



(51) International Patent Classification:

G02F 1/313 (2006.01) *G02B 6/14* (2006.01)

(21) International Application Number:

PCT/US2019/063150

(22) International Filing Date:

26 November 2019 (26.11.2019)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

62/772,667 29 November 2018 (29.11.2018) US

(71) Applicants: **KENT STATE UNIVERSITY** [US/US];
P.O. Box 5190, Kent, Ohio 44242 (US). **VALEO VISION**
[FR/FR]; 34, rue Saint Andre, F93012 Bobigny Cedex (FR).

(72) Inventors: **JAKLI, Antal**; 752 Admore Dr., Kent, Ohio
44240 (US). **GUIMARAES, Veridiana Garcia**; 346
Parangua Street, 87020-190 Maringa (BR). **SATHAYE,**
Kedar; 31 Rue Adam Ledoux, 92400 Courbevoie (FR).
WANG, Junren; 9877 174th CT NE, Redmond, Washing-
ton 98052 (US).

(74) Agent: **KLINKO, Mark D.**; 1228 Euclid Avenue, 5th
Floor, Cleveland, Ohio 44115 (US).

(81) Designated States (unless otherwise indicated, for every
kind of national protection available): AE, AG, AL, AM,
AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ,
CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO,
DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN,
HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP,
KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME,
MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ,
OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA,
SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN,
TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every
kind of regional protection available): ARIPO (BW, GH,
GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ,
UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ,
TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK,
EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV,
MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM,
TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW,
KM, ML, MR, NE, SN, TD, TG).

(54) Title: FAST OPTICAL SWITCH

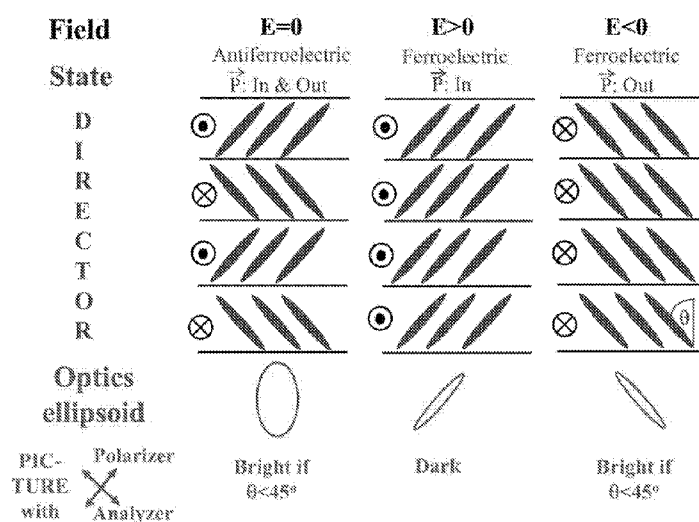


FIG. 1

(57) Abstract: A fast optical switch includes a pair of liquid crystal films disposed between two transparent substrates. Each liquid crystal film includes an antiferroelectric liquid crystal doped with a dichroic dye. The switch may have a response time of less than 1 millisecond.

Published:

— *with international search report (Art. 21(3))*

FAST OPTICAL SWITCH

[0001] This application claims the priority benefit of U.S. Provisional Application No. 62/772,667 filed November 29, 2018 and titled "FAST OPTICAL SWITCH", which is incorporated by reference in its entirety.

BACKGROUND

[0002] The present exemplary embodiment relates to the fast electro-optical switching of devices containing dichroic dye-doped antiferroelectric liquid crystals. In some embodiments, devices containing the switches are polarizer-free.

[0003] It is known that pleiochroic dyes align along the liquid crystal director, thus leading to a color change when the liquid crystal director is switched by an applied electric field. Such switching typically requires one polarizer instead of two polarizers as usually used in field-effect liquid crystal displays without the dye.

[0004] One improved guest-host system uses unpolarized light and dichroic azo-dyes, which permit the device to operate in the reflective mode with very good brightness in the clear state and an acceptable contrast ratio.

[0005] Another improvement involves the use of black dyes, thereby allowing black-and-white switching. Since then, dye-doped guest-host nematic (N), cholesteric (N*) and polymer dispersed liquid crystals (PDLC) have been extensively used for polarizer free electro-optical devices. In all these displays, the director is switched between random, helical or planar (director is parallel to film surface) and homeotropic (the director is perpendicular to the substrate) alignments. In planar alignment, the electric field component of unpolarized light is parallel to the dichroic dye molecules and is absorbed by the dye molecules, resulting in a dark image. In homeotropic alignment, the average orientation of the dyes is perpendicular to the electric vector of light; consequently, they do not absorb light leading to bright image. In practice, due to director fluctuations and partial director order (order parameter, $S < 1$), the contrast is limited to about 10:1. This is about the same as of the contrast of printed text, so it is acceptable for various applications. The limiting factor is the switching time that is limited by the nematic rotational viscosity, to typically well above 1 millisecond.

[0006] Liquid crystals that can switch below 1 millisecond include the ferroelectric

(chiral rod-shape SmC*, or achiral bent-shape SmCP_F) and antiferroelectric (chiral rod-shape SmC_A* or bent-shape SmCP_A) tilted smectic liquid crystal materials. However, due to constant layer spacing requirements of smectic liquid crystals, the director can only rotate on a tilt cone and for both positive and negative field the director is basically parallel to the substrate. Furthermore, fine optical properties rely on good alignment of smectic materials, which is very difficult. Despite this, guest-host effects in SmA and SmC* liquid crystals have been studied, but mainly to understand the effect of dyes on thermal effects, surface anchoring, switching properties (between crossed polarizers), and dielectric properties.

[0007] It would be desirable to develop new optical switches with fast response times.

BRIEF DESCRIPTION

[0008] The present disclosure relates to optical switches including liquid crystal films. The films contain an antiferroelectric liquid crystal dope with a dichroic dye.

[0009] Disclosed, in some embodiments, is an optical switch for a liquid crystal device comprising in sequence: a first transparent substrate; a first transparent electrode; a first alignment layer a first liquid crystal film comprising a first antiferroelectric liquid crystal doped with a first dichroic dye a second liquid crystal film comprising a second antiferroelectric liquid crystal doped with a second dichroic dye; optionally a second alignment layer; a second transparent electrode; and a second transparent substrate.

[0010] The first liquid crystal film and the second liquid crystal film may be aligned perpendicular to each other.

[0011] In some embodiments, the first liquid crystal film and the second liquid crystal film are smectic layers.

[0012] The first antiferroelectric liquid crystal and the second antiferroelectric liquid crystal may be the same.

[0013] In some embodiments, the first dichroic dye and the second dichroic dye are the same.

[0014] The first antiferroelectric liquid crystal and the second antiferroelectric liquid

crystal may have a tilt angle in the range of about 40° to about 50°.

[0015] In some embodiments, the tilt angle is about 45°.

[0016] The switch may be switchable in less than 1 millisecond.

[0017] In some embodiments, the switch is switchable in less than 200 microseconds.

[0018] Devices containing the switch are also disclosed. The normal state of the devices may be a dark state or a bright state.

[0019] In some embodiments, the device is a privacy window, a refrigerator, an oven, a microwave, a windshield, or goggles.

[0020] Disclosed, in other embodiments, is a method for switching an electronic device from a first state to a second state. The method includes applying an electric field to the electronic device. The electronic device may contain the components of the optical switch described above in some embodiments.

[0021] Disclosed, in further embodiments, is a method of forming an optical switch. The method includes sandwiching a first liquid crystal film and a second liquid crystal film between two transparent substrates. Both the first liquid crystal film and the second liquid crystal film comprise an antiferroelectric liquid crystal doped with a dichroic dye. The first liquid crystal film and the second liquid crystal film may be aligned perpendicular to each other.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022] The following is a brief description of the drawings, which are presented for the purposes of illustrating the exemplary embodiments disclosed herein and not for the purposes of limiting the same.

[0023] **FIG. 1** is an illustration of the structure of the antiferroelectric SmC_A* liquid crystals viewed from the direction normal to the plane of drawing.

[0024] **FIG. 2** is an illustration of the combined rubbed surface and AC electric field treatment during cooling a 3-μm CS4000+5wt% S-428 sample from the I-SmA phase transition through the SmC* down to the SmC_A* phase. (a-c): Illustration of the effect of $U=90 V_{p-p}$ square wave field at different frequencies. Pictures are taken at zero fields at room temperature rotating the crossed polarizers to find the darkest image. (a) $f=5$ Hz; (b) $f=15$ Hz; (c) $f=70$ Hz. (d and e): Effect of $U=94 V_{p-p}$ $f=45$ Hz square wave field. (d) In

the ferroelectric phase while $U_{DC}=47$ V is applied and one of the crossed polarizers is aligned along the director; (e) in the antiferroelectric state with the same crossed polarizers alignment as in (d).

[0025] FIG. 3 is an illustration of the switching principle of an antiferroelectric liquid crystal guest-host system using one polarizer. (a-c) Sketch of the director structures when fields applied across the film (ferroelectric states) and when the field is turned off (antiferroelectric state). (a) Applying field in the direction where the director and the dye molecules tilt along the polarizer direction. (b) Reversing the field, the director and the dye molecules make an angle equal to twice the tilt angle (2θ). Note this state would be the brightest when $2\theta=90^\circ$, i.e., $\theta=45^\circ$. (c) When the field is turned off, the average director and the average orientation of the dye molecules make angle θ with respect to the polarizer. (d-f) Typical texture of 3 μm thick CS4000 with 2wt% G-472 dye molecules in the darkest (d), brightest (e) and medium brightness (f) states corresponding to the directors shown in (a-c), respectively. (g) An oscillogram trace of the switching between (a) and (b) states of CS4000 with 2wt% G-472 at room temperature.

[0026] FIG. 4 is an illustration of the layer and director structure of double layer cell configurations. Top row: Smectic layers (and rubbing directions) in the cells are oriented perpendicular to each other. Bottom row: Smectic layers (and rubbing directions) in the cells are oriented parallel to each other. Left column: $E=0$ on both cells (antiferroelectric state) with anticlinic director structures. Right column: $E>E_c$ (ferroelectric states) on both cells, but the ferroelectric polarizations point opposite directions. Top-Left: Layers are perpendicular, and the directors are anticlinic, consequently the average direction of the dye molecules is perpendicular to each other, i.e. no light goes through (dark state). Top-Right: Layers are perpendicular to each other; the directors are synclinic in opposite direction, so the angle between the directors (direction of the dye molecules in two cells) is $90^\circ-2\theta$. For $\theta=45^\circ$ it would be zero resulting in maximum brightness. Bottom-Left: Layers are parallel with anticlinic director structure, the average dye directions are normal to the layers, so they are parallel to each other. Such state is bright. Bottom right: Layers are parallel, and the directors are synclinic, but they tilt in opposite directions in the top and bottom cells. Consequently, the angle between the average dye orientations of the

bottom and top cells is 2θ , which is 90° when $\theta=45^\circ$ (darkest state).

[0027] FIG. 5 is an illustration of the switching of double layered antiferroelectric liquid crystal guest-host system (CS4000+5wt% S-428, 5 μm gap thickness and planar alignment) without polarizers. (a) Rubbing directions of individual films make 90 degrees with each other (along the edges of the electrodes) (a) picture when $U=30\text{ V}$, $f=80\text{ Hz}$ square wave voltage is applied; (b) Field is OFF; (c) Time dependence of the applied voltage (left axis, blue circles) and of the transmission (right axis, red squares). (d and e): Images of parallel cells in the antiferroelectric OFF state and (d) and in the ferroelectric ON state (e).

[0028] FIG. 6 illustrates one example of a double-layered display which may be free of polarizers.

[0029] FIG. 7 illustrates another example of a double-layered display which may be free of polarizers.

[0030] FIG. 8 illustrates an electro-optical device with one polarizer.

DETAILED DESCRIPTION

[0031] The present disclosure may be understood more readily by reference to the following detailed description of desired embodiments included therein. In the following specification and the claims which follow, reference will be made to a number of terms which shall be defined to have the following meanings.

[0032] Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art. In case of conflict, the present document, including definitions, will control. Preferred methods and materials are described below, although methods and materials similar or equivalent can be used in practice or testing of the present disclosure. All publications, patent applications, patents, and other references mentioned herein are incorporated by reference in their entirety. The materials, methods, and articles disclosed herein are illustrative only and not intended to be limiting.

[0033] The singular forms “a,” “an,” and “the” include plural referents unless the context clearly dictates otherwise.

[0034] As used in the specification and in the claims, the term “comprising” may

include the embodiments “consisting of” and “consisting essentially of.” The terms “comprise(s),” “include(s),” “having,” “has,” “can,” “contain(s),” and variants thereof, as used herein, are intended to be open-ended transitional phrases that require the presence of the named ingredients/steps and permit the presence of other ingredients/steps. However, such description should be construed as also describing compositions, mixtures, or processes as “consisting of” and “consisting essentially of” the enumerated ingredients/steps, which allows the presence of only the named ingredients/steps, along with any impurities that might result therefrom, and excludes other ingredients/steps.

[0035] Unless indicated to the contrary, the numerical values in the specification should be understood to include numerical values which are the same when reduced to the same number of significant figures and numerical values which differ from the stated value by less than the experimental error of the conventional measurement technique of the type used to determine the particular value.

[0036] All ranges disclosed herein are inclusive of the recited endpoint and independently combinable (for example, the range of “from 2 to 10” is inclusive of the endpoints, 2 and 10, and all the intermediate values). The endpoints of the ranges and any values disclosed herein are not limited to the precise range or value; they are sufficiently imprecise to include values approximating these ranges and/or values.

[0037] As used herein, approximating language may be applied to modify any quantitative representation that may vary without resulting in a change in the basic function to which it is related. Accordingly, a value modified by a term or terms, such as “about” and “substantially,” may not be limited to the precise value specified, in some cases. The modifier “about” should also be considered as disclosing the range defined by the absolute values of the two endpoints. For example, the expression “from about 2 to about 4” also discloses the range “from 2 to 4.” The term “about” may refer to plus or minus 10% of the indicated number. For example, “about 10%” may indicate a range of 9% to 11%, and “about 1” may mean from 0.9-1.1.

[0038] For the recitation of numeric ranges herein, each intervening number there between with the same degree of precision is explicitly contemplated. For example, for the range of 6-9, the numbers 7 and 8 are contemplated in addition to 6 and 9, and for the range 6.0-7.0, the number 6.0, 6.1, 6.2, 6.3, 6.4, 6.5, 6.6, 6.7, 6.8, 6.9, and 7.0 are

explicitly contemplated.

[0039] As used herein, a “ferroelectric” liquid crystal is defined as a crystal which shows spontaneous electric polarization and whose direction of spontaneous polarization can be reversed via the application of an electric field.

[0040] As used herein, an “antiferroelectric” liquid crystal is defined as a smectic or columnar liquid crystal where subsequent smectic layers or columns are composed of two sublattices polarized spontaneously in antiparallel directions and in which a ferroelectric phase can be induced by applying an electric field.

[0041] The present disclosure relates to fast optical switches. Fast electro-optical switching can be achieved without polarizers by using dichroic dye-doped antiferroelectric liquid crystals. In some embodiments, two films of dye-doped antiferroelectric liquid crystals can be used to switch the transmitted light intensity between dark and bright states without the need of polarizer filters.

[0042] The normal state may be a dark state or a bright state. In some embodiments, the normal state is a dark state and the switch is used in a privacy window, a microwave, or a smart refrigerator (e.g., when one does not see contents but can have a peak view without opening the door).

[0043] In some embodiments, the normal state is a bright state and the device can be used in navigation systems built in windshields, ski goggles, welding goggles, or where the voltage is triggered by light, thereby attenuating it within the fraction of 1 millisecond and preventing eye damage.

[0044] **FIG. 1** illustrates the director structure and the optics looking from the top on a film with bookshelf alignment (smectic layers are normal to the substrate) when no field applied and under sufficiently large fields applied in opposite directions to an antiferroelectric liquid crystal system. In this view, the smectic layers are illustrated by lines. At zero applied fields, the average orientation of the molecules (illustrated by elongated ellipses), is tilting alternately from one layer to the other and the spontaneous polarizations points in and out of the plane of the drawing. The effective birefringence of this structure is small, and the index ellipsoid is fat with long axis along the layer normal (vertical direction in the drawing). In fact, the antiferroelectric state would appear optically isotropic, if the tilt angle were precisely 45° . Such a structure is called orthoscopic and is

promising for fast displays with large viewing angle. When large enough fields are applied in the viewing direction pointing in or out of the plane of drawing, the anticlinic structure becomes synclinic, in which the director tilts uniformly left or right, depending on the direction of the applied field. In these two states, the directions of the optical axes make angle $\pm\theta$ with respect to the layer normal. Turning the crossed polarizers so that the polarizer or analyzer is parallel to one of the optic axes (in **FIG. 1** to the $E>0$ state), then this state appears black, whereas the state with the opposite ferroelectric polarization direction appears bright when $0<\theta<45^\circ$. The brightest state appears when $\theta=45^\circ/2=22.5^\circ$, whereas the state remains dark when $\theta=45^\circ$. Four rows are included in **FIG. 1** to demonstrate that there is a periodic structure with two layers periodicity. In other embodiments, there are 2 rows, 6 rows, 8 rows, etc.

[0045] In some embodiments, the antiferroelectric liquid crystals have a tilt angle of 45° .

[0046] The systems, apparatuses, and methods of the present disclosure may use electro-optical switching of a room temperature antiferroelectric liquid crystal mixture, both in single layer with the use of one polarizer, and/or in double layer configurations without the need of any polarizer.

[0047] In some embodiments, the antiferroelectric liquid crystal phases include one or more of the following: anticlinic chiral tilted smectic phase (SmC^*A – used in the examples), anticlinic chiral tilted columnar phase of disc-shaped molecules, and antiferroelectric tilted polar smectic or columnar phase of bent-shaped molecules.

[0048] **FIG. 6** illustrates one example of a double-layered display **100** which may be free of polarizers. The display **100** includes, in sequence, a first transparent substrate **110a**, a first transparent electrode **120a**, a first transparent alignment layer **130a**, a first liquid crystal layer **140a**, a second transparent alignment layer **130b**, a second transparent electrode **120b**, a second transparent substrate **110b**, a third transparent substrate **110b**, a third transparent electrode **120c**, a third transparent alignment layer **130c**, a second liquid crystal layer **140b**, a fourth transparent alignment layer **130d**, a

fourth transparent electrode **120d**, and a fourth transparent substrate **110d**.

[0049] In some embodiments, one or more of the aforementioned layers is omitted.

[0050] Where multiple layers of the same type are present, the layers may include the same or different materials. For example, the transparent substrates **110a**, **110b**, **110c**, **110d** may be made of the same or different materials. Similarly, the transparent electrodes **120a**, **120b**, **120c**, **120d** may be made of the same or different materials. Also, the transparent alignment layers **130a**, **130b**, **130c**, **130d** may be made of the same or different materials. The liquid crystal layers **140a**, **140b** may also be made of the same or different materials. The same principle applies to the thicknesses of the various layers of the same type which may be the same or different.

[0051] **FIG. 7** illustrates another example of a double-layered display **200** which may be free of polarizers. The display **200** includes, in sequence, a first transparent substrate **210a**, a first transparent electrode **220a**, a first transparent alignment layer **230a**, a first liquid crystal layer **240a**, a second transparent alignment layer **230b**, a second transparent electrode **220b**, a second transparent substrate **210b**, a third transparent electrode **220c**, a third transparent alignment layer **230c**, a second liquid crystal layer **240b**, a fourth transparent alignment layer **230d**, a fourth transparent electrode **220d**, and a third transparent substrate **210c**.

[0052] In some embodiments, one or more of the aforementioned layers is omitted.

[0053] Where multiple layers of the same type are present, the layers may include the same or different materials. For example, the transparent substrates **210a**, **210b**, **210c** may be made of the same or different materials. Similarly, the transparent electrodes **220a**, **220b**, **220c**, **220d** may be made of the same or different materials. Also, the transparent alignment layers **230a**, **230b**, **230c**, **230d** may be made of the same or different materials. The liquid crystal layers **240a**, **240b** may also be made of the same or different materials. The same principle applies to the thicknesses of the various layers of the same type which may be the same or different.

[0054] **FIG. 8** illustrates an electro-optical device **300** with one polarizer. The device includes a polarizer **350**, and, in sequence, a first transparent substrate **310a**, a first transparent electrode **320a**, a first transparent alignment layer **330a**, a liquid crystal layer **340**, a second transparent alignment layer **330b**, a second transparent electrode **320b**,

and a second transparent substrate **310b**.

[0055] In some embodiments, one or more of the aforementioned layers is omitted.

[0056] Where multiple layers of the same type are present, the layers may include the same or different materials. For example, the transparent substrates **310a**, **310b** may be made of the same or different materials. Similarly, the transparent electrodes **320a**, **320b** may be made of the same or different materials. Also, the transparent alignment layers **330a**, **330b**. The same principle applies to the thicknesses of the various layers of the same type which may be the same or different.

[0057] The following examples are provided to illustrate the devices and methods of the present disclosure. The examples are merely illustrative and are not intended to limit the disclosure to the materials, conditions, or process parameters set forth therein.

EXAMPLES

[0058] For the examples, a room temperature antiferroelectric liquid crystal mixture CS4000 from Chisso Corporation (now Japan New Chisso) doped with either a blue dichroic dye (G-472 from Hayashibara Chemicals) or black dichroic dye (S-428 from Mitsui Chemicals) was used. The black dye comprises a mixture of a red azo dye, a yellow azo dye, and a blue anthraquinone dye in amounts of 16wt%, 7wt% and 77wt%, respectively. The phase sequence, alignment properties, tilt angle, polarization and switching time measurements of CS4000 are known. The phase sequence of the pure CS4000 was reported as Isotropic (98.5°C) SmA (83°C) SmC_α* (81.2°C) SmC* (79.9°C) SmC_γ* (79°C) SmC_α* (-10°C) Crystal.

[0059] The dyes were mixed in CS4000 by dissolving a proper amount of dye and liquid crystal in chloroform, followed by complete evaporation of chloroform. No phase separation was found either in 2wt% G-472 or up to 5wt% S-428 mixtures, and the transition temperatures were found to be suppressed by less than 1°C. The mixtures of blue and black dye-doped antiferroelectric liquid crystal were then capillary-filled into 3 μm, 5 μm and 12 μm thick sandwiched cells in a vacuum oven at 120°C. The glass substrates are treated with transparent ITO (indium tin oxide), spin-coated with polyimide (PI-2555) and rubbed unidirectionally to promote planar alignment. As a control, 3 μm and 12 μm thick pure CS4000 samples were also prepared and studied.

[0060] Alignment

[0061] To achieve “bookshelf alignment”, an electric field (square waveform) was applied onto the dye doped antiferroelectric liquid crystal cells while cooling from the SmA to SmC_A* phase, at a rate of 1.0°C/min. It was found that the quality of the alignment strongly depends on the strength and frequency of the applied square wave field, and, to a lesser extent, on the cooling rate. For 3μm cells, it was found that f=15 Hz is the optimal frequency. It can be seen by comparing the images of the textures obtained after applying U=90 V_{p-p} square wave voltage at (a) f=5 Hz; (b) f=15 Hz; (c) f=70 Hz frequencies (see **FIG. 2a**, **b** and **c**), respectively. Similar results were found for 5μm thick cells and for both dyes. Pictures are taken at zero fields at room temperature (antiferroelectric state) by rotating the crossed polarizers parallel and perpendicular to the rubbing direction to find the darkest image. The darker is the image, better is the alignment (see **FIG. 1** for explanation). We can judge that the alignment obtained at 70 Hz (**FIG. 2c**) is much worse than that obtained under 5 Hz (**FIG. 2a**) and 15 Hz (**FIG. 2b**). Careful inspection of **FIG. 2a** (5Hz) reveals presence of defect lines, which are completely missing in **FIG. 2b** (15Hz).

[0062] The quality of the electro-optical switching between crossed polarizers can be judged by looking at **FIG. 2d** and **FIG. 2e**. In these cases, the crossed polarizers were rotated by about 25° to find the darkest state when +47 V (DC) was applied on the cell. This angle is slightly smaller than the tilt angle $\theta=27^\circ$ measured in pure CS4000, indicating that the dye molecules are shorter than of the average length of the CS4000 molecules. The alignment is practically perfect in macroscopic (over mm) scale, which is a significant improvement compared to the alignments published on pure CS4000 with similar methods, but with different alignment layers and different voltages applied on thicker samples.

[0063] The physical mechanism of the combined electric field treatment and surface alignment is not clear yet. Since the spontaneous polarization is restricted along the layers, switching it between up and down along the field across the substrate will definitely pull the layers along the electric field. However, the field alone would not distinguish any direction normal to the field. The rubbing direction would do it, but in a tilted SmC* phase, it still would allow two equally possible orientation of the layers, namely with angle $\pm\theta$

with respect the rubbing direction. The absence of these two directions is possibly due to the alternating flow induced by the switching of the director on a cone while switching the direction of the ferroelectric polarization. This flow aligns the smectic layers in one direction by sweeping away domains in wrong layer directions. Having only a small bias toward one direction (possibly due to surface pretilt induced by unidirectional rubbing) may also facilitate the complete disappearance of the unfavorable layer direction.

[0064] Electro-optics with one polarizer

[0065] Looking at the $E=0$, $E>0$ and $E<0$ states shown in **FIG. 1** with no polarizer, there would be no difference in the transmitted light intensities. However, placing the film behind (or in front of) a linear polarizer, contrast is seen (see **FIG. 3**). The image is the darkest (**FIG. 3d**) when the polarizer is parallel to the director in one of the ferroelectric states (see **FIG. 3a**). This is because the dye molecules, parallel to the electric vector of light coming through the linear polarizer, absorb the light. In this polarizer direction, the image becomes bright (**FIG. 3e**) when the polarity of the ferroelectric state is switched to the opposite direction, because now the dye molecules make an angle 2θ with respect to the electric vector of the incoming light, and only the projection of the electric vector parallel to the dye molecules will be absorbed (**FIG. 3b**). One can realize that this state is the brightest when the tilt angle is 45° , i.e., the director (and the dye molecules) will be orthogonal to the incoming electric vector. At zero electric field, when the director relaxes back to the anticlinic configuration, the average dye direction will be parallel to the layer normal, i.e., it will make an angle θ with respect to the electric vector of the incoming light. Since the projection of the electric vector to the average dye direction is larger, the image will be darker (**FIG. 3f**) than in **FIG. 3e**. Since when $E=0$ the image is brighter than shown in **FIG. 3e**, the brightness in **FIG. 3f** lies in between the brightest and darkest states, hence the label “medium” in **FIG. 3f**. **FIG. 3g** shows the oscillogram trace of the switching between (a) and (b) states of CS4000 with 2wt% G-472 at room temperature under $\pm 40V$ applied. The switching time is about 100 μs . Finally, **FIG. 3h** shows the time dependences of the transmittances of a 12- μm film of CS4000+2wt% G-472 under switching by square wave field of various peak-to-peak values. One can see that switching times are less than 200 μs for all voltages above 40V_{p-p}. In **FIGS. 3a-c**, the vertically oriented elements are

intended to represent the periodic molecular density modulation. The dyes are parallel to the molecules, which in (a) and (b) are the same in each layer, whereas they are anticlinic in (c). When switching from (a), (b) to (c), the directions of the dyes change.

[0066] Note that in the above examples, the dye-doped antiferroelectric liquid crystal film behaves like a switchable polarizer, implying that the polarizer may be substituted by another dye-doped antiferroelectric liquid crystal film. The expected switching behaviors are sketched in **FIG. 4**. In the top row of **FIG. 4**, the director configurations when the smectic layers (and rubbing directions) in the cells are oriented perpendicular to each other are shown. The bottom row illustrates the situation when the smectic layers (and rubbing directions) in the cells are oriented parallel to each other. Left column of **FIG. 4** correspond to AFE states in both layers ($E=0$ on both films) with anticlinic director structures, whereas the right column illustrates the director configurations in the ferroelectric states ($E>E_c$) on both cells, but they point in opposite directions. When the smectic layers are perpendicular and the directors are anticlinic (top-left) the average directions of the dye molecules are perpendicular to each other in the top and bottom cells, consequently no light should go through (dark state). When the smectic layers are perpendicular and the directors are synclinic in opposite directions (top-right), the angle between the directors and the directions of the dye molecules in the two cells is $\alpha=90^\circ-2\theta$. For $\theta=45^\circ$, α would be zero, thus resulting in maximum brightness. In the situation when the layers are parallel with anticlinic director structures (bottom-left), the average dye directions are normal to the layers, so they are parallel to each other, resulting in a bright state. Finally, if the smectic layers are parallel and the directors are synclinic, but the tilt in opposite directions in the top and bottom cells (bottom-right), the angle between the average dye orientations of the bottom and top cells is $\alpha=2\theta$, resulting in a dark state. The darkest state is realized when $\alpha=90^\circ$, i.e., $\theta=45^\circ$ (orthoscopic state).

[0067] When the smectic layers in the two cells are perpendicular to each other, a normally dark state that can be switched to a bright state is expected, and vice versa, when the orientation of the rubbing directions are parallel in the two cells, a normally bright state that can be switched to dark by an applied electric field is expected. In both cases the optimum contrasts can be achieved in the orthoscopic structures, when the tilt angle

is 45°.

[0068] Since the antiferroelectric liquid crystal material CS4000 available for us has a tilt angle much smaller than 45°, it is not expected to achieve the best contrast, but can achieve the darkest state possible in the perpendicular anticlinic cells (top-left configuration), since that does not rely on the 45° tilt angle. Switching time of less than 1 millisecond was also demonstrated.

[0069] The experimental verification of the principles is shown in **FIG. 5** for two 5-μm films of CS4000+5wt% S-428 mixtures on top of each other with no polarizer.

[0070] The image in **FIG. 5a** represents the bright state of the perpendicular cells in the ferroelectric (*FE*) state when $U=30\text{ V}$, $f=80\text{ Hz}$ square wave voltage is applied; while **FIG. 5b** shows dark state of the perpendicular cells in the antiferroelectric (*AFE*), OFF state. It can be seen that the image is really dark, darker than typical guest-host nematic cells have in homeotropic alignments. This is because the order parameter of the dyes is probably larger in the smectic than in the nematic phase (another advantage of smectic guest host systems in addition to the faster speed). **FIG. 5c** shows the time dependence of the transmittance when a bipolar square wave field is turned OFF and ON. Although the relaxation time from the ferroelectric to the antiferroelectric state is larger than the switching time measured while switching between two ferroelectric states (**FIG. 2**), it is still less than 1 millisecond. The switching between the normally bright OFF state and the dark ON state of parallel cells is shown in **FIG. 5d** and **e**. The dark state is not optimal, and it appears less dark than the OFF state of the perpendicular cells. The bright OFF state is indeed brighter than of the bright ON state of perpendicular cells, although it should be less bright than what would be observed for synclinic director with 45° tilt. Slight green tone of the bright cells was observed due to the imperfect black dye, which shows a smaller absorption in the green range. Also, the images outside the electrode areas are in between the darkest and brightest states of the electrode areas, as outside the electrodes the layers are not aligned perpendicular to the film substrates.

[0071] To summarize, the alignment and electro-optical properties of a dye-doped antiferroelectric liquid crystal were studied. Unprecedentedly good uniform alignment on macroscopic scale with the combination of proper surface alignment and electric field treatments was achieved. Also, it was successfully demonstrated that two films of

antiferroelectric liquid crystals in their SmC_A^* phase can be used to switch the transmitted light intensity between dark and bright states without the need of polarizer filters. Furthermore, it was also shown that one could get either normally dark or bright states. Normally dark states can be useful, for example, in privacy windows, or smart refrigerators, when one does not see the food inside, but can have a peak view without opening the door. The normally transparent display can be used in navigation systems built in windshields, in ski or welding goggles or where the voltage is triggered by light, thus attenuating it within the fraction of 1 millisecond preventing eye damage.

[0072] It will be appreciated that variants of the above-disclosed and other features and functions, or alternatives thereof, may be combined into many other different systems or applications. Various presently unforeseen or unanticipated alternatives, modifications, variations or improvements therein may be subsequently made by those skilled in the art which are also intended to be encompassed by the following claims.

CLAIMS:

1. An optical switch for a liquid crystal device comprising in sequence:
a first transparent substrate;
a first transparent electrode;
a first alignment layer;
a first liquid crystal film comprising a first antiferroelectric liquid crystal doped with a first dichroic dye;
a second liquid crystal film comprising a second antiferroelectric liquid crystal doped with a second dichroic dye;
optionally a second alignment layer;
a second transparent electrode; and
a second transparent substrate.
2. The optical switch of claim 1, wherein the first liquid crystal film and the second liquid crystal film are aligned perpendicular to each other.
3. The optical switch of claim 1, wherein the first liquid crystal film and the second liquid crystal film are smectic layers.
4. The optical switch of claim 1, wherein the first antiferroelectric liquid crystal and the second antiferroelectric liquid crystal are the same.
5. The optical switch of claim 1, wherein the first dichroic dye and the second dichroic dye are the same.
6. The optical switch of claim 1, wherein the first antiferroelectric liquid crystal and the second antiferroelectric liquid crystal have a tilt angle in the range of about 40° to about 50°.
7. The optical switch of claim 6, wherein the tilt angle is about 45°.

8. The optical switch of claim 1, wherein the switch is switchable in less than 1 millisecond.
9. The optical switch of claim 1, wherein the switch is switchable in less than 200 microseconds.
10. A device comprising the optical switch of claim 1.
11. The device of claim 10, wherein the normal state is a dark state.
12. The device of claim 10, wherein the normal state is a bright state.
13. The device of claim 10, wherein the device is a privacy window, a refrigerator, an oven, a microwave, a windshield, or goggles.
14. A method for switching an electronic device from a first state to a second state, the method comprising:
 - applying an electric field to the electronic device;
 - wherein the electronic device comprises:
 - a first transparent substrate;
 - a first transparent electrode;
 - a first alignment layer;
 - a first liquid crystal film comprising a first antiferroelectric liquid crystal doped with a first dichroic dye;
 - a second liquid crystal film comprising a second antiferroelectric liquid crystal doped with a second dichroic dye;
 - optionally a second alignment layer;
 - a second transparent electrode; and
 - a second transparent substrate.
15. The method of claim 14, wherein the first state is a bright state and the second state is a dark state.

16. The method of claim 14, wherein the first state is a dark state and the second state is a bright state.

17. The method of claim 14, wherein electric field comprises a square wave AC field having an amplitude greater than about 2 V/ μ m and a frequency in the range of about 100 Hz to about 500 Hz.

18. The method of claim 14, wherein the first antiferroelectric liquid crystal and the second antiferroelectric liquid crystal have a tilt angle of about 45°.

19. The method of claim 14, wherein the switching occurs in a time period of less than 1 millisecond.

20. A method of forming an optical switch comprising:
sandwiching a first liquid crystal film and a second liquid crystal film between two transparent substrates;
wherein both the first liquid crystal film and the second liquid crystal film comprise an antiferroelectric liquid crystal doped with a dichroic dye; and
wherein the first liquid crystal film and the second liquid crystal film are aligned perpendicular to each other.

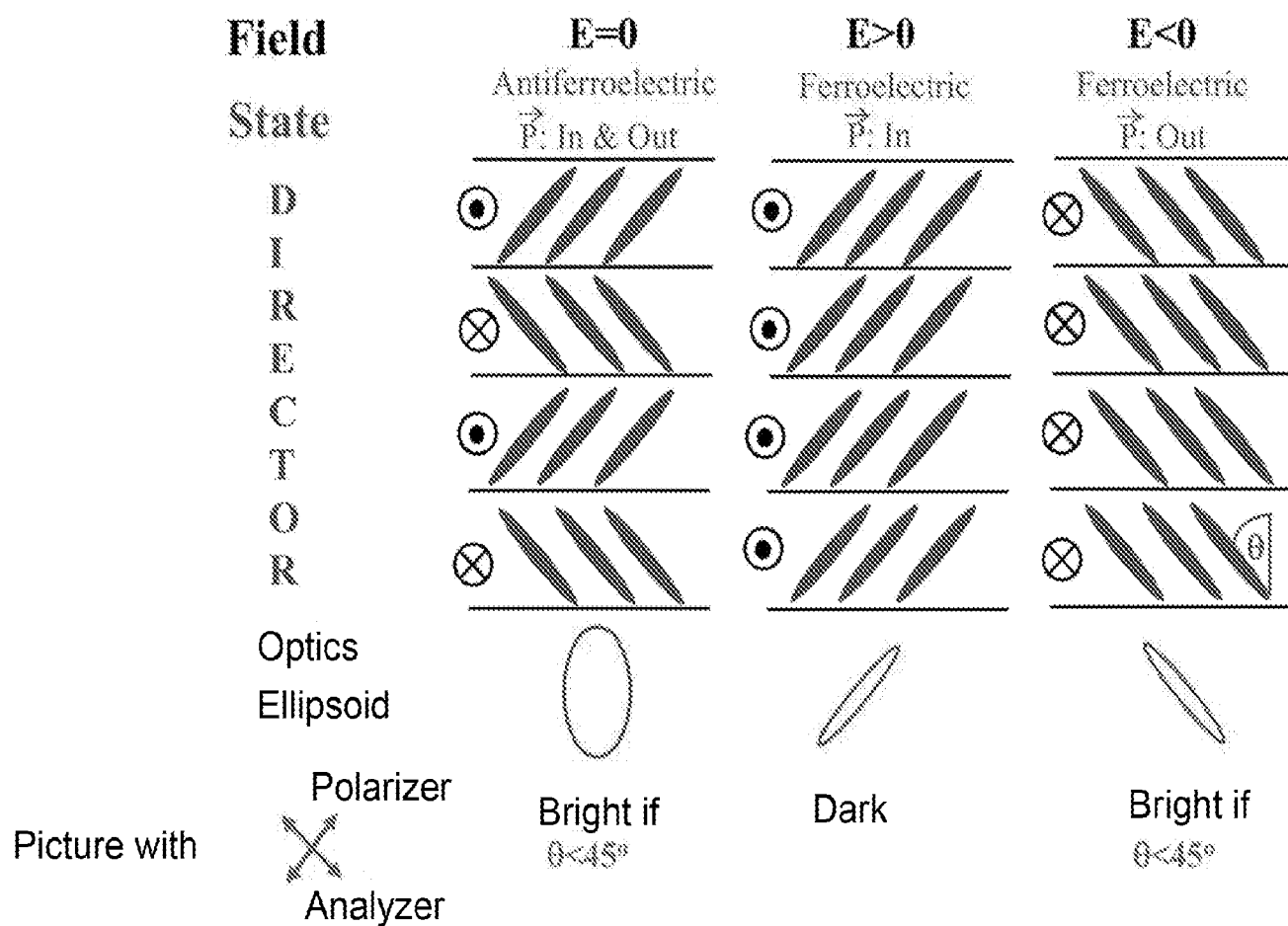


FIG. 1

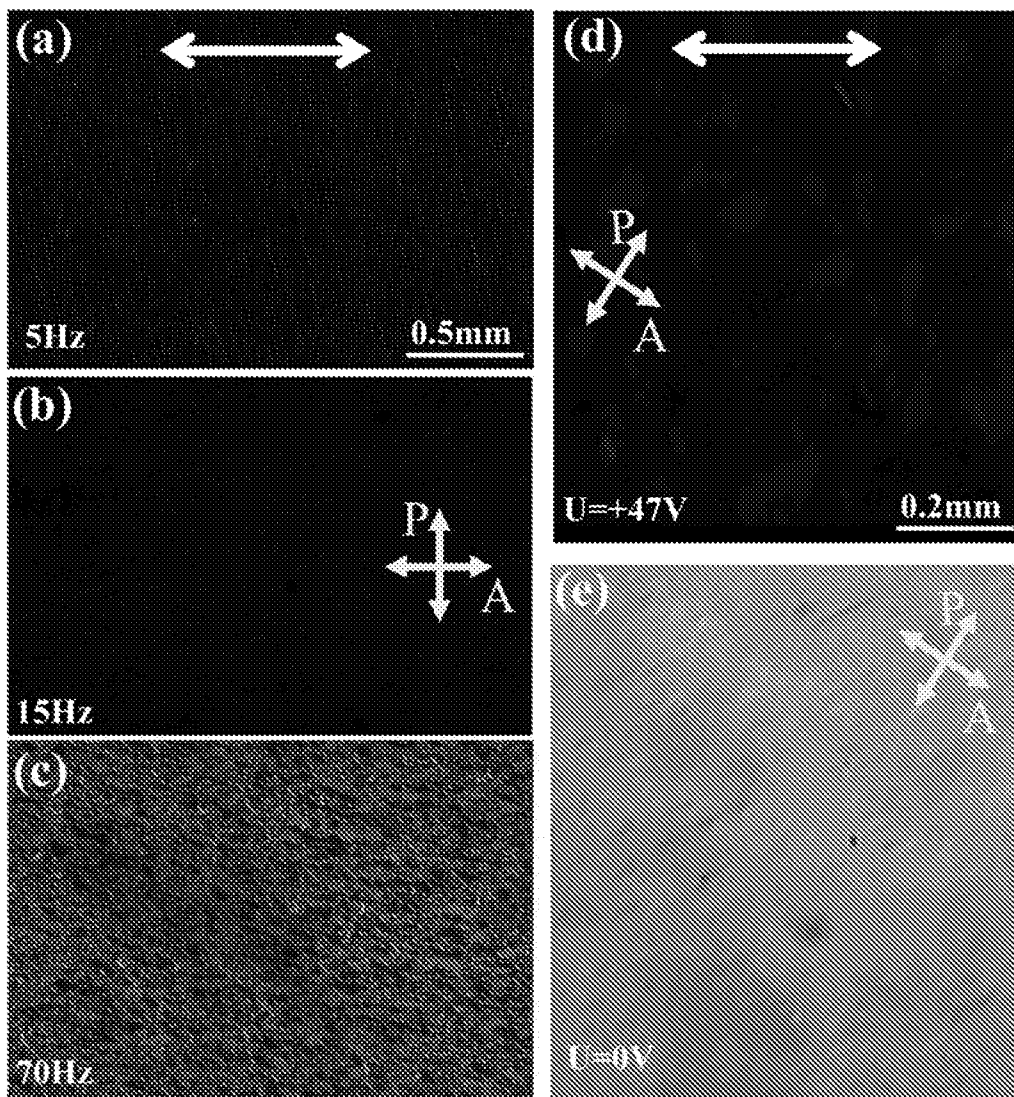


FIG. 2

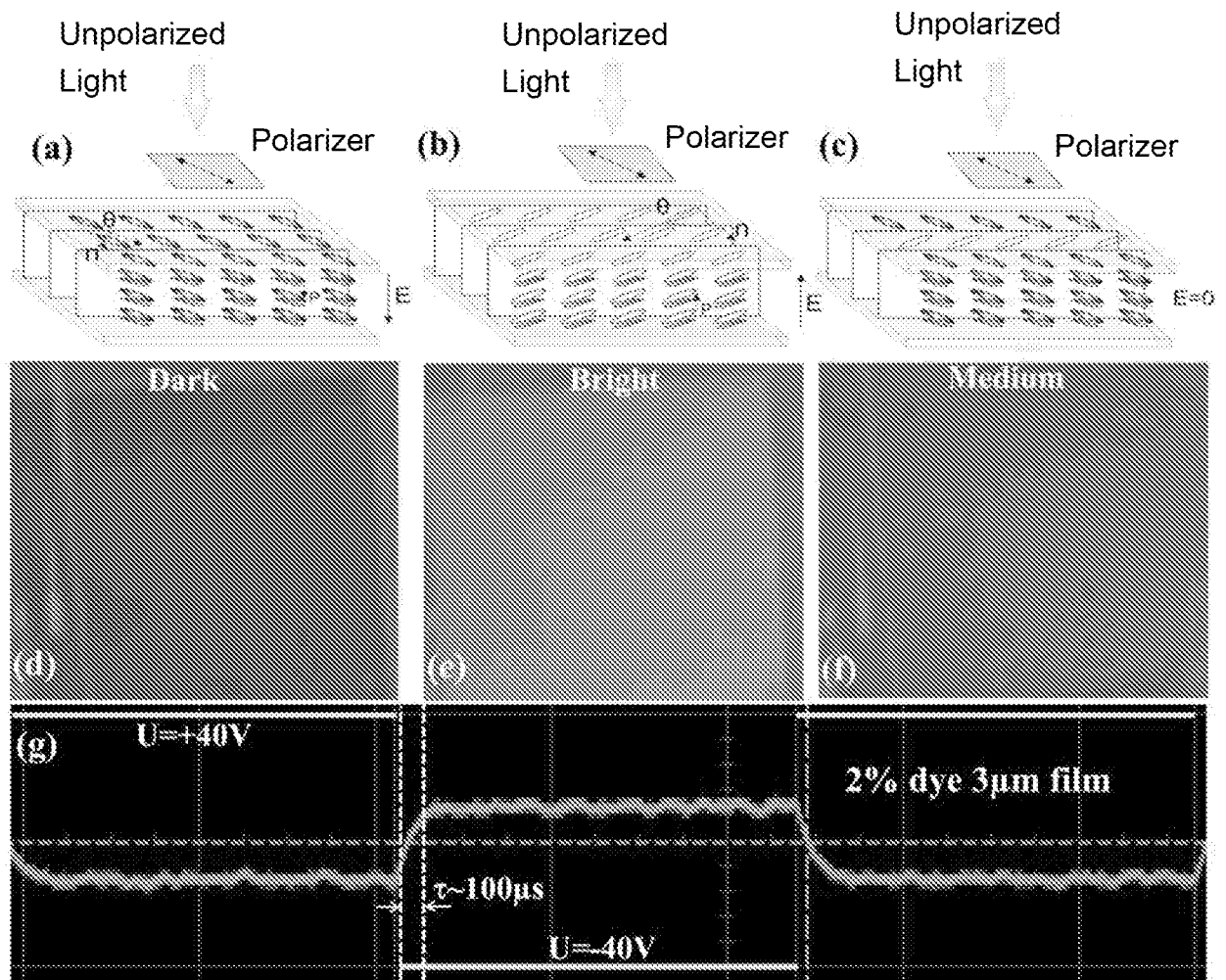


FIG. 3

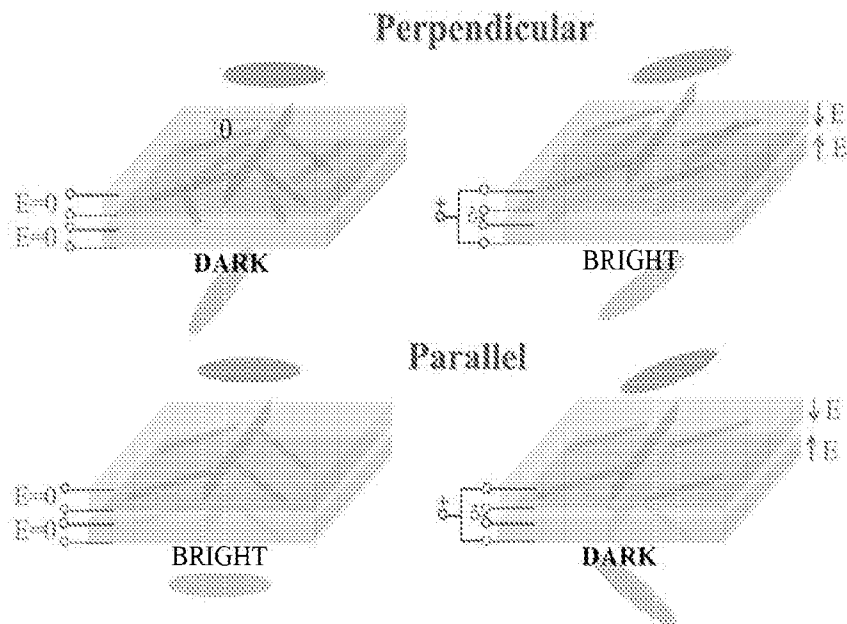


FIG. 4

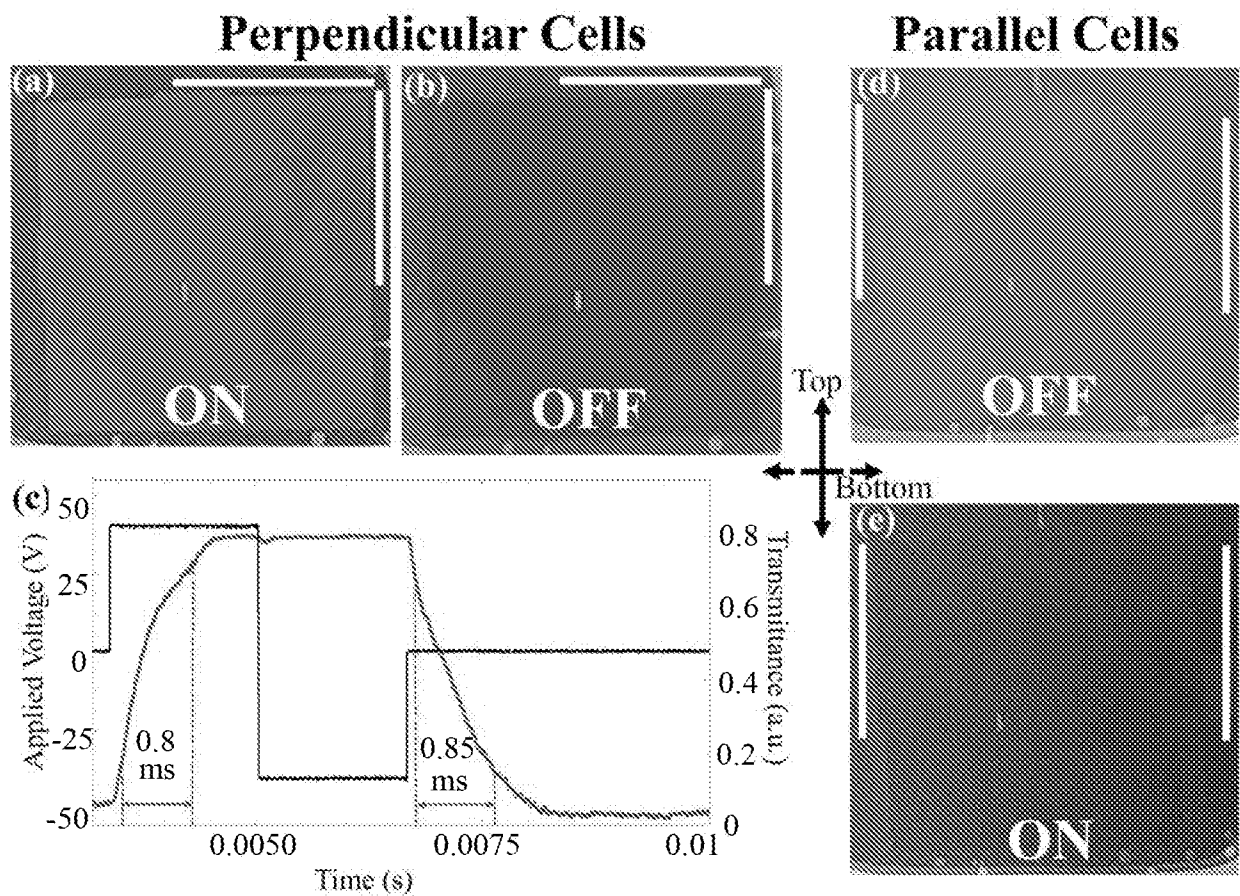


FIG. 5

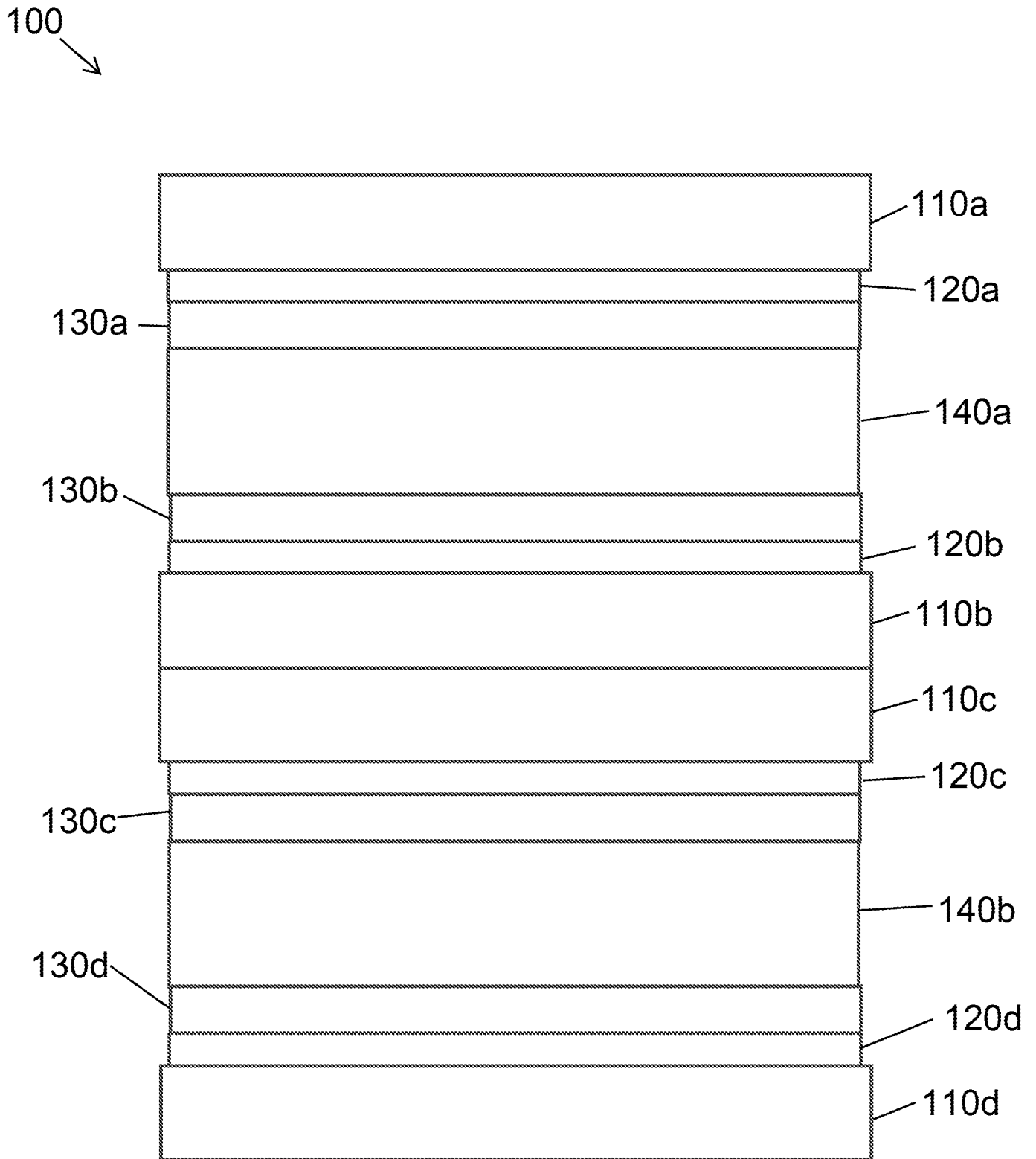


FIG. 6

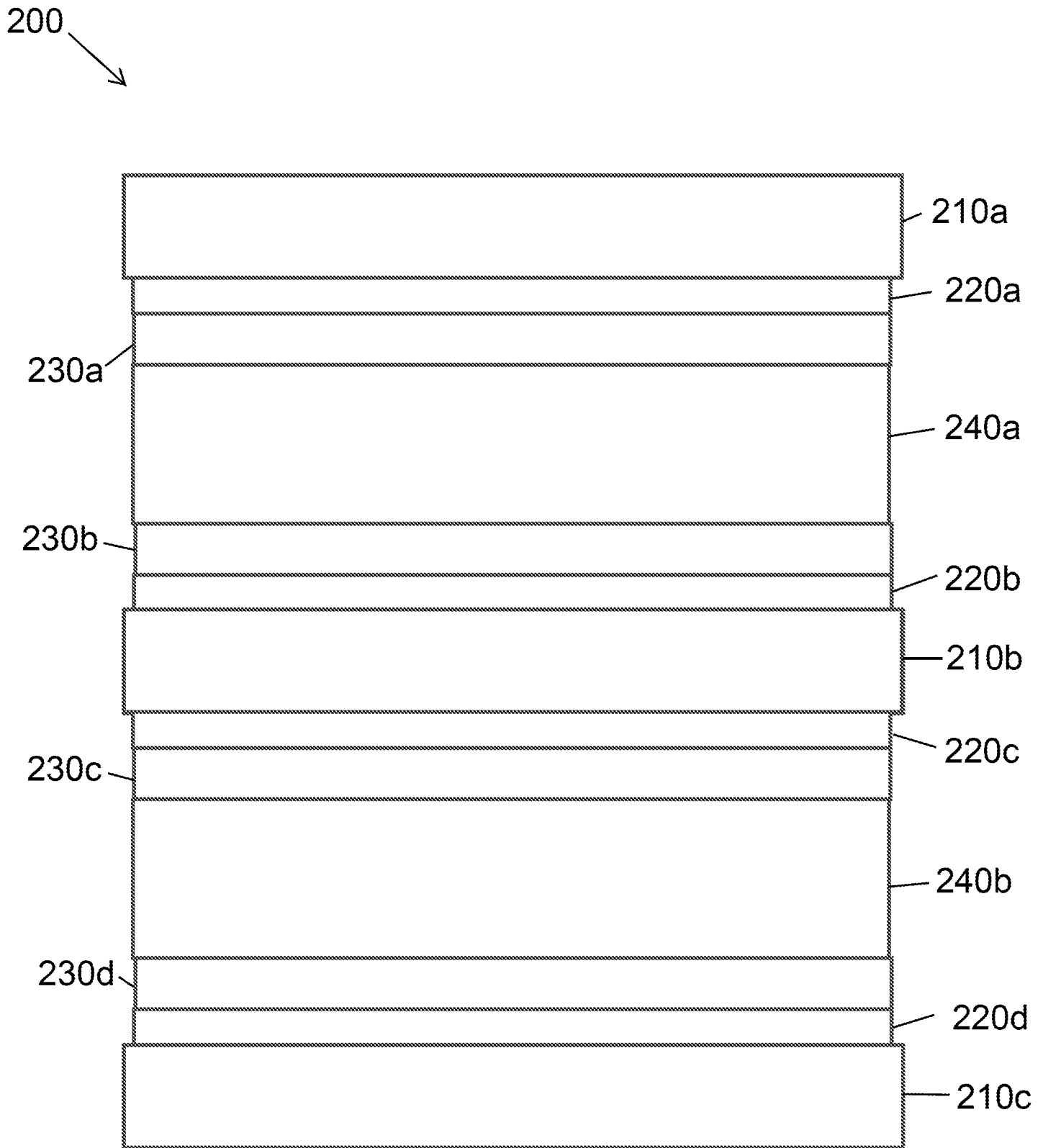


FIG. 7

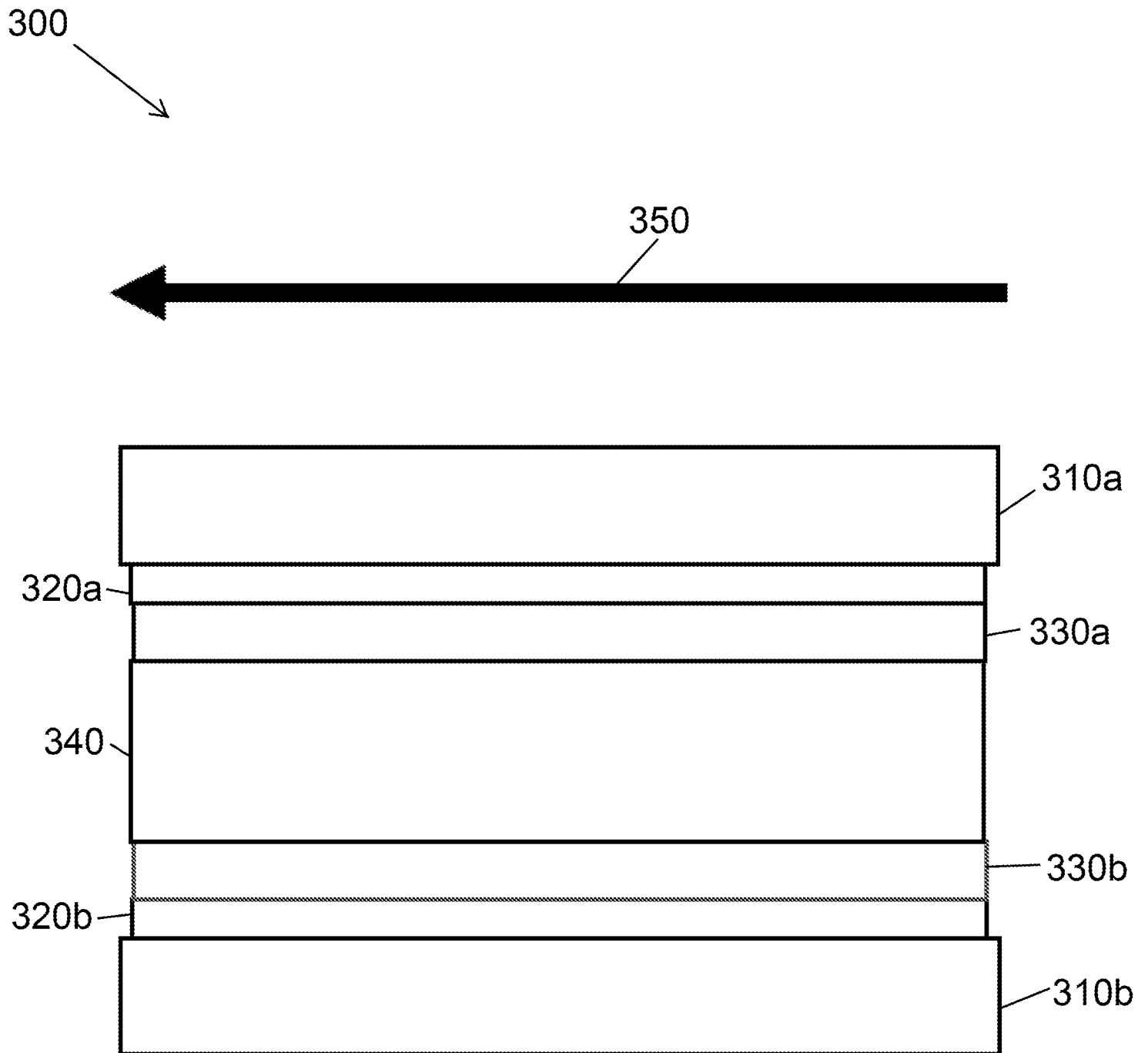


FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 19/63150

A. CLASSIFICATION OF SUBJECT MATTER

IPC - G02F 1/313; G02B 6/14 (2020.01)

CPC - G02F 1/3133; G02F 1/3134; G02F 1/3138; G02F 2201/12

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

See Search History document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X ---- Y	US 5,729,307 A (Koden et al.) 17 March 1998 (17.03.1998) col. 3 ln. 43, col. 4 ln. 23, col. 4 ln. 37, col. 6 ln. 1, col. 6 ln. 6, col. 6 ln. 7, col. 6 ln. 13, col. 6 ln. 38, col. 6 ln. 60, col. 7 ln. 50, col. 8 ln. 16, col. 13 ln. 35	1-11, 14, 16-20 ----- 12, 13, 15
Y	JP H04122913 A (Idemitsu Kosan Co.) 23 April 1992 (23.04.1992) pg 2 para 2, pg 2 para 3 translated to english via espacenet	12, 15
Y	US 6,924,009 B2 (Jakli et al.) 02 August 2005 (02.08.2005) col. 14 ln. 7	13
A	Dunmr et al. 'Liquid crystal display', Encyclopedia Britannica 03 August 2015 (03.08.2015) pg. 11 para 2 [retrieved from the internet on 22 January 2020 (22.01.2020) at < https://www.britannica.com/technology/liquid-crystal-display >]	3
A	US 2001/0052948 A1 (Okamoto et al.) 20 December 2001 (20.12.2001) entire document	1-20

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"D" document cited by the applicant in the international application

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published 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; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

22 January 2020

Date of mailing of the international search report

11 FEB 2020

Name and mailing address of the ISA/US

Mail Stop PCT, Attn: ISA/US, Commissioner for Patents
P.O. Box 1450, Alexandria, Virginia 22313-1450

Facsimile No. 571-273-8300

Authorized officer

Lee Young

Telephone No. PCT Helpdesk: 571-272-4300