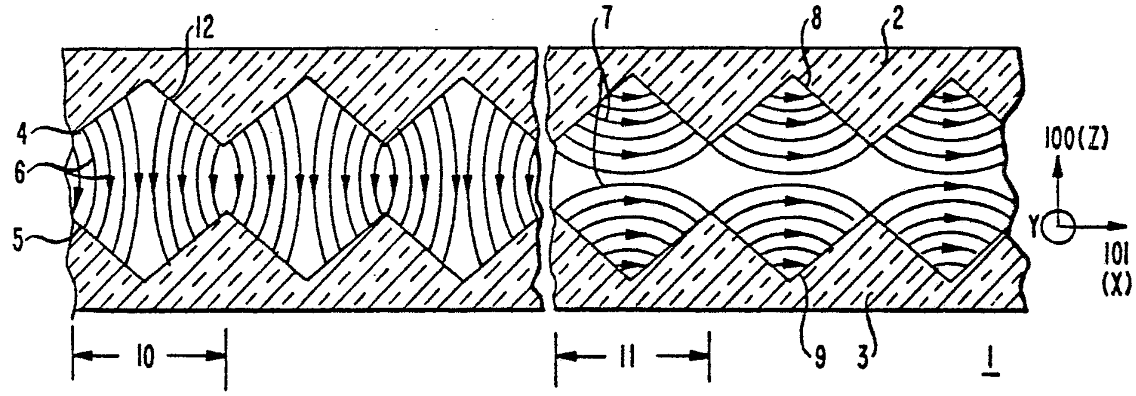


FIG. 14

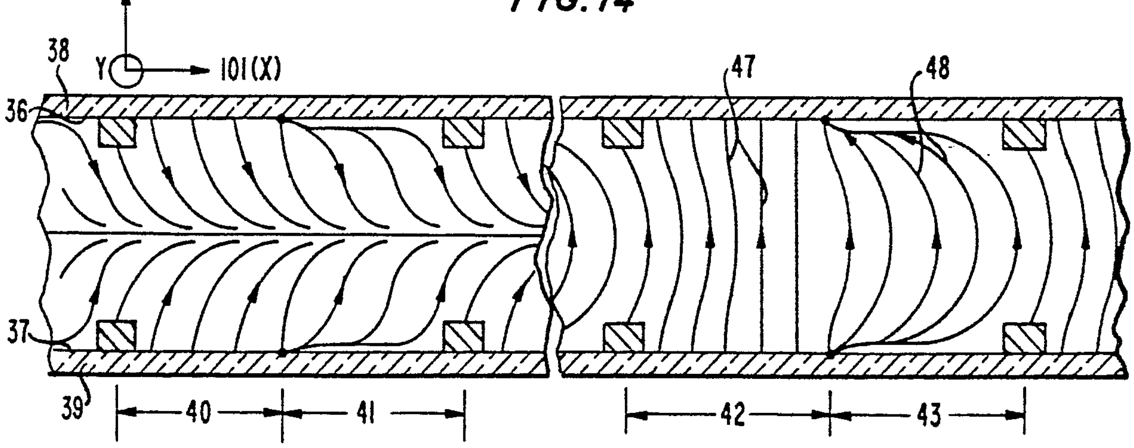


FIG. 15

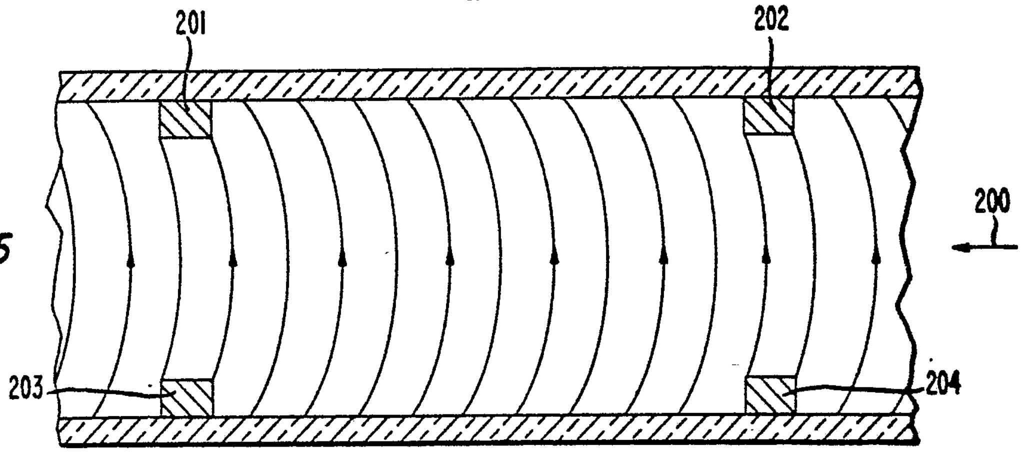


FIG. 16

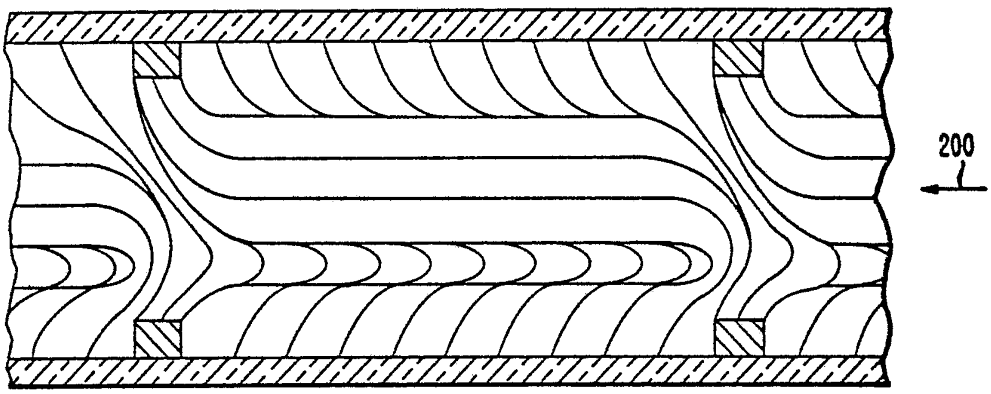


FIG. 17

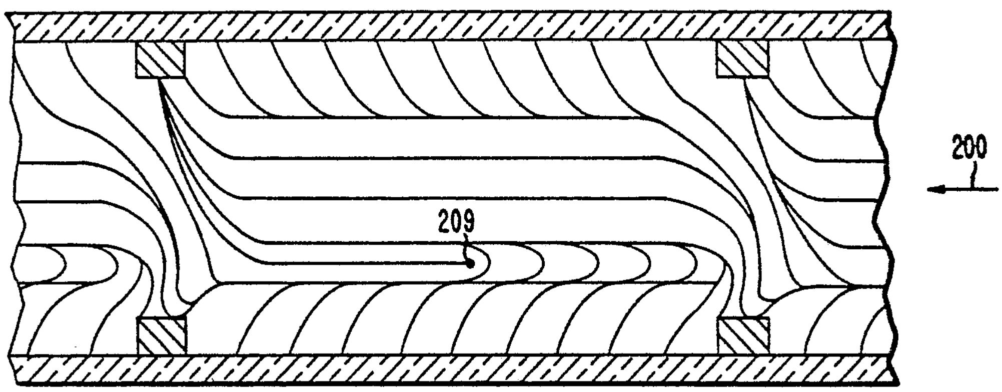


FIG. 18

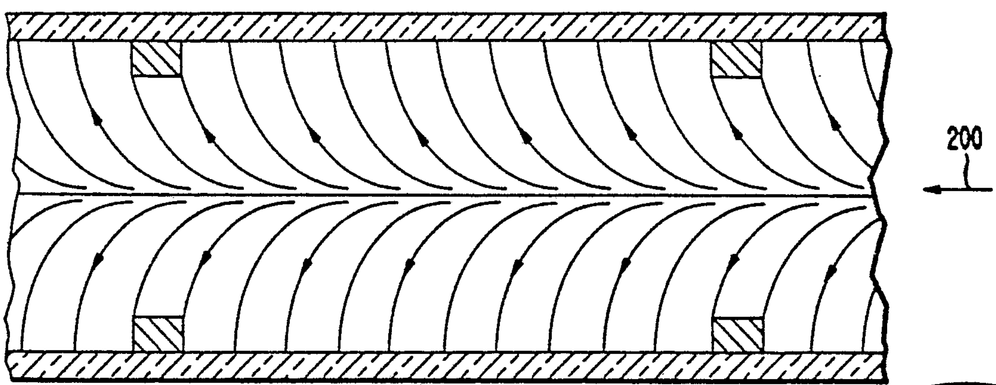


FIG. 19

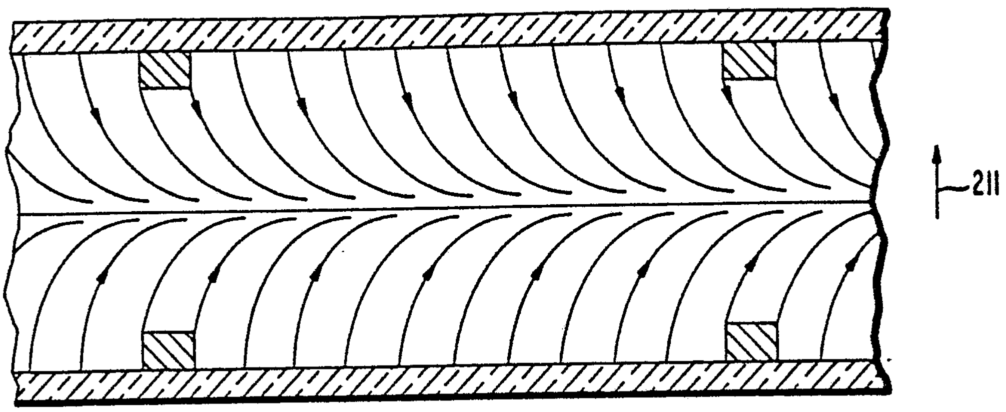


FIG. 20

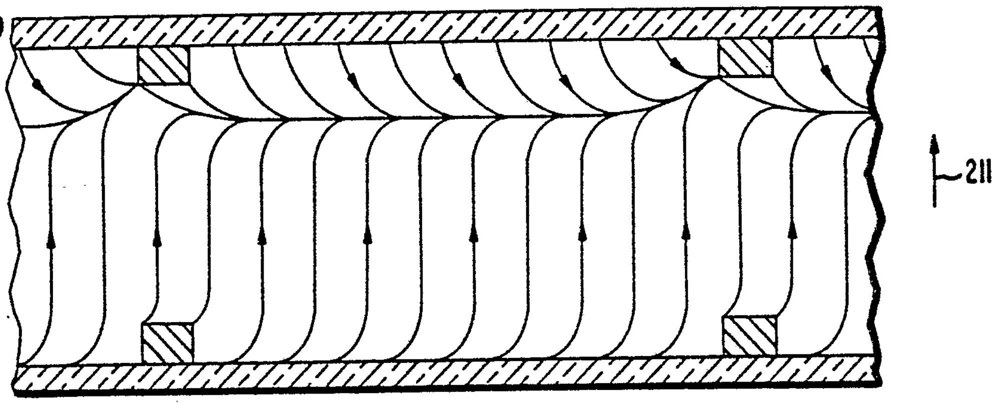


FIG. 21

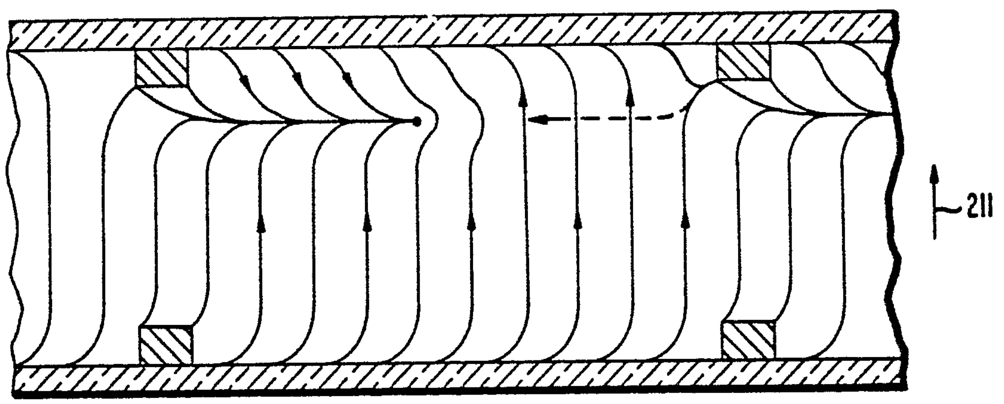


FIG. 22

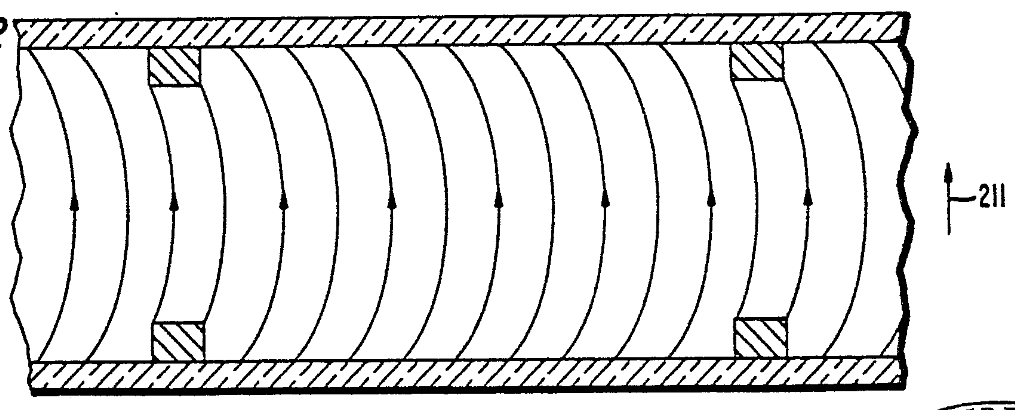


FIG. 23

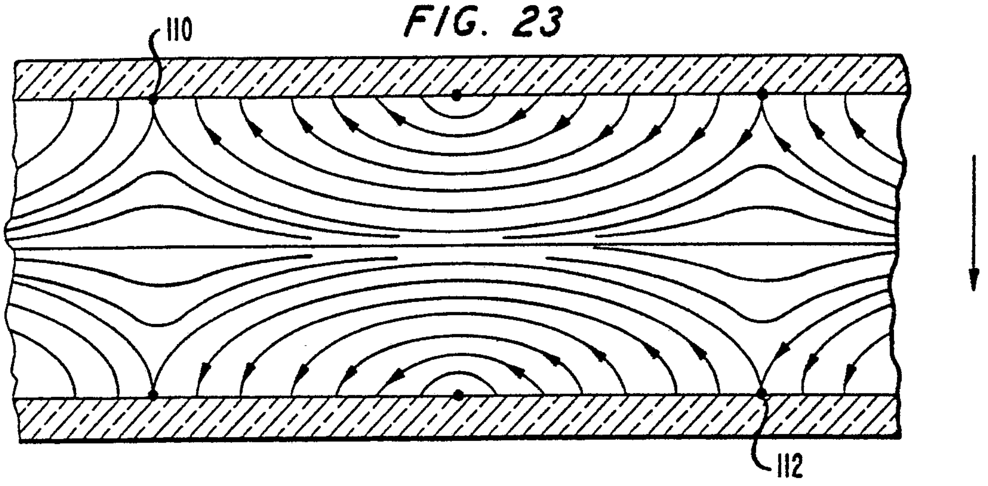


FIG. 24

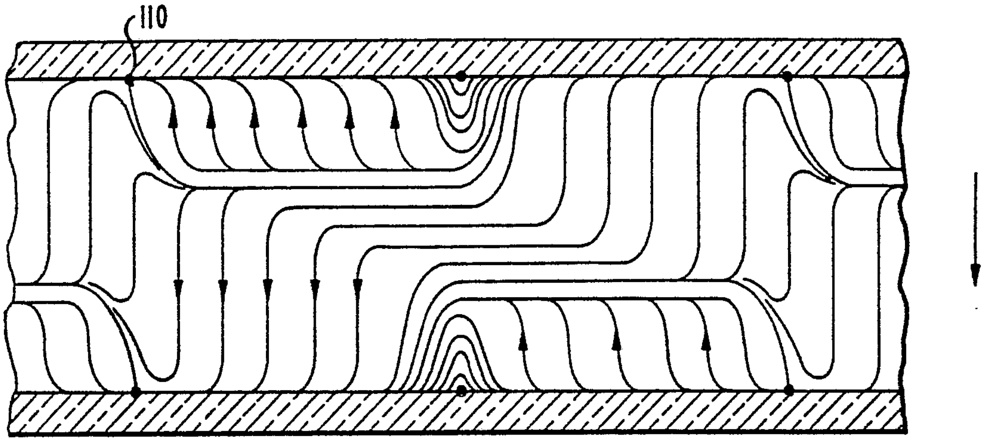


FIG. 25

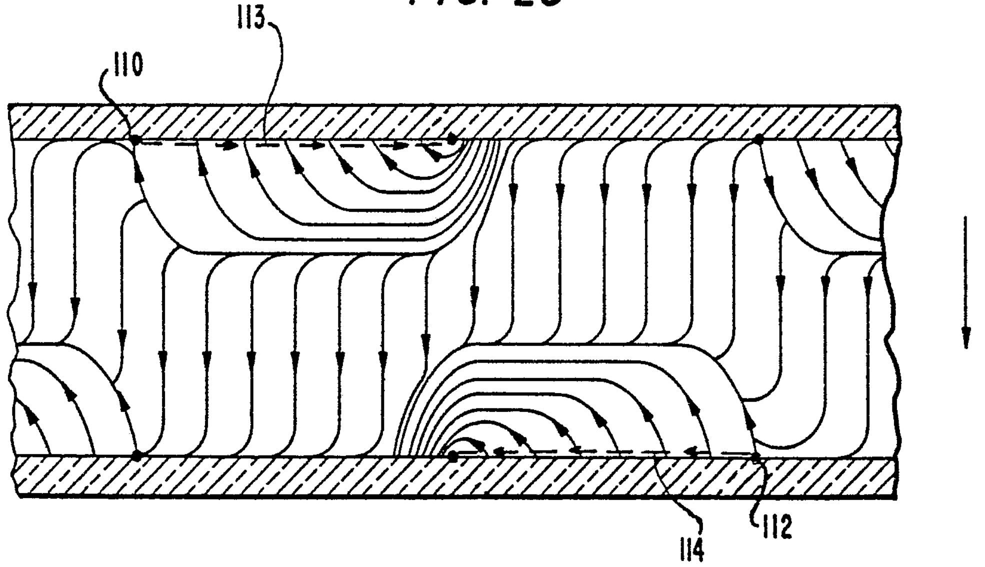


FIG. 26

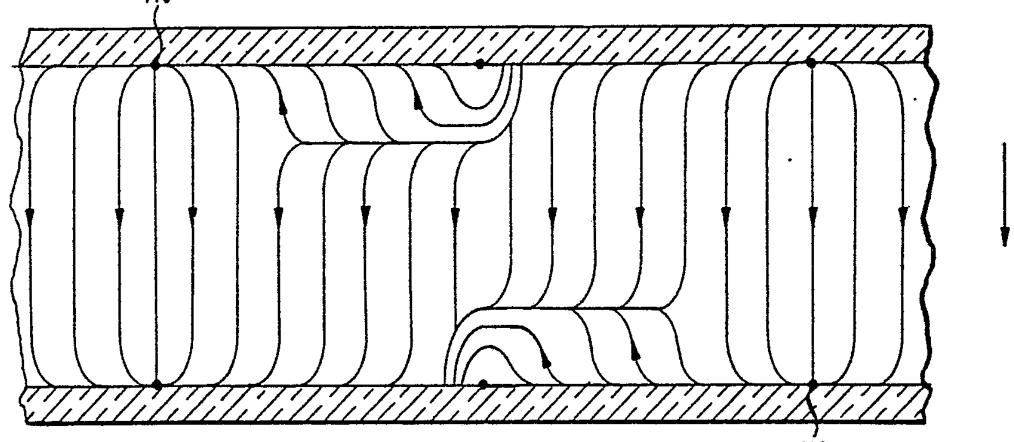


FIG. 27

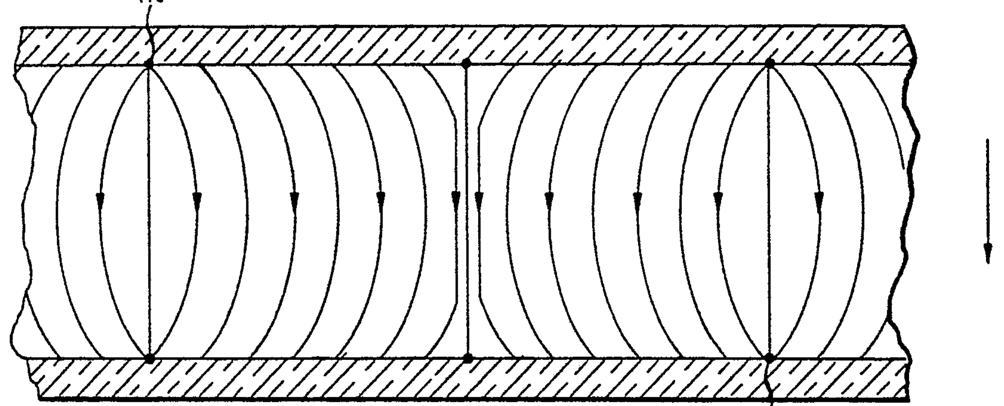


FIG. 28

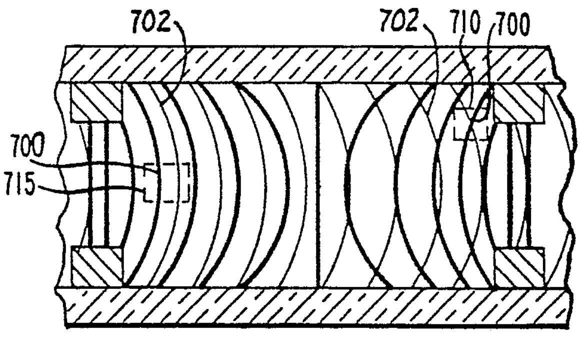


FIG. 29

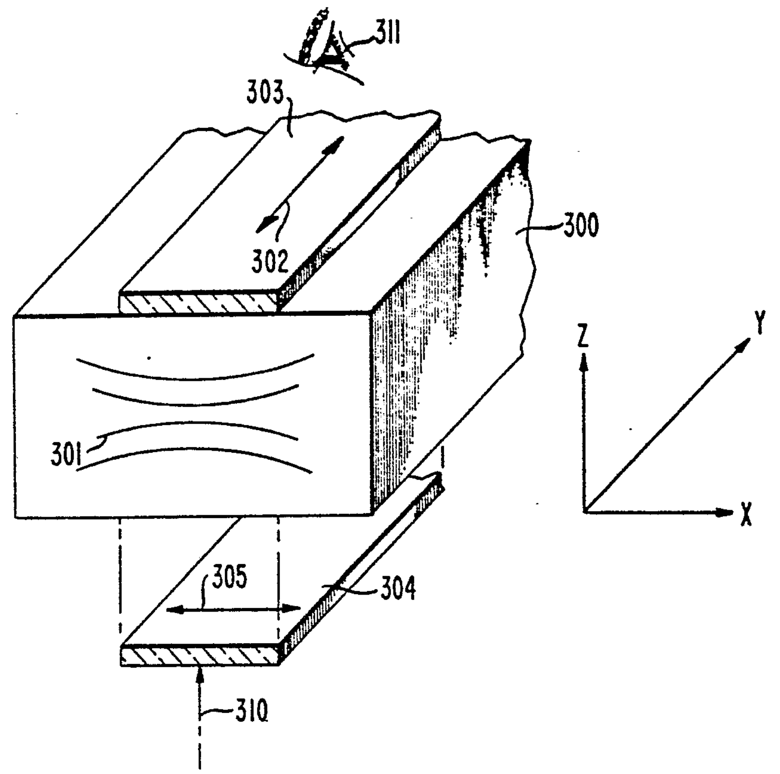


FIG. 30

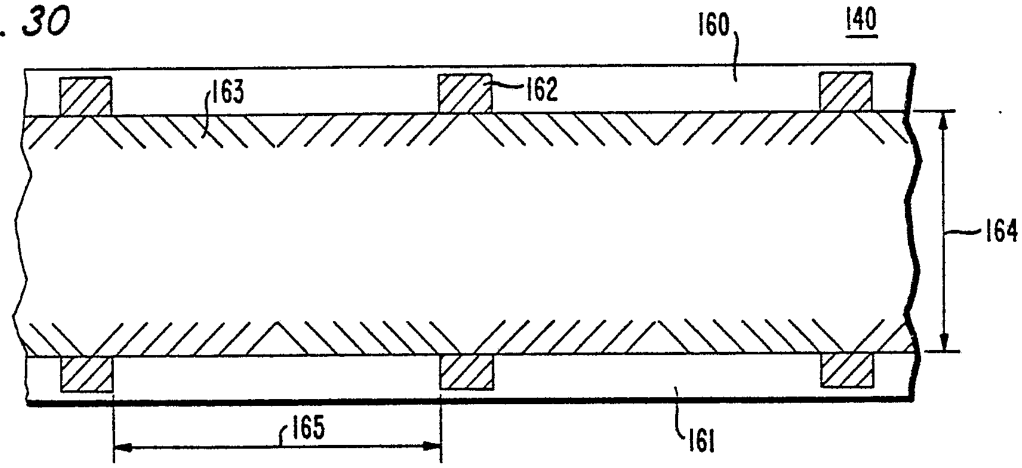


FIG. 31

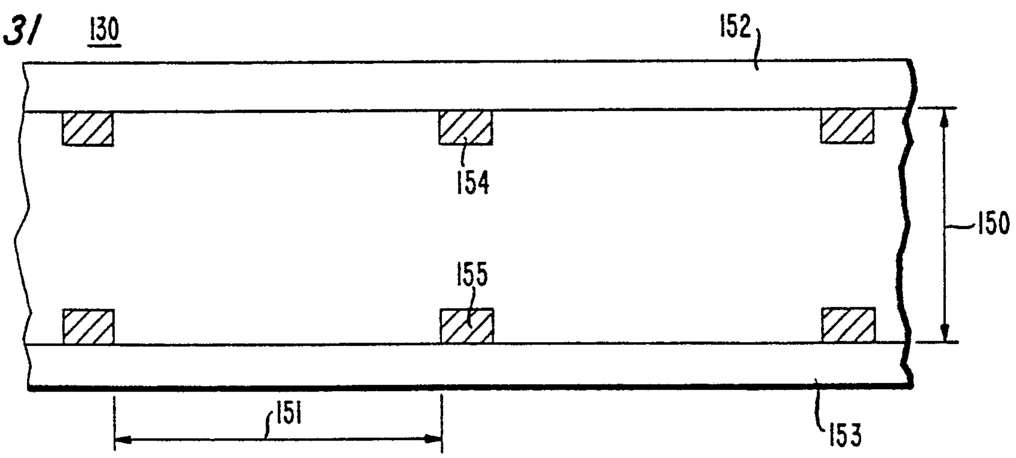


FIG. 32

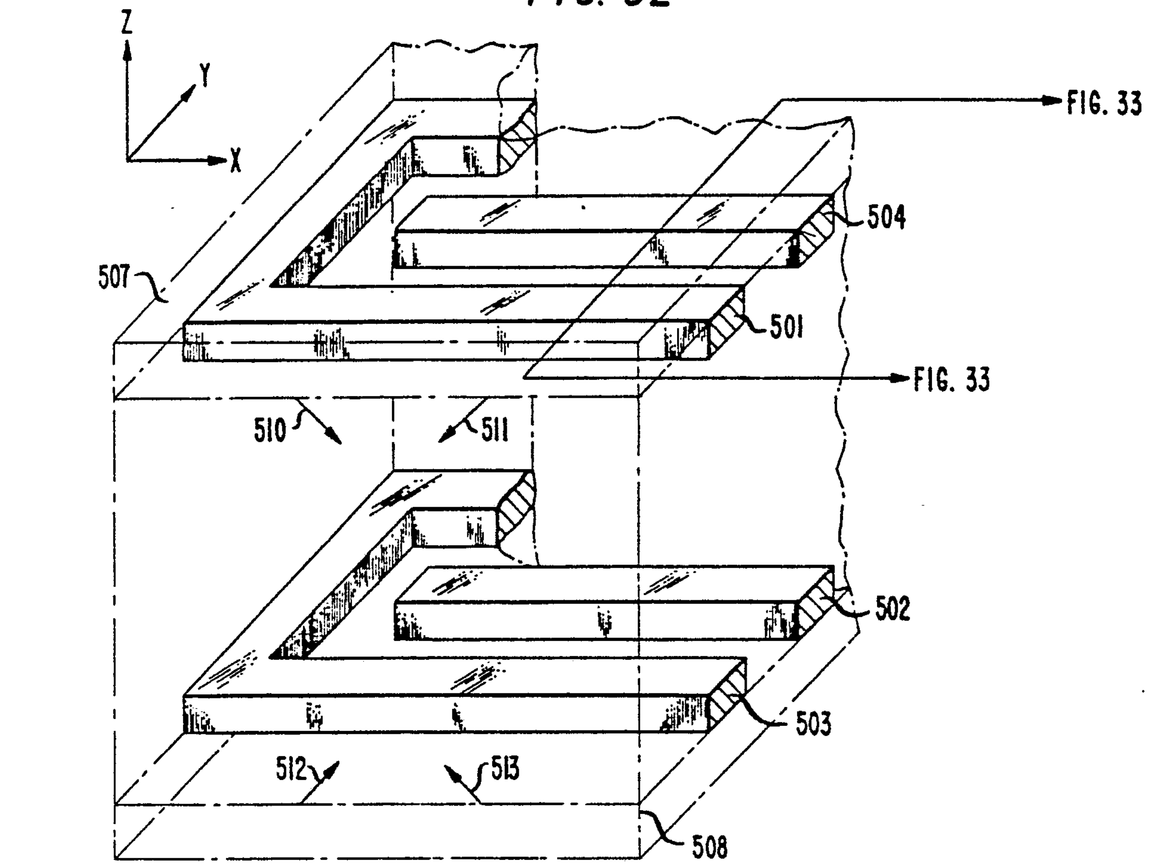


FIG. 33

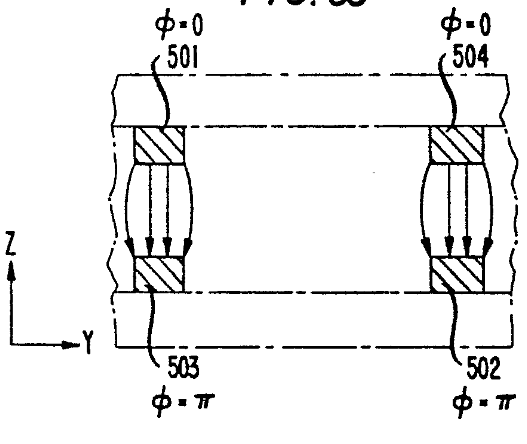
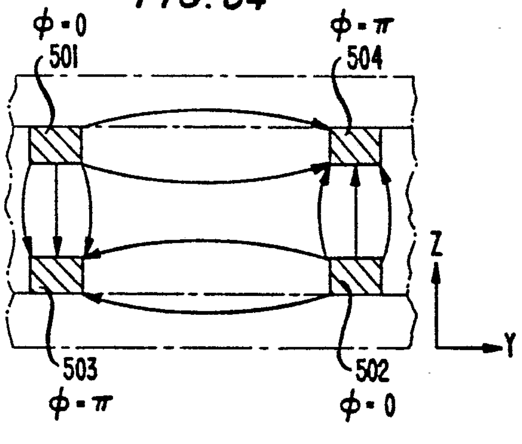


FIG. 34



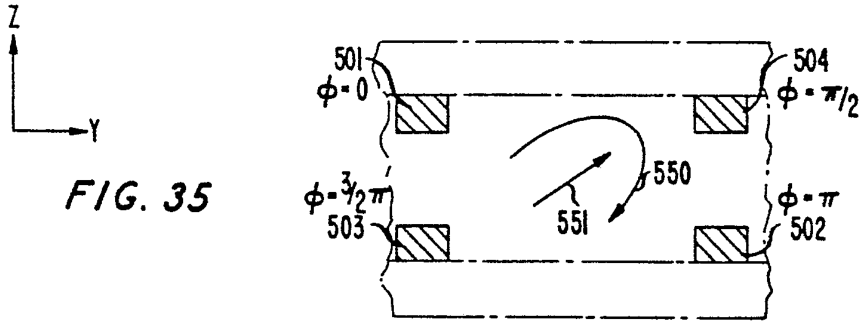


FIG. 35

FIG. 36

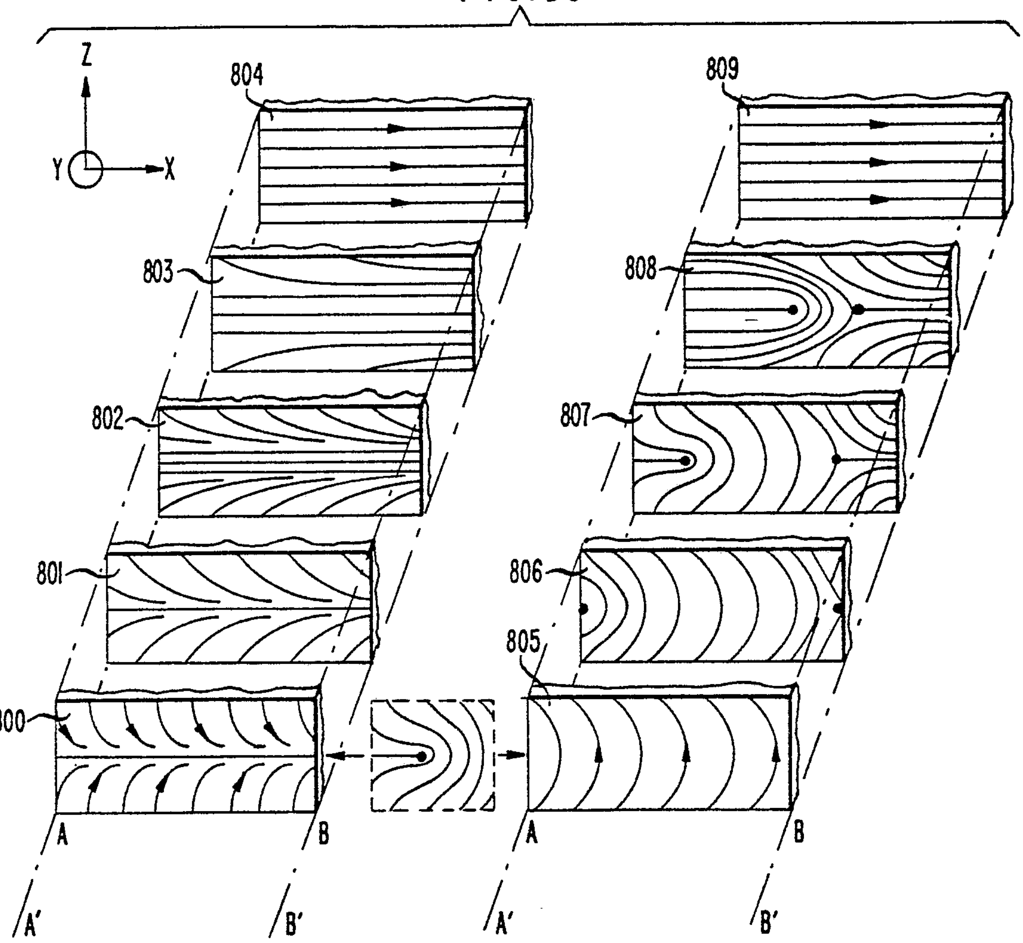
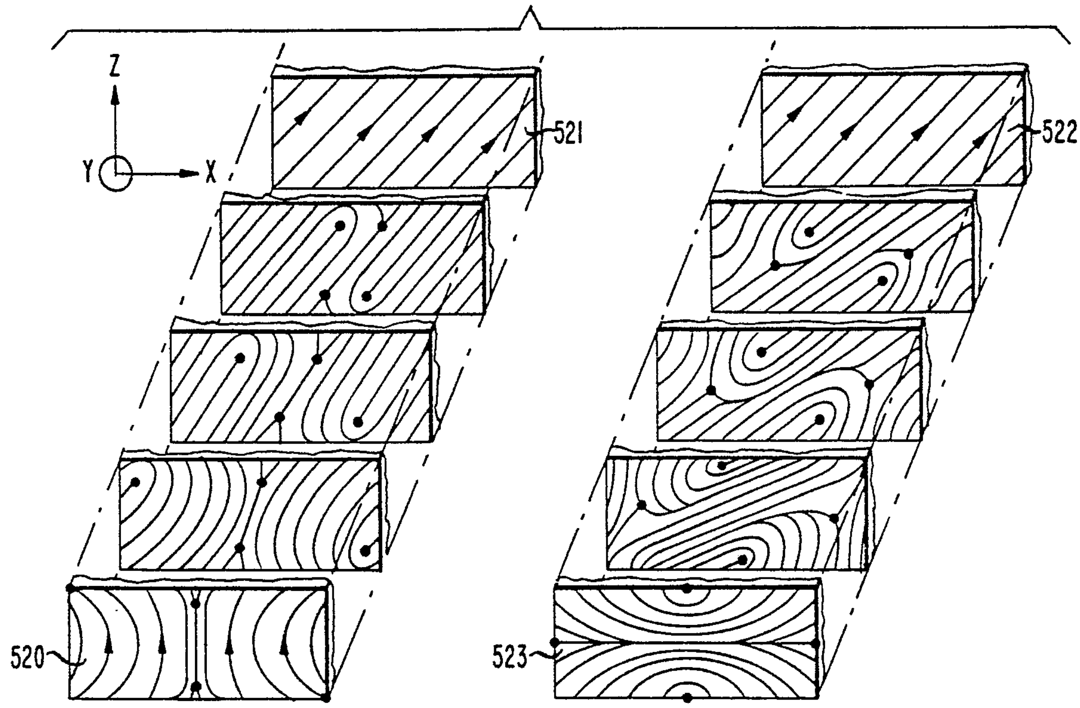

Z
Y
X
804
809
803
808
802
807
801
806
805
800
A
B
A
B
A'
B'
A'
B'

FIG. 37


Z
Y
X
521
522
520
523

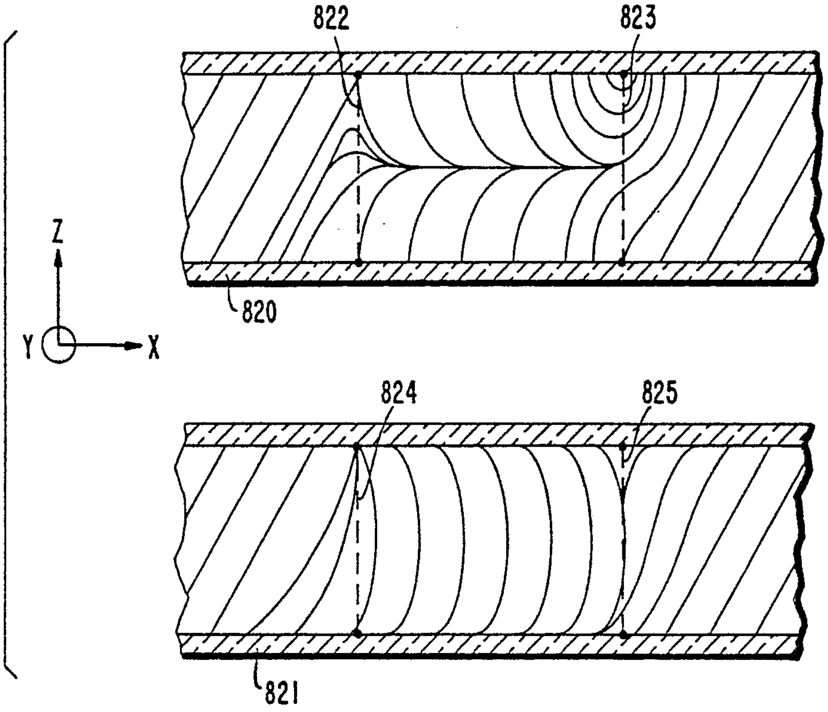

822
823
Z
Y
X
820
824
825
821

FIG. 38

FIG. 39

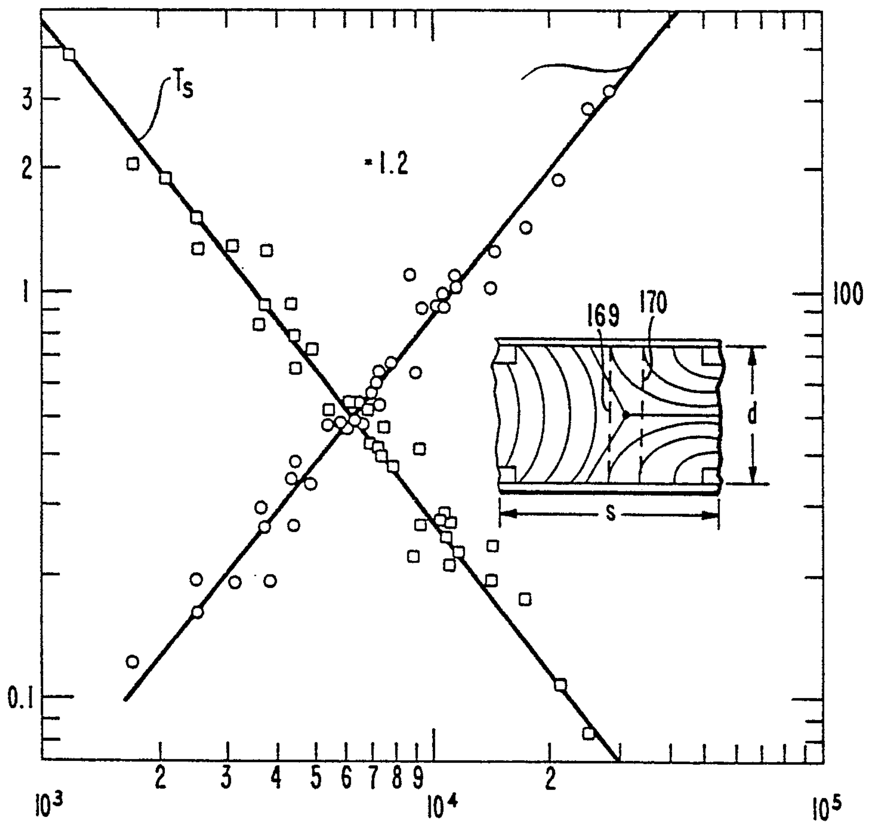

T_s
=1.2
3
2
1
0.1
100
169
170
d
s
2
3
4
5
6
7
8
9
2
10^3
10^4
10^5

FIG. 40

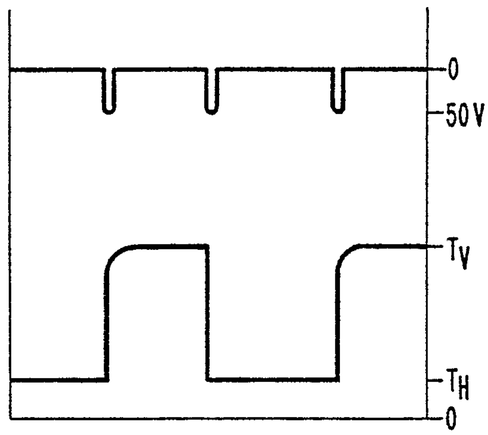


FIG. 41

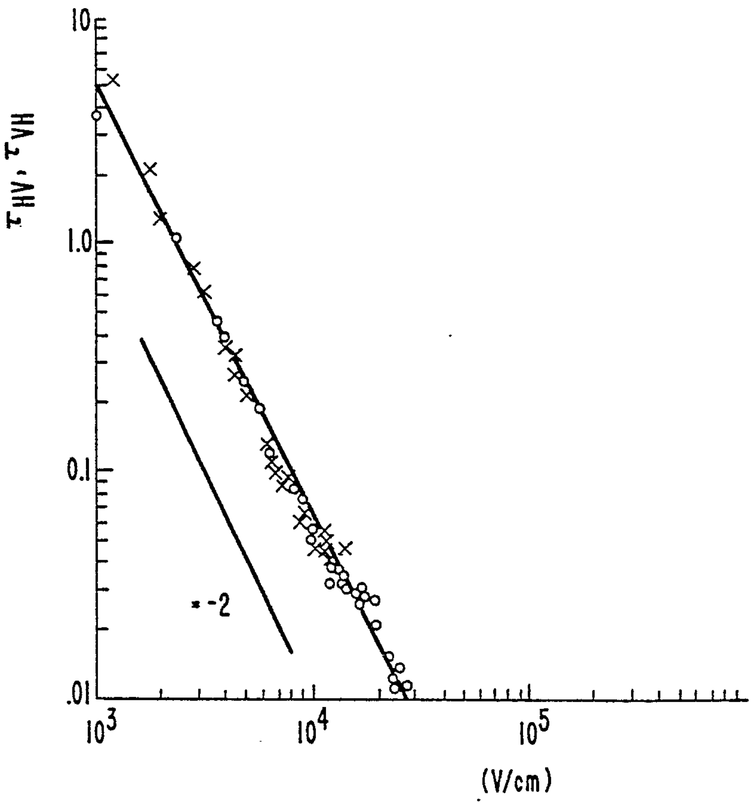


FIG. 42

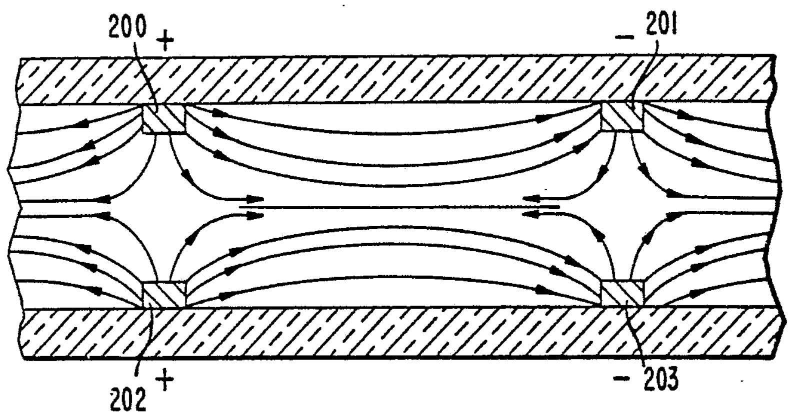


FIG. 43

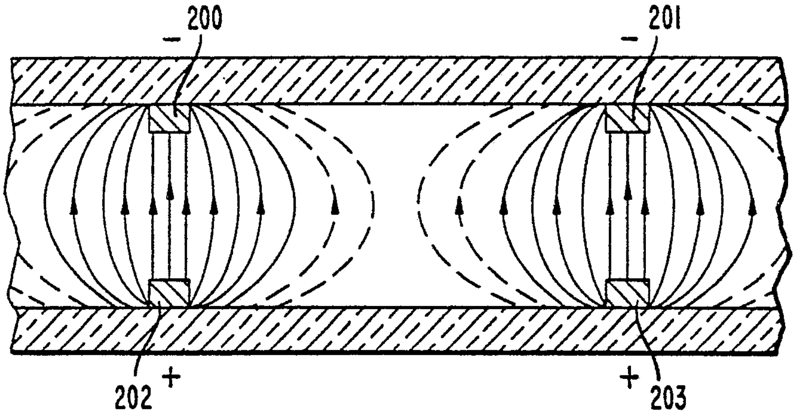
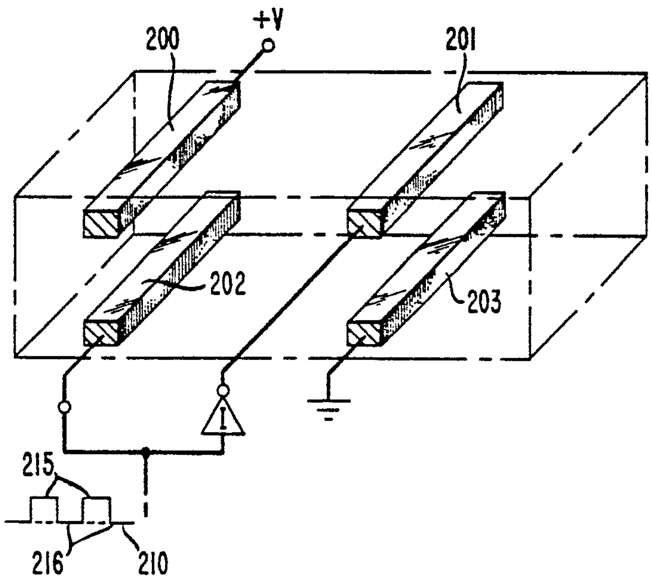


FIG. 44



INTERNATIONAL SEARCH REPORT

International Application No PCT/US80/01587

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [3]

According to International Patent Classification (IPC) or to both National Classification and IPC

INT. CL.[3] G02F 1/33
U.S. CL. 350/341

II. FIELDS SEARCHED

Minimum Documentation Searched [4]

Classification System	Classification Symbols
US.	350/334, 336, 340, 341, 346

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [5]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [14]

Category *	Citation of Document, [16] with indication, where appropriate, of the relevant passages [17]	Relevant to Claim No. [18]
X	US, A, 4,002,404, Published 11 January 1977, DIR	1-9
X	US, A, 4,030,997, Published 21 June 1977, MILLER ET AL	1-9
X	US, A, 4,128,313, Published 5 December 1978 COLE, JR. ET AL	1-9
X	N, Le Journal De Physique, Published May, 1977, PORTE, Surface Disclination Lines Observed in Nematic Liquid Crystals When the Surfaces Induce Homogeneously Tilted Alignment.	1-9
X	N, Le Journal De Physique, Issued February 1978, PORTE ET AL., A Phase Transition-Like Instability in Static Samples of Twisted Nematic Liquid Crystals When the Surfaces Induce Tilted Alignments.	1-9
X	N, IEEE Transactions on Electron Devices, Issued September, 1975, BIGELOW ET AL, Observations of a Bistable Twisted Nematic Liquid-Crystal Effect.	1-9
X	N, Japanese Journal of Applied Physics, Issued 1979, SAITO ET AL, Field Induced Distortion of the Molecular Orientation Pretilted Reversely at Both Surfaces of a Nematic Liquid Crystal Cell.	1-9

* Special categories of cited documents: [15]

"A" document defining the general state of the art
"E" earlier document but published on or after the international filing date
"L" document cited for special reason other than those referred to in the other categories
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but on or after the priority date claimed
"T" later document published on or after the international filing date or priority date and not in conflict with the application, but cited to understand the principle or theory underlying the invention
"X" document of particular relevance

IV. CERTIFICATION

Date of the Actual Completion of the International Search [2]	Date of Mailing of this International Search Report [2]
20 February 1981	04 MAR 1981
International Searching Authority [1]	**Signature of Authorized Officer [20]**
ISA/US	Edward S. Bauer Edward S. Bauer

Form PCT/ISA/210 (second sheet) (October 1977)