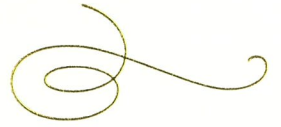


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America



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of Science and Useful Arts

The Director

of the United States Patent and Trademark Office has received an application for a patent for a new and useful invention. The title and description of the invention are enclosed. The requirements of law have been complied with, and it has been determined that a patent on the invention shall be granted under the law.

Therefore, this United States

Patent

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Katherine Kelly Vidal

DIRECTOR OF THE UNITED STATES PATENT AND TRADEMARK OFFICE

(12) **United States Patent**
Ohe et al.

(10) **Patent No.:** **US 11,550,192 B1**
(45) **Date of Patent:** **Jan. 10, 2023**

(54) **LIQUID CRYSTAL DEVICE AND SYSTEM FOR THZ ELECTROMAGNETIC WAVES**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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(21) Appl. No.: **17/522,911**

Primary Examiner — James A Dudek
(74) *Attorney, Agent, or Firm* — JCIPRNET

(22) Filed: **Nov. 10, 2021**

(57) **ABSTRACT**

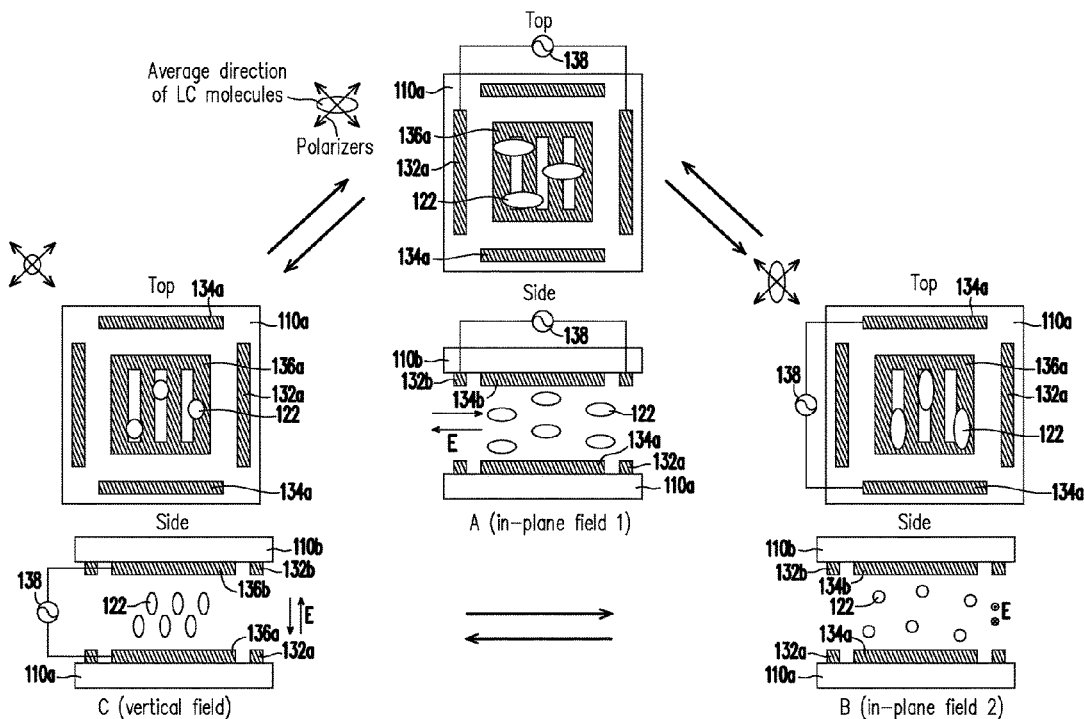
(51) **Int. Cl.**
G02F 1/1343 (2006.01)
G02F 1/1337 (2006.01)
G02F 1/1335 (2006.01)

A liquid crystal device including a single or a plurality of pixel elements is provided. Each pixel element includes: a first substrate, a second substrate parallel to the first substrate, a liquid crystal layer disposed between the first substrate and the second substrate, a first plurality of electrodes formed between the first substrate and the liquid crystal layer, a second plurality of electrodes formed between the second substrate and the liquid crystal layer. The first plurality of electrodes and the second plurality of electrodes are composed to generate electric fields in three orthogonal directions, and the electric fields in two of the three orthogonal directions are in-plane electric fields, while the other electric field of the three orthogonal directions is an out-of-plane electric field.

(52) **U.S. Cl.**
CPC **G02F 1/13439** (2013.01); **G02F 1/1337** (2013.01); **G02F 1/133531** (2021.01); **G02F 1/134363** (2013.01)

(58) **Field of Classification Search**
CPC G02F 1/13439; G02F 1/133531; G02F 1/1337; G02F 1/134363; G02F 1/134381
See application file for complete search history.

16 Claims, 25 Drawing Sheets



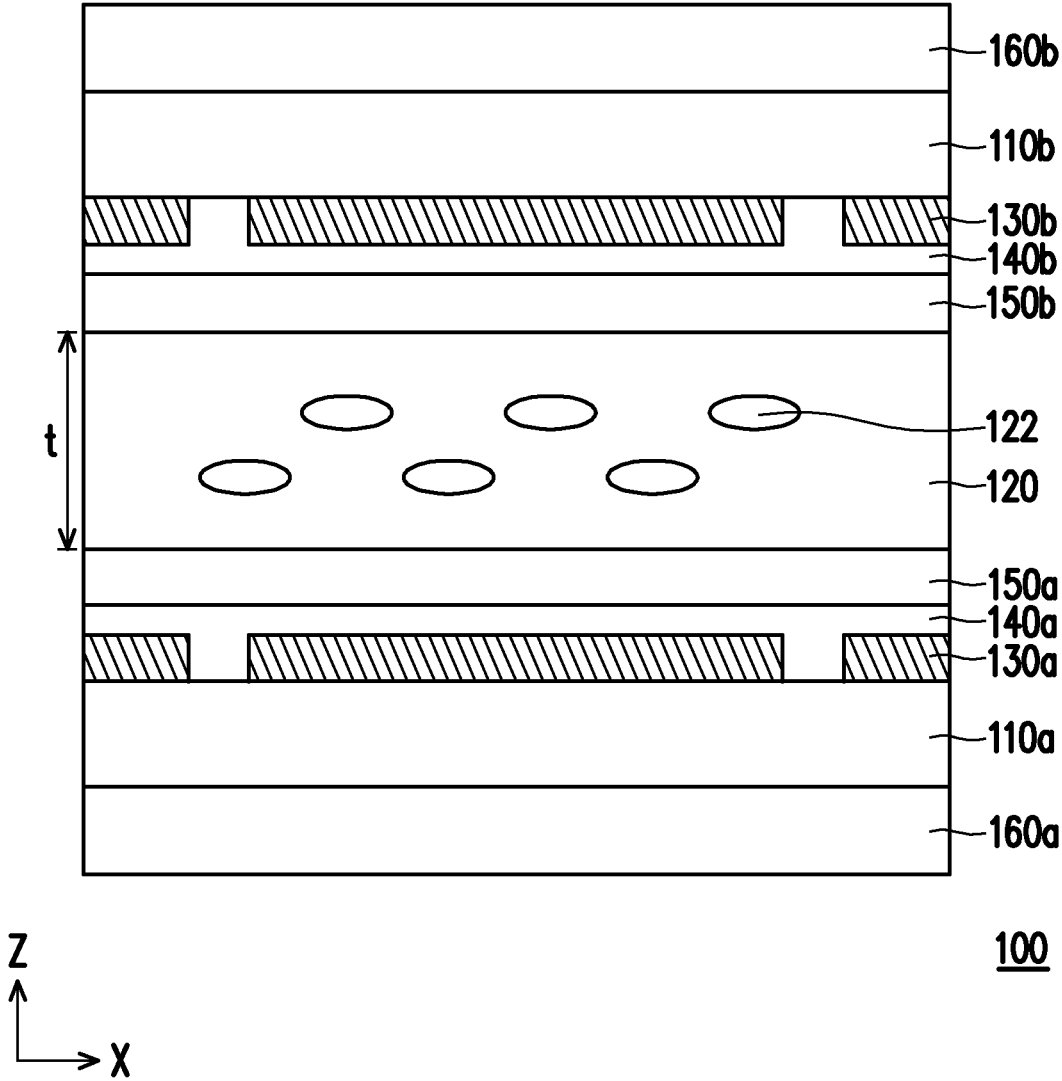


FIG. 1

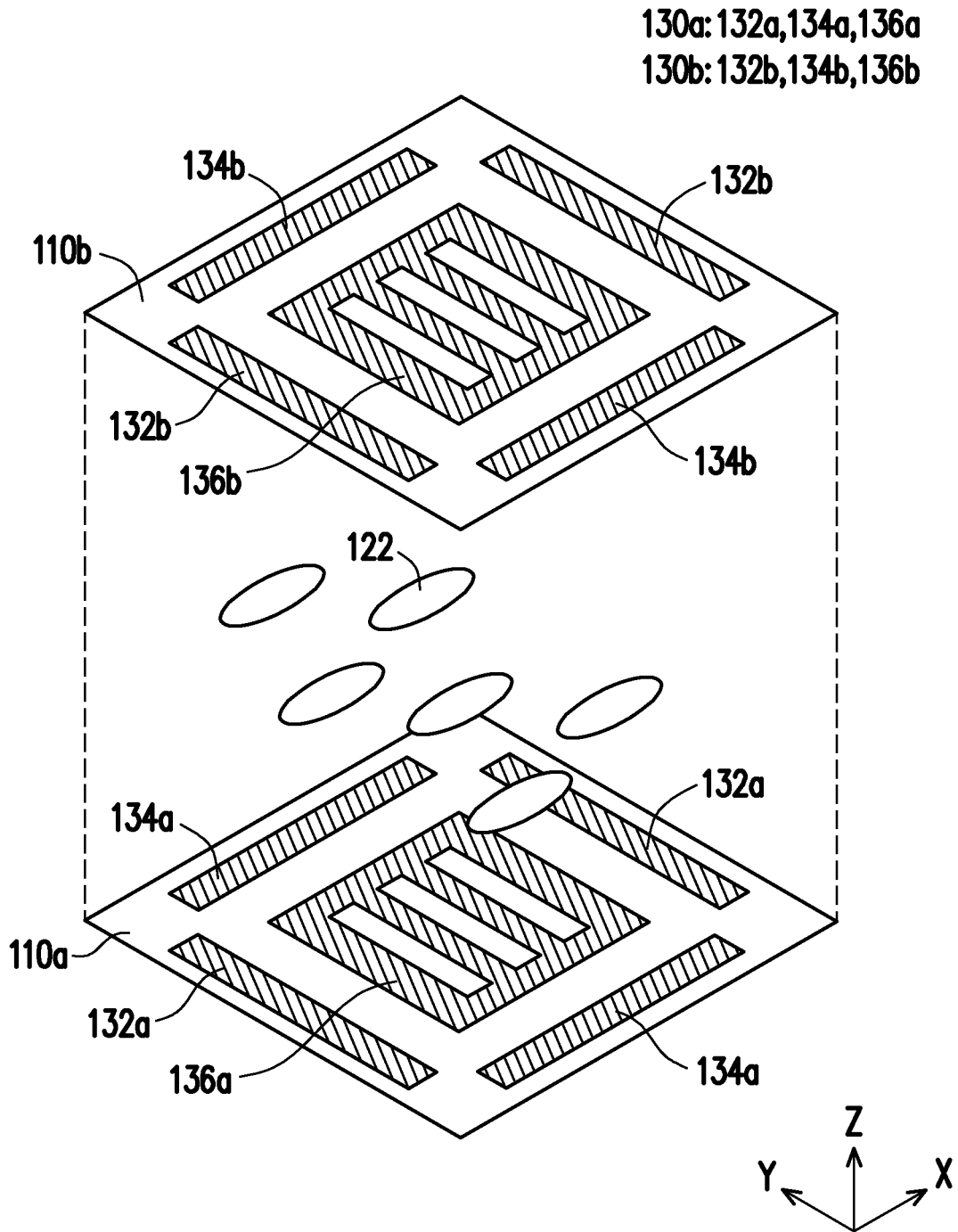


FIG. 2A

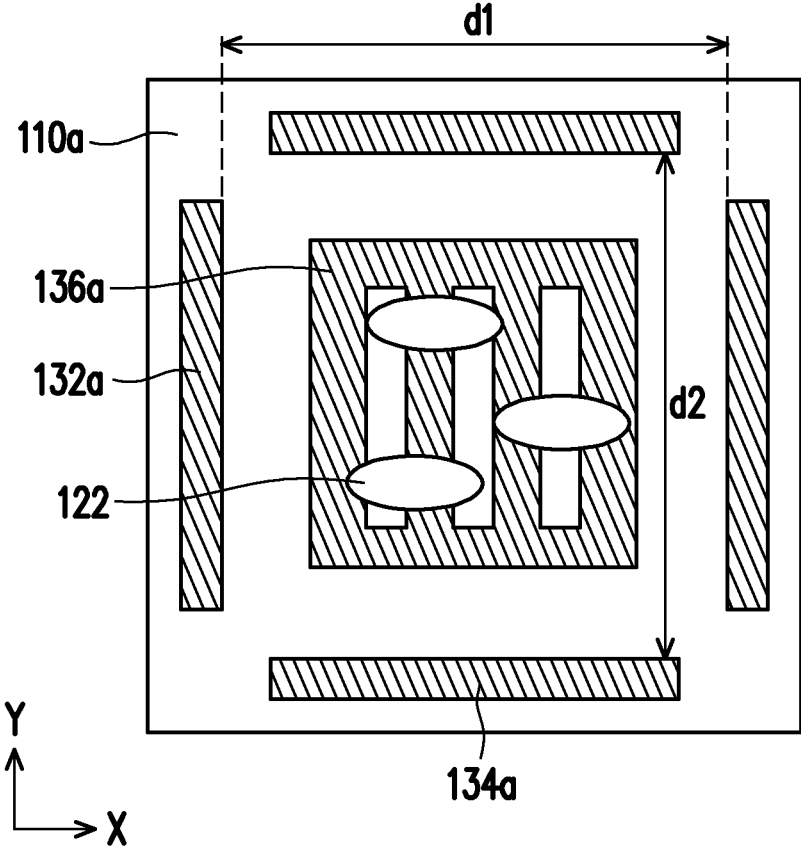


FIG. 2B

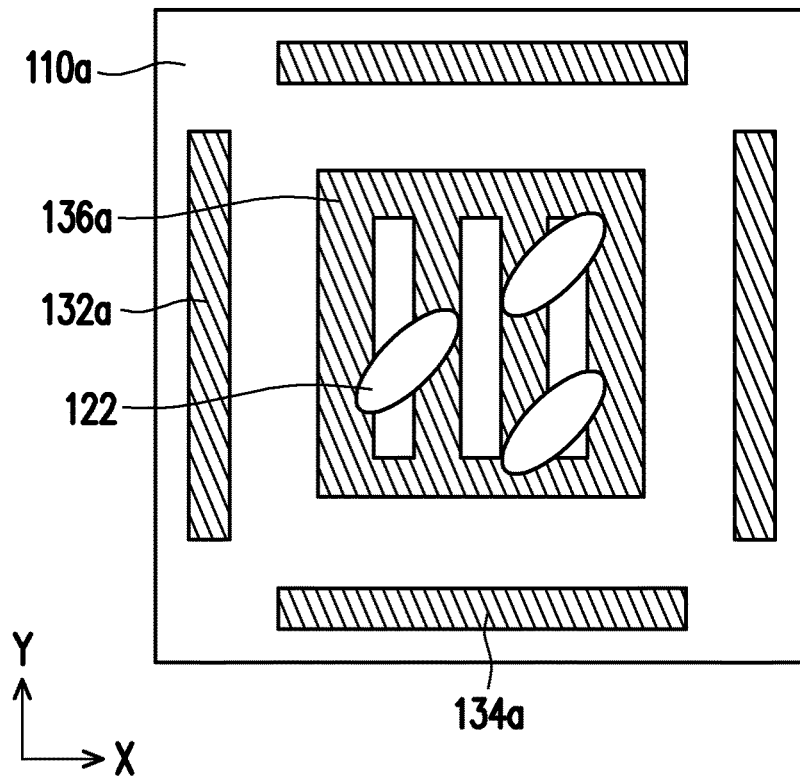


FIG. 2C

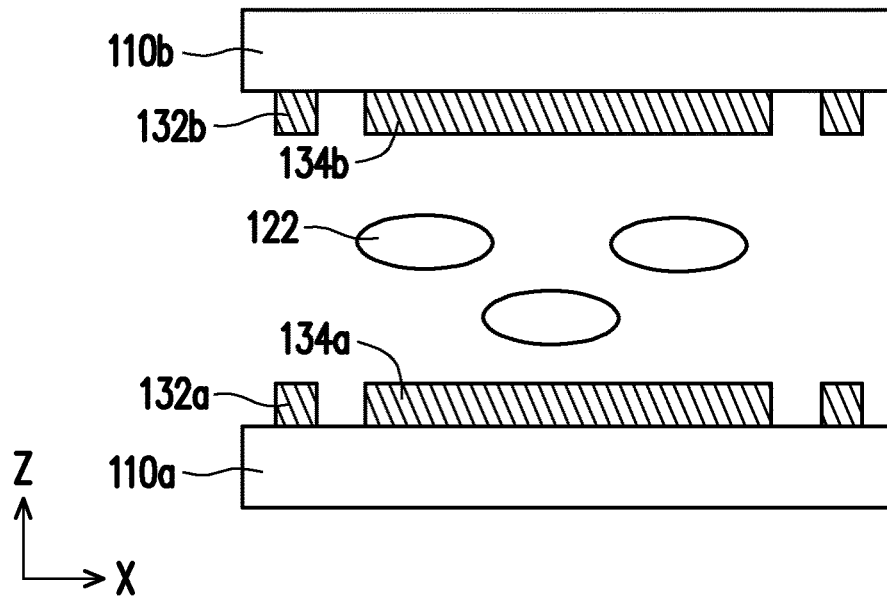


FIG. 2D

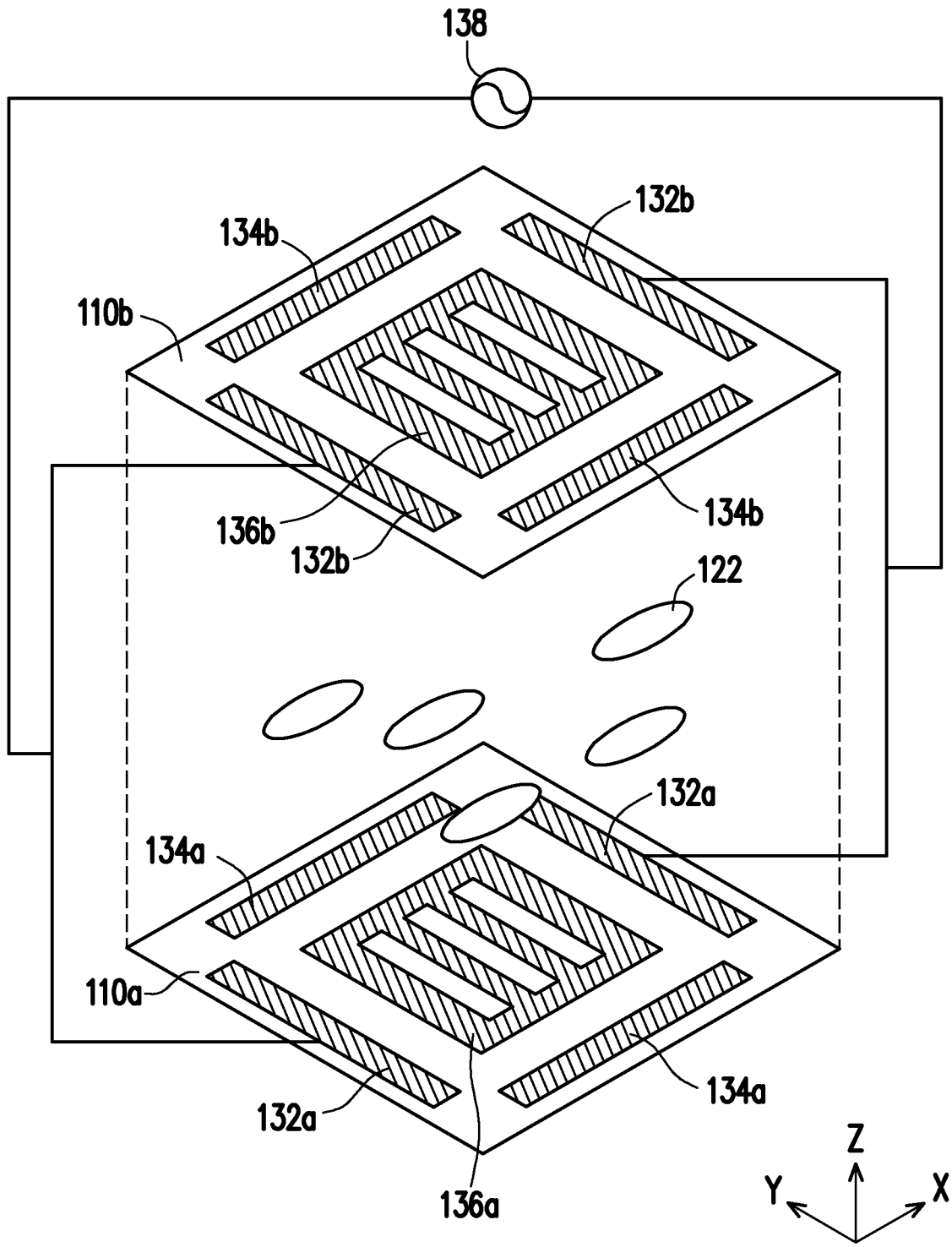


FIG. 3A

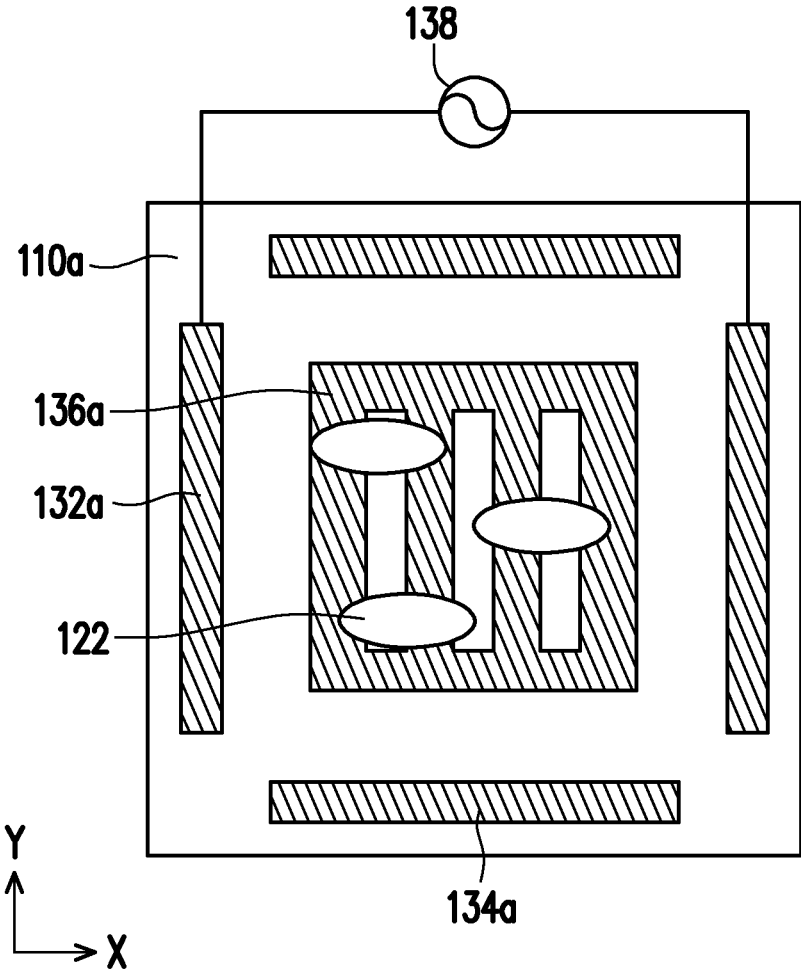


FIG. 3B

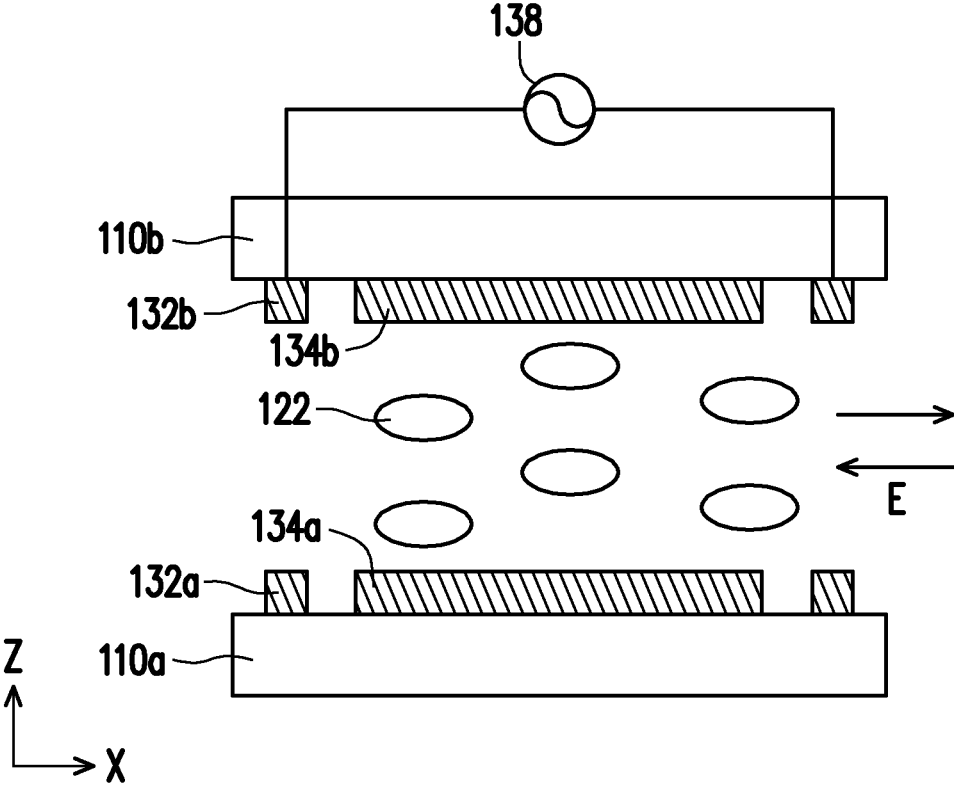


FIG. 3C

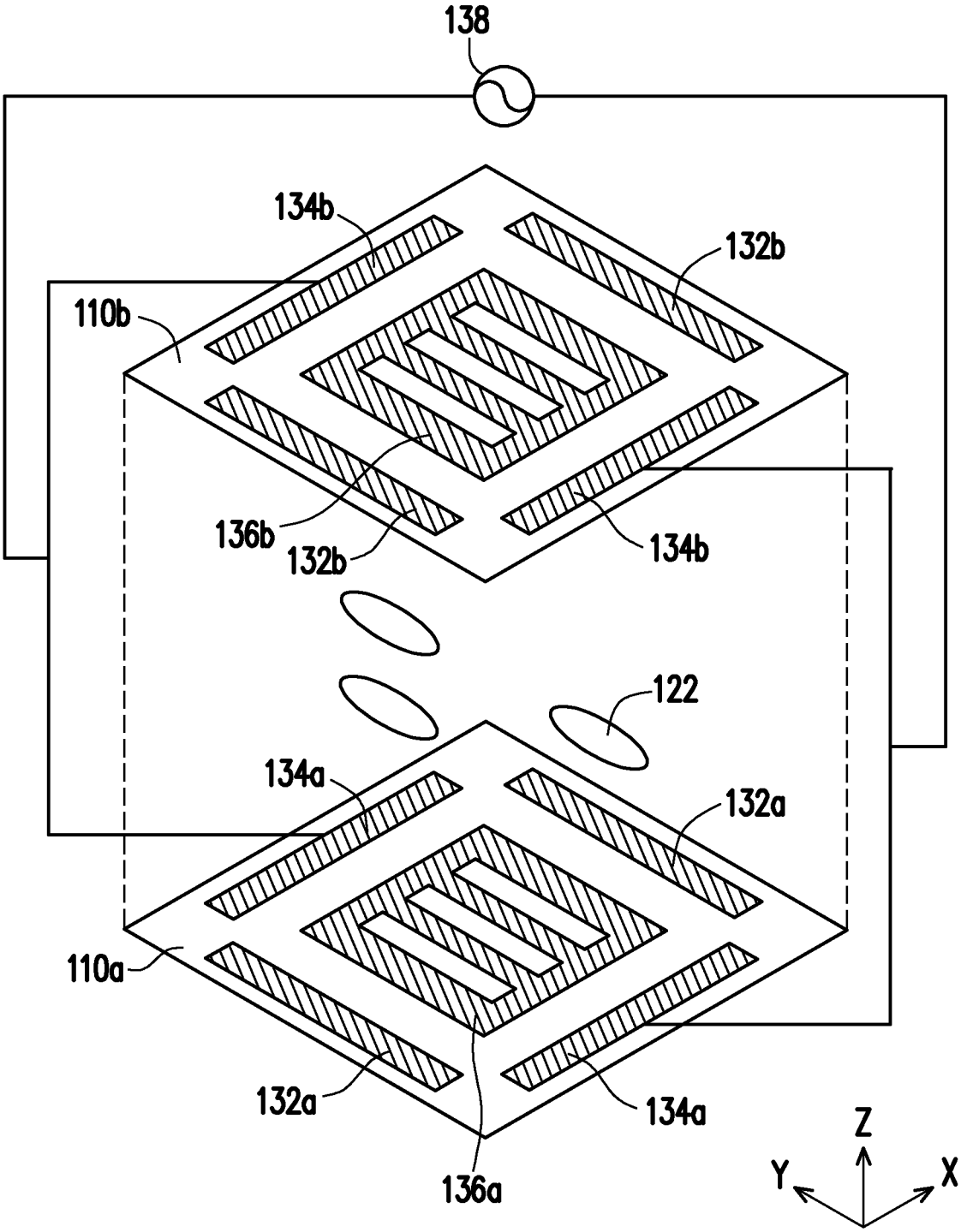


FIG. 4A

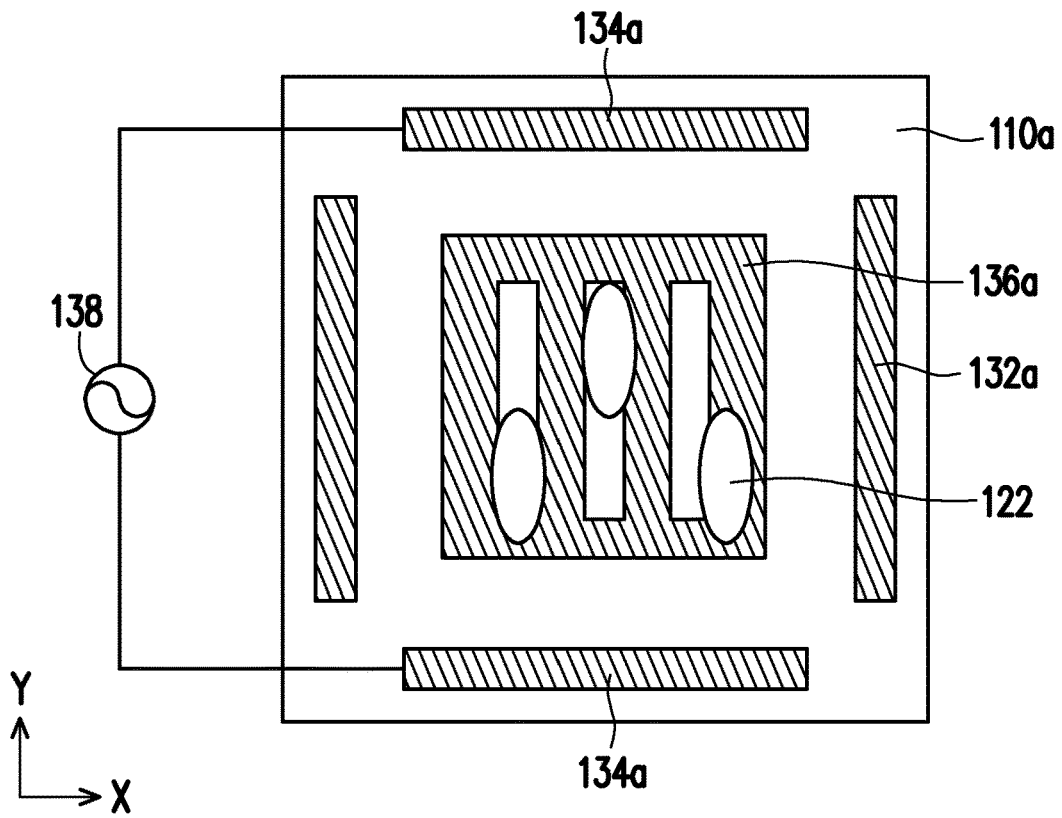


FIG. 4B

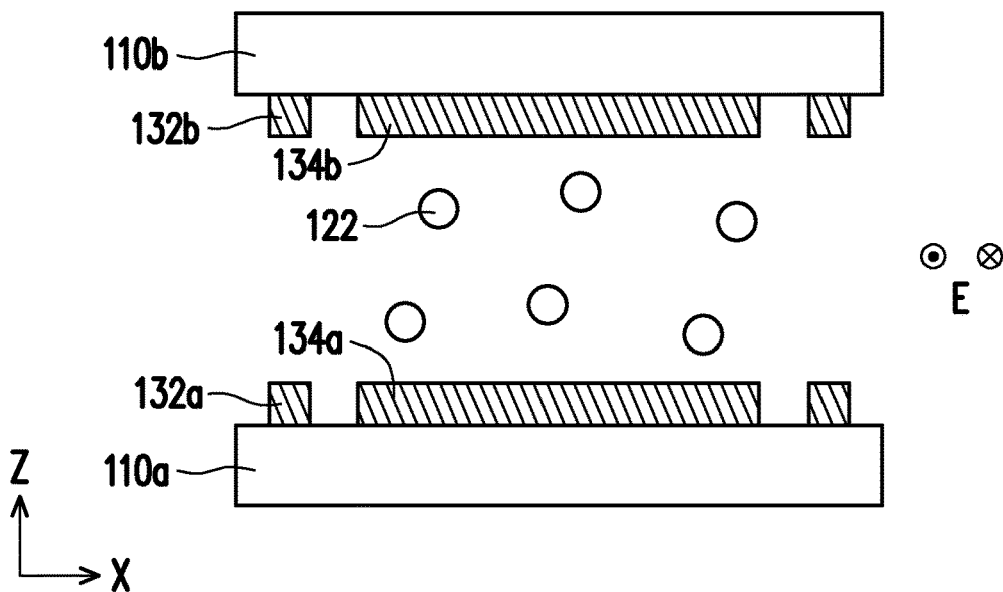


FIG. 4C

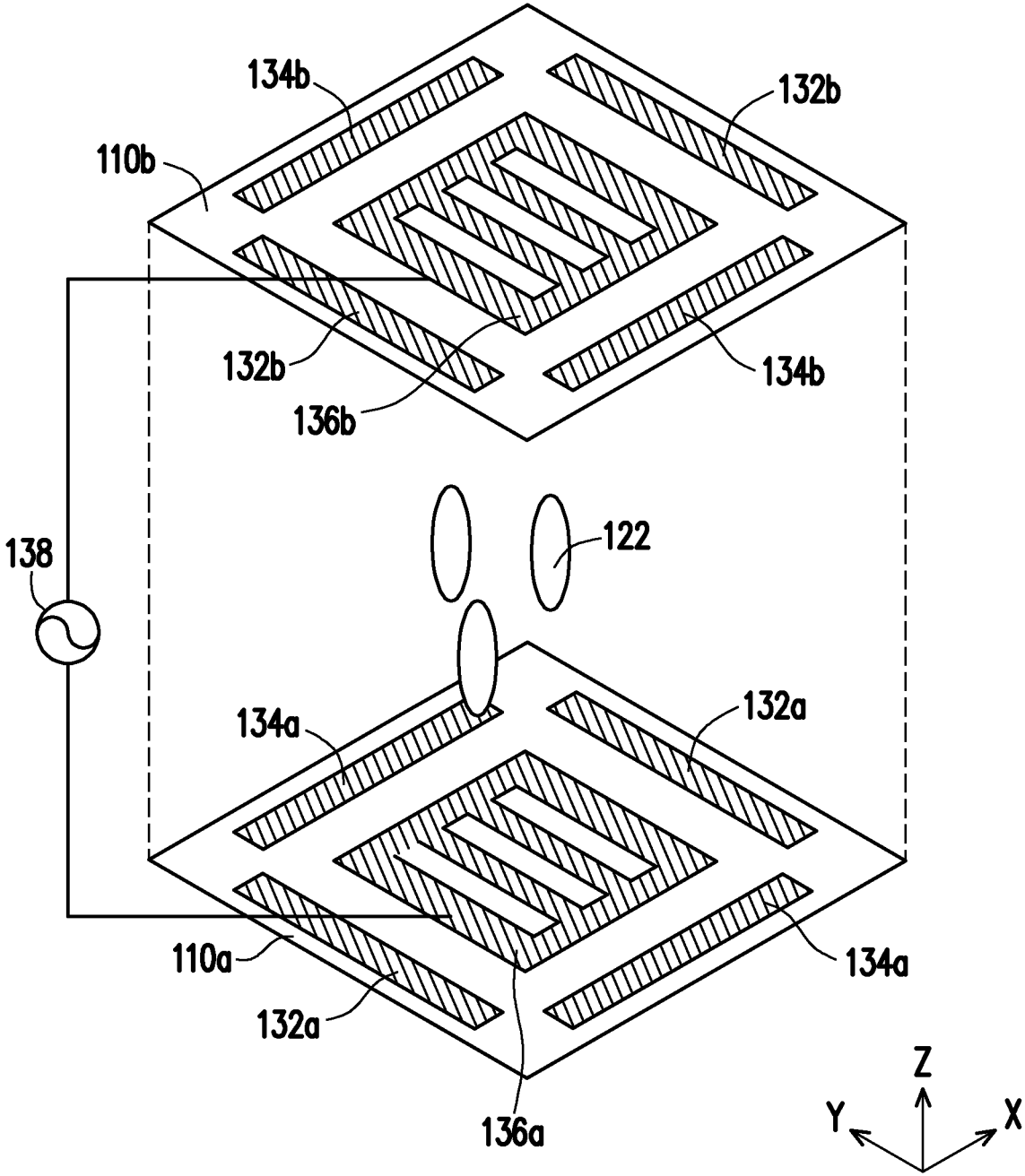


FIG. 5A

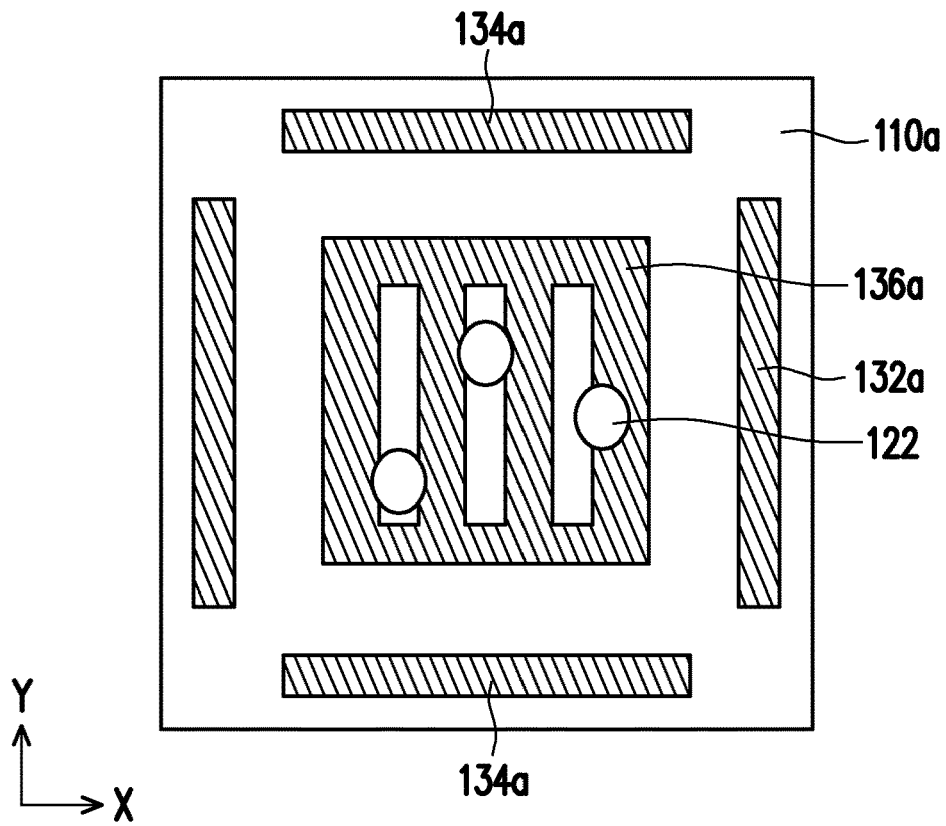


FIG. 5B

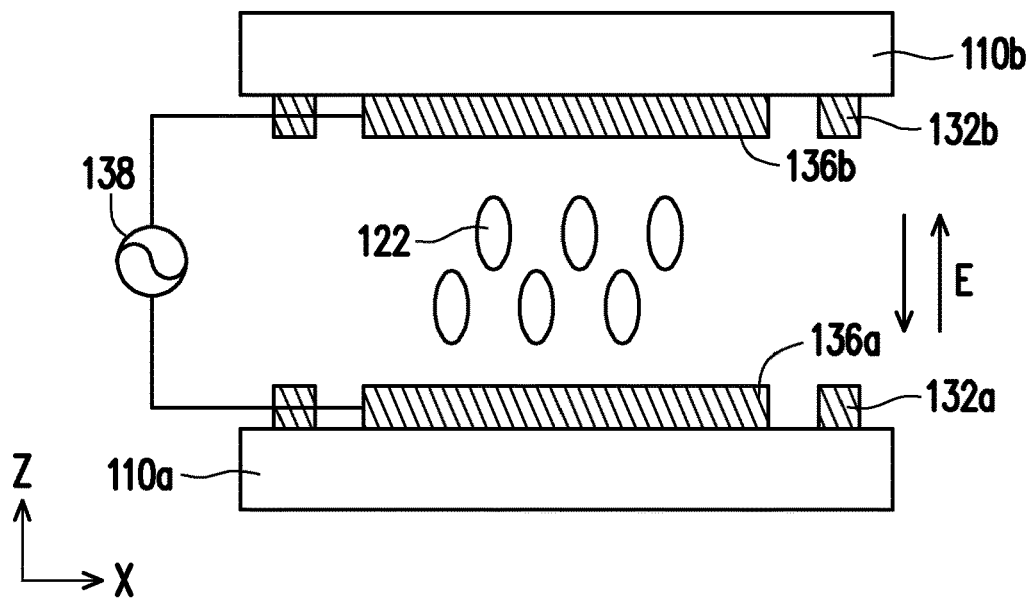


FIG. 5C

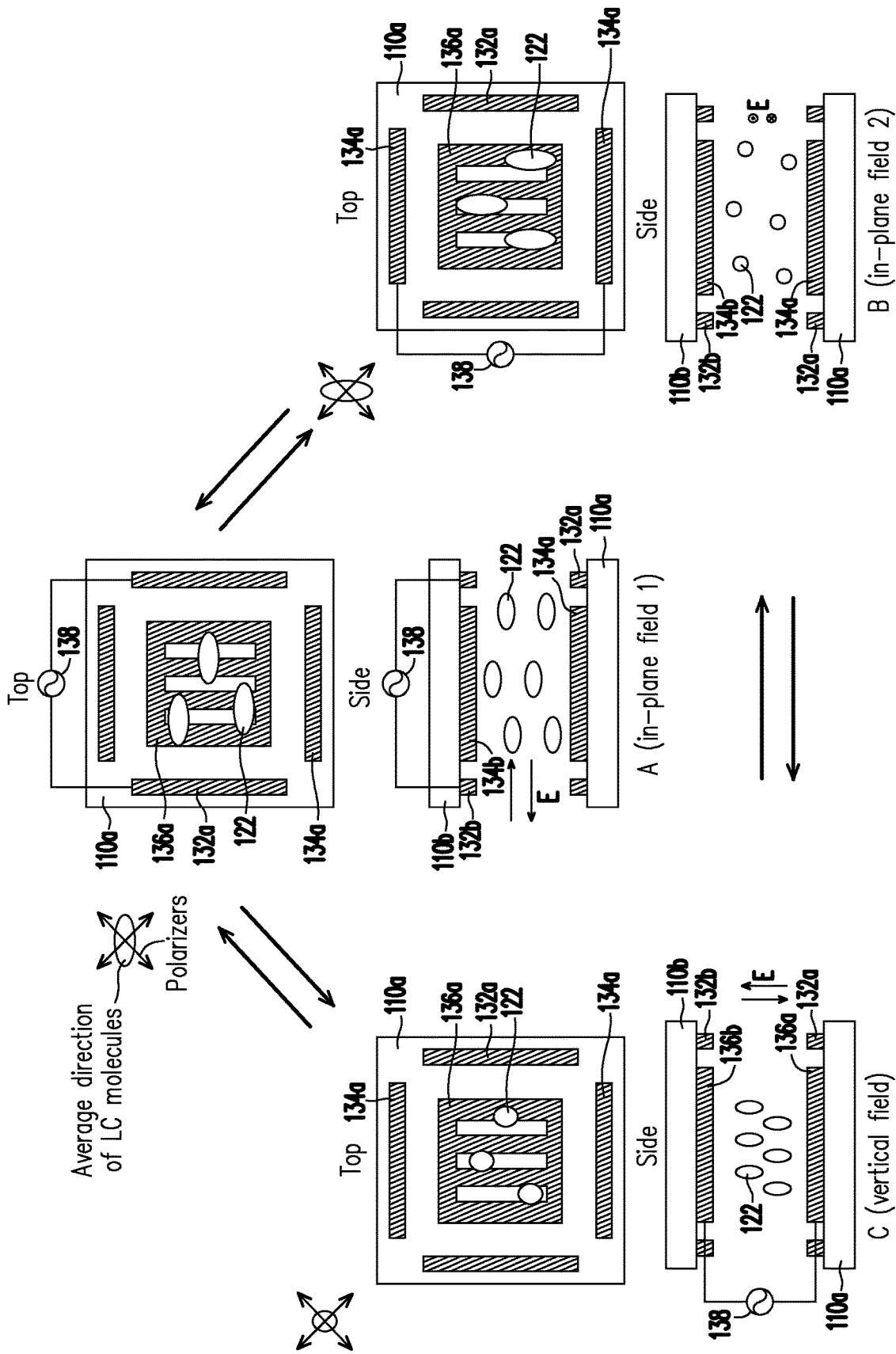


FIG. 6

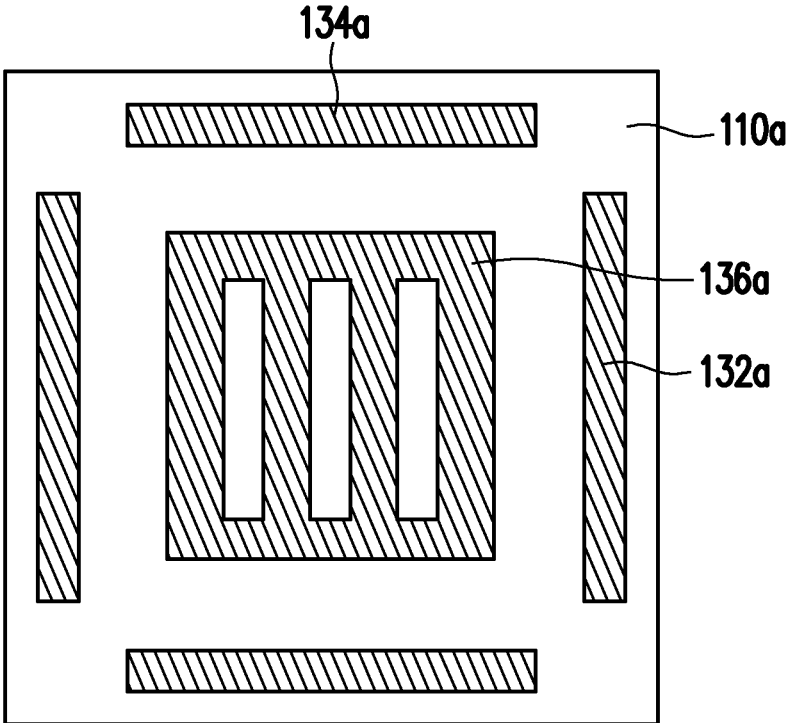


FIG. 7A

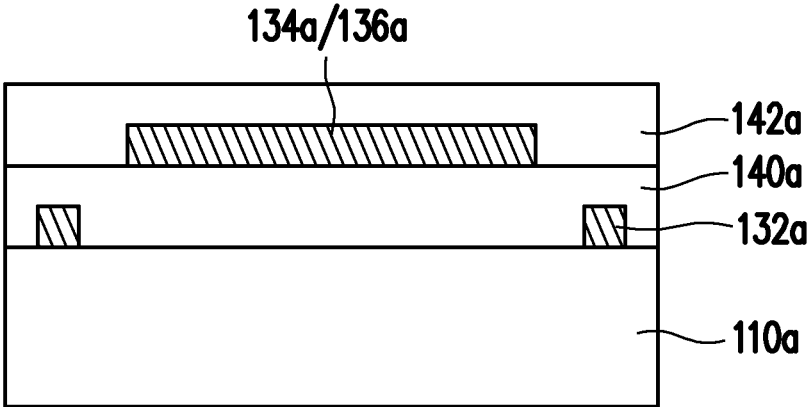


FIG. 7B

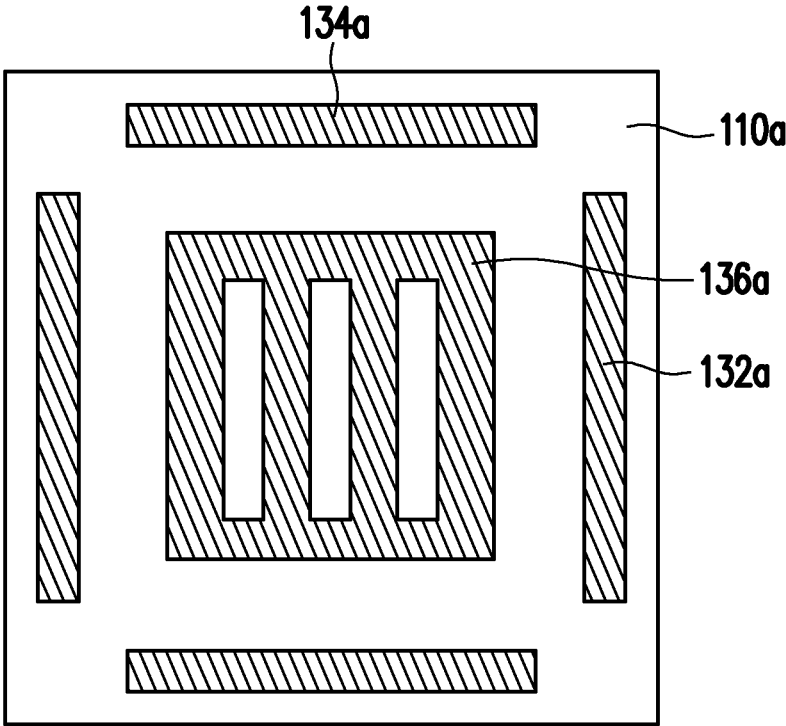


FIG. 8A

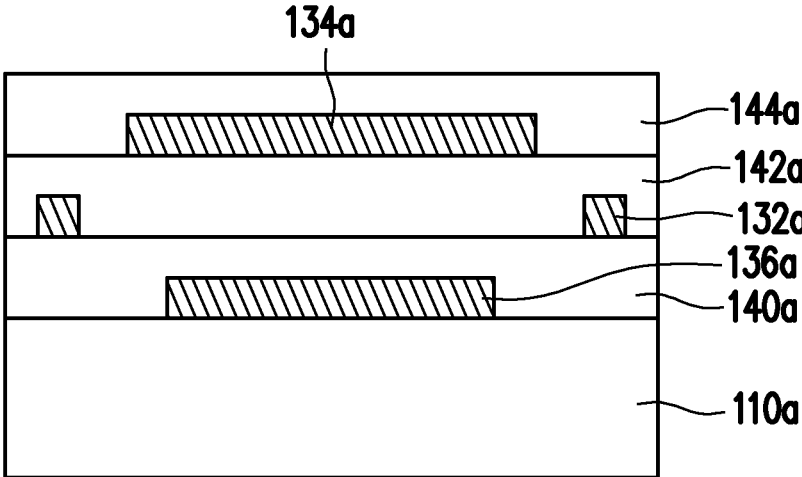


FIG. 8B

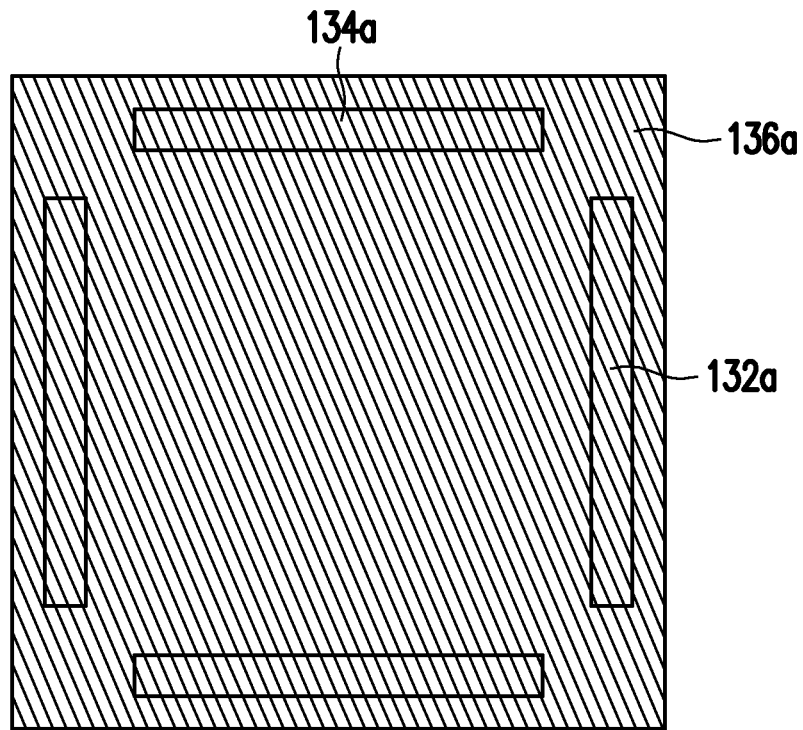


FIG. 9A

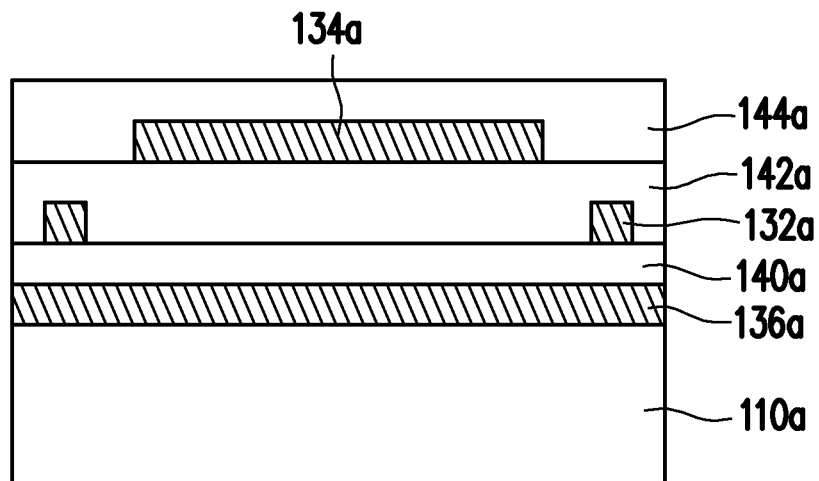


FIG. 9B

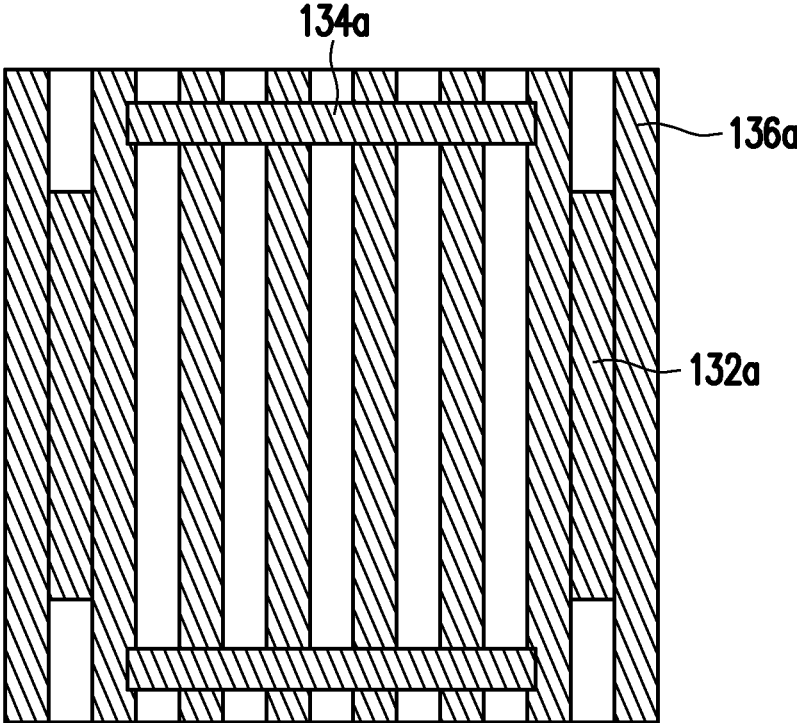


FIG. 10A

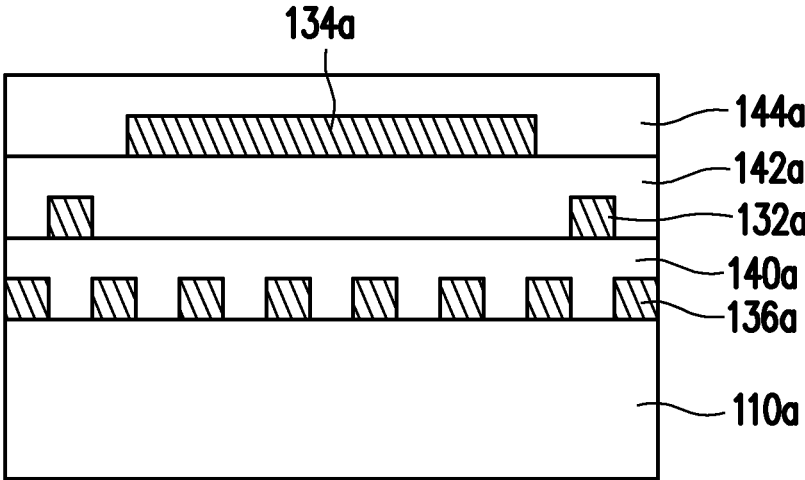


FIG. 10B

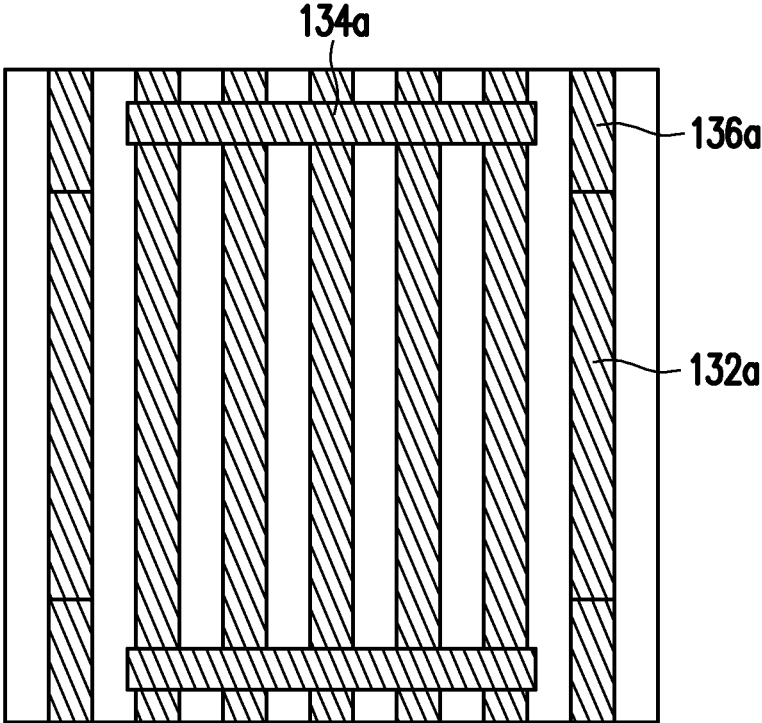


FIG. 11A

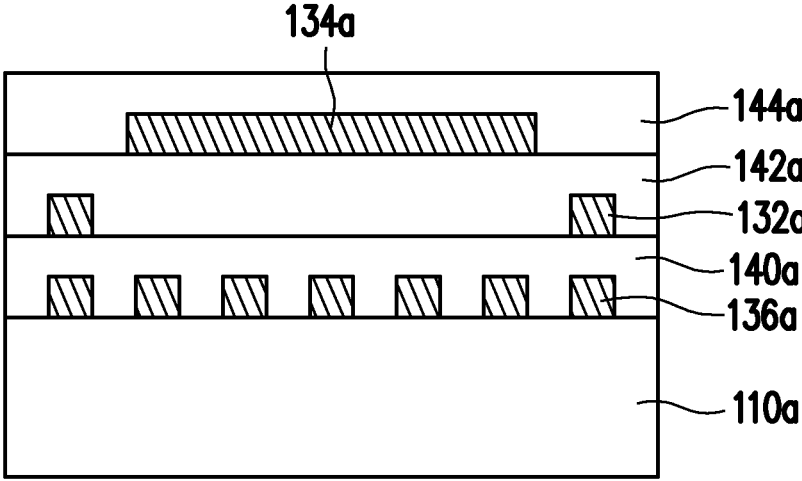


FIG. 11B

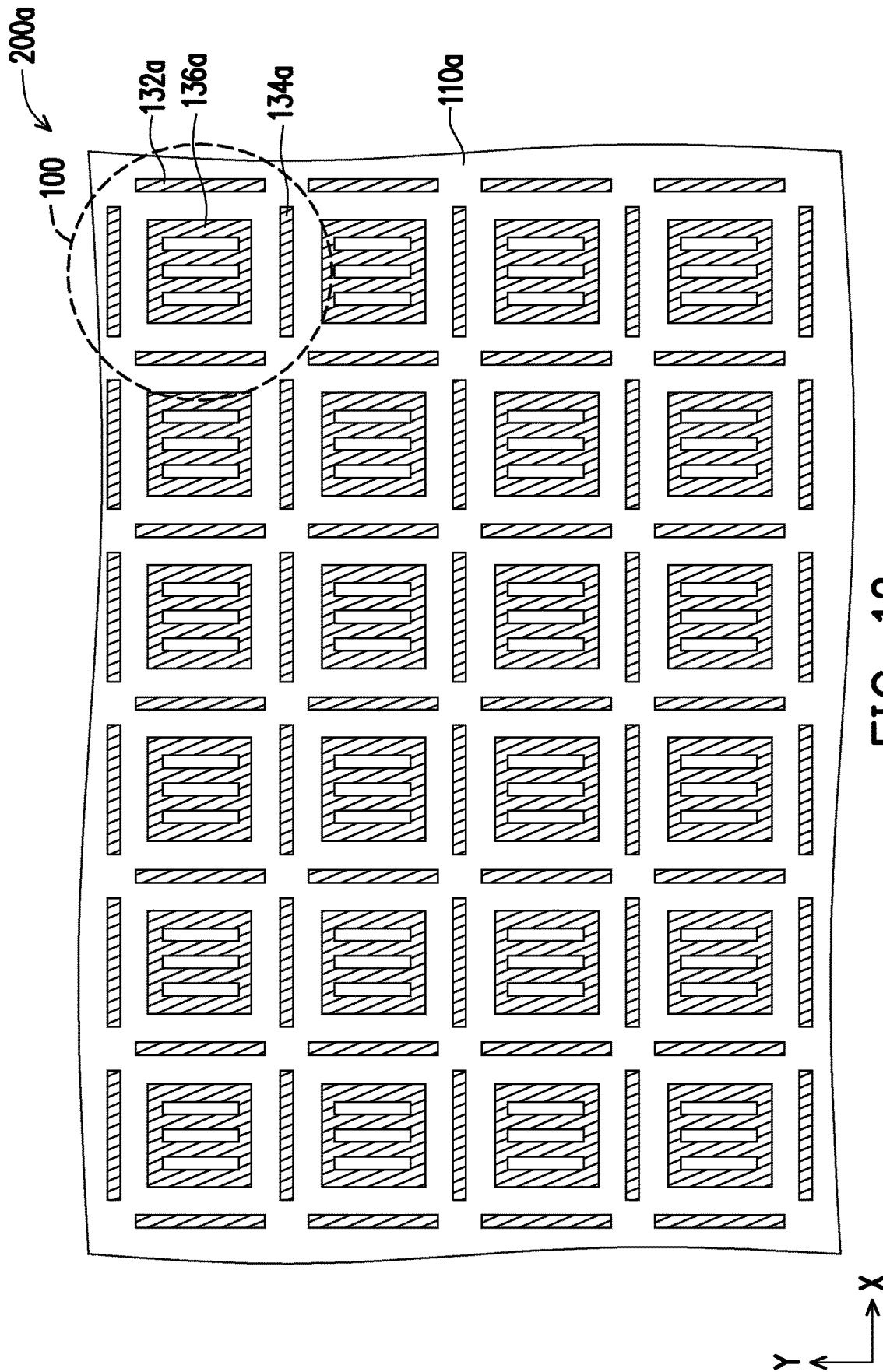


FIG. 12

200b

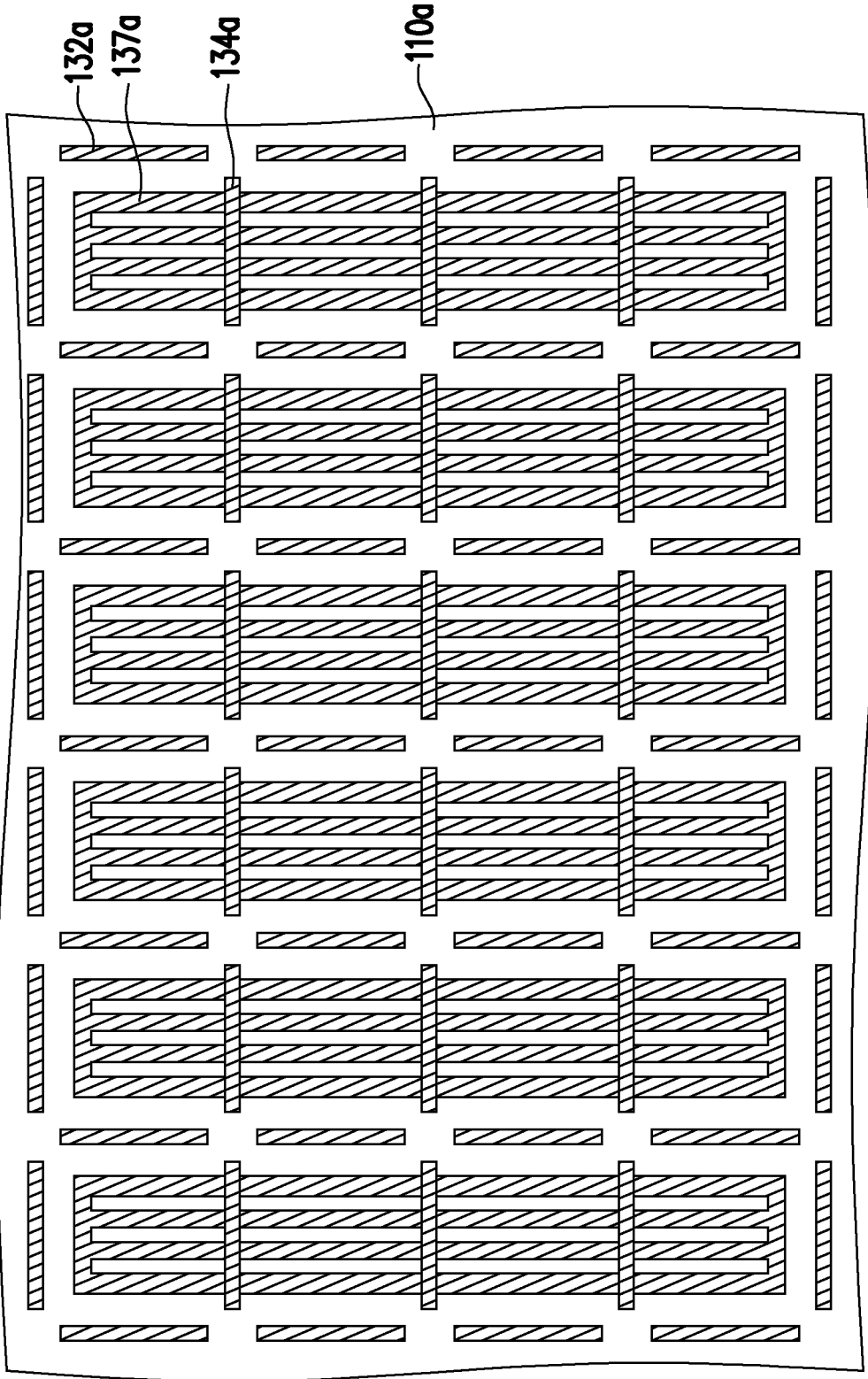
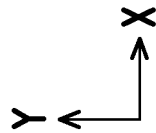
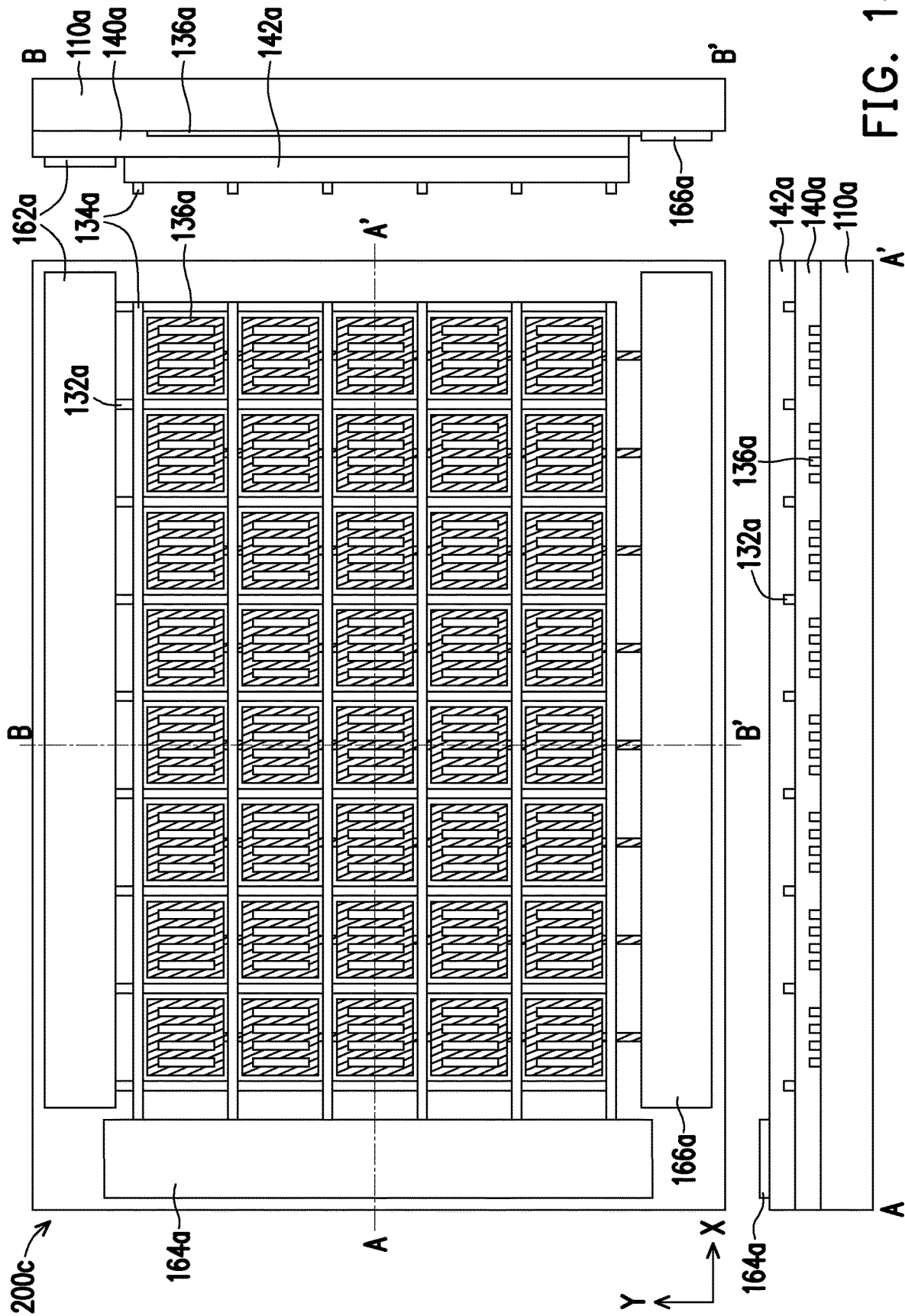


FIG. 13





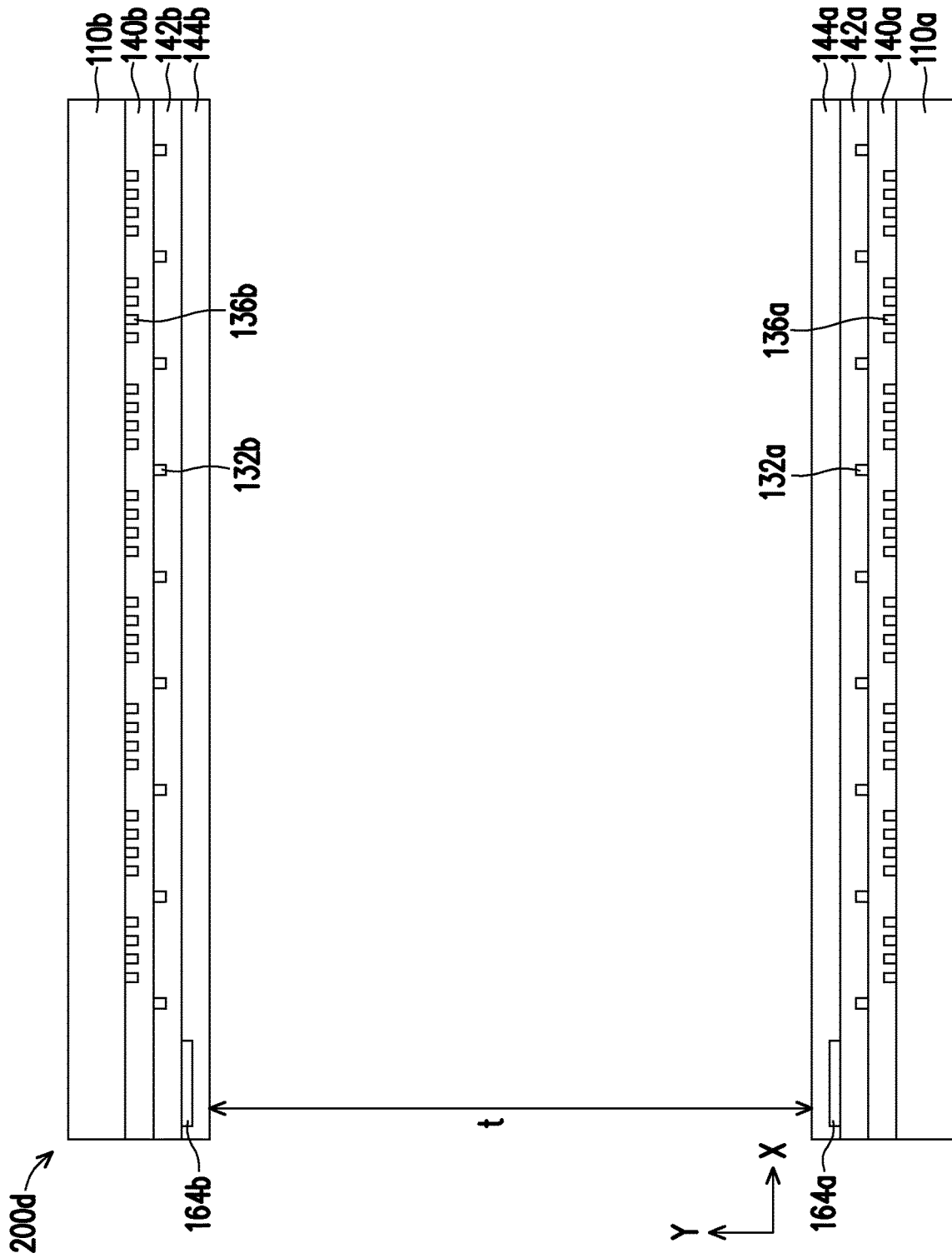


FIG. 15

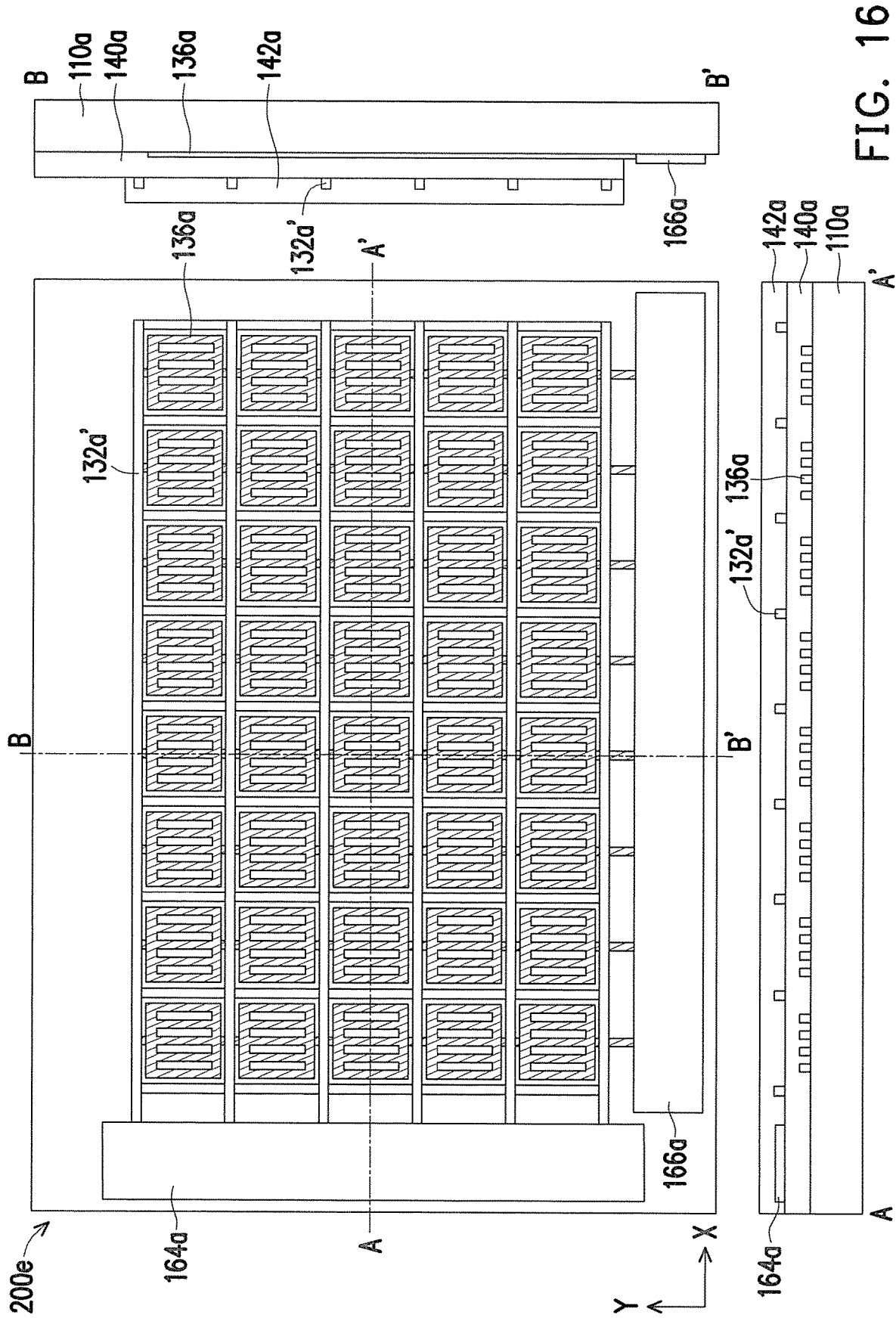


FIG. 16

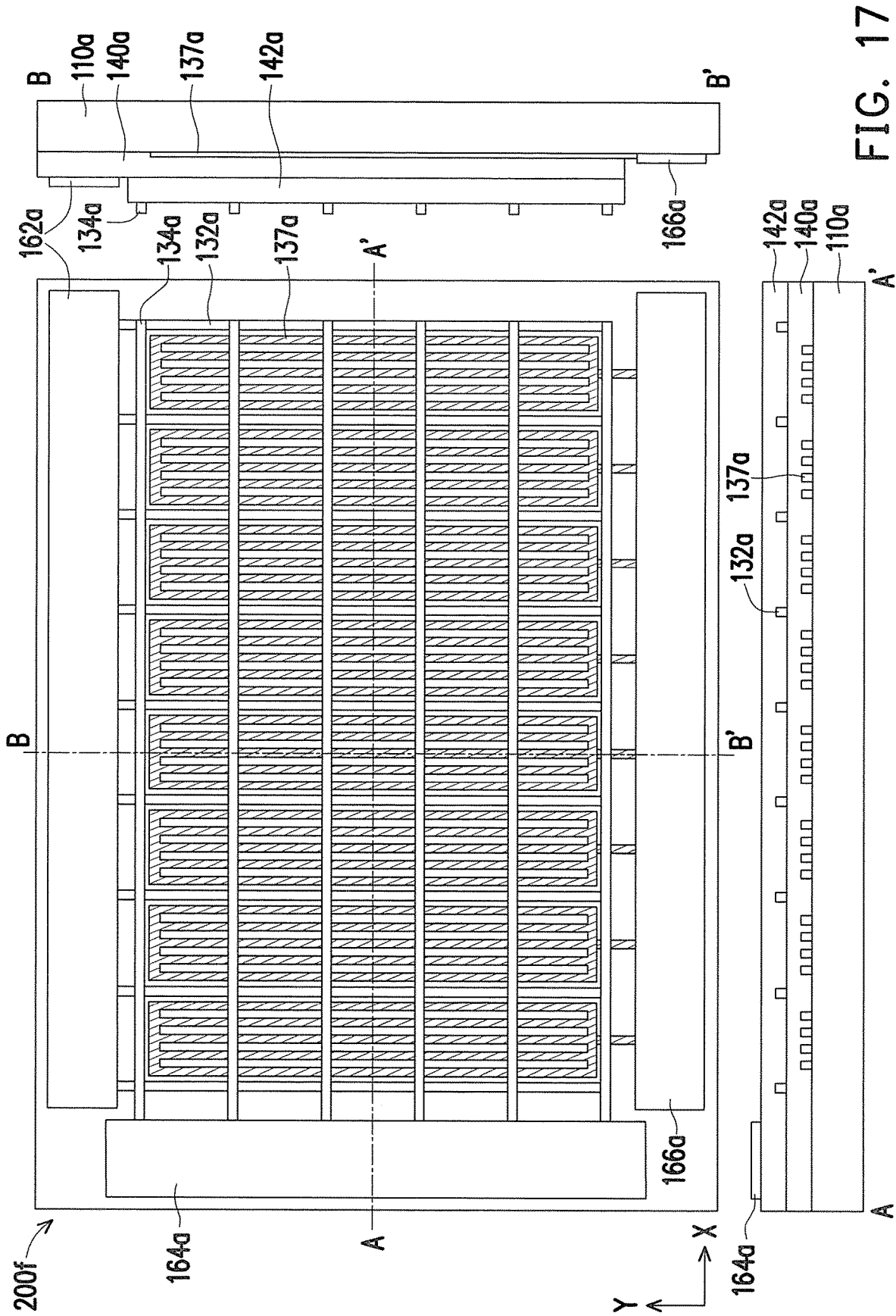


FIG. 17

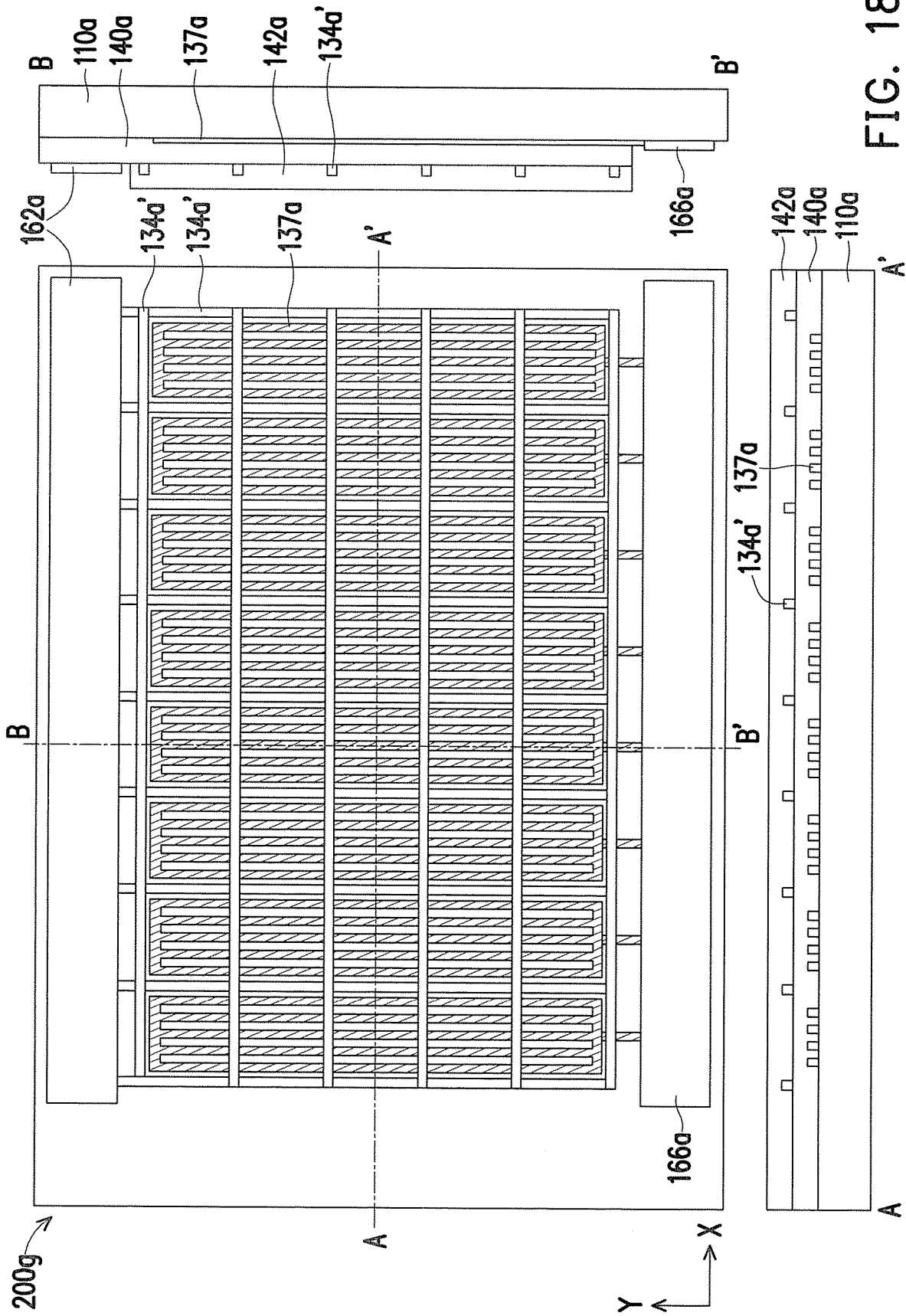


FIG. 18

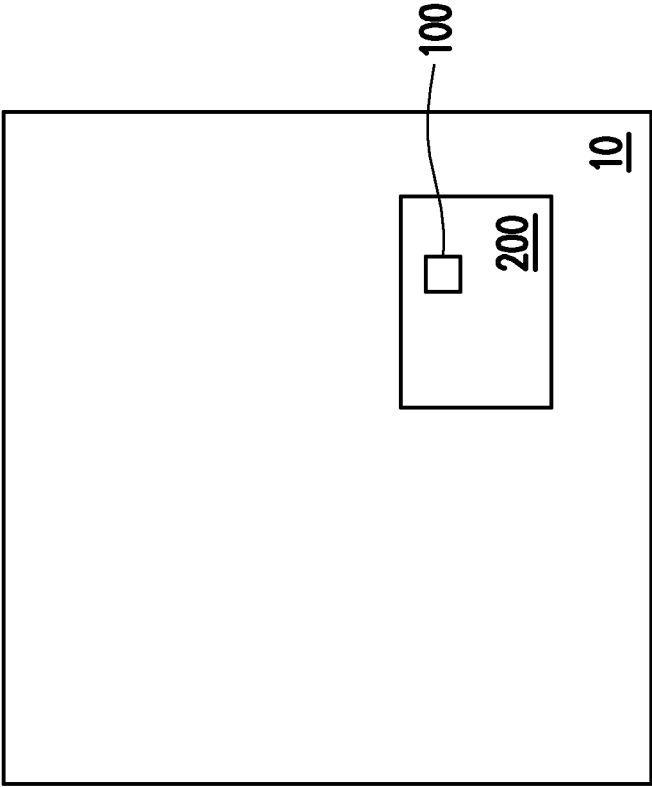


FIG. 19

LIQUID CRYSTAL DEVICE AND SYSTEM FOR THZ ELECTROMAGNETIC WAVES

TECHNICAL FIELD

The disclosure relates to a liquid crystal device, more specifically, to the implement of liquid crystals to provide a device with continuously adjusting phase shift or delay, i.e. a phase shifter, for various applications in terahertz (THz) ($1 \text{ THz} = 10^{12} \text{ Hz}$) electromagnetic wave or sub-mm electromagnetic wave.

BACKGROUND

THz wave technology has shown great potential for development in fields including time-domain spectroscopy, THz imaging, and medical applications. Further, THz communication and phase array radar also become feasible. The above applications all need THz quasi-optical devices such as polarizers, filters, phase shifters, and modulators, etc., for signal processing.

Liquid crystal (LC) devices are widely used in THz frequencies. In order to operate at THz frequencies, LC devices use a thick cell gap to satisfy the required retardation. However, the thick cell gap leads to an extremely slow response.

SUMMARY

The disclosure provides a liquid crystal device, and specifically, a liquid crystal phase shifter for THz electromagnetic waves with a type of LC switching, which results in hexa-directional switching among initial, intrinsic in-plane and out-of-plane reorientations of the LCs providing a broader range of phase shifts while maintaining a fast response time.

The liquid crystal device according to an exemplary embodiment may include not limited to a single or a plurality of pixel elements as each pixel element may include a first substrate, a second substrate facing the first substrate and parallel to the first substrate, a liquid crystal layer disposed between the first substrate and the second substrate, a first plurality of electrodes formed between the first substrate and the liquid crystal layer, wherein the first plurality of electrodes is grating-type and/or finger-type electrodes, a second plurality of electrodes formed between the second substrate and the liquid crystal layer, wherein the second plurality of electrodes, is grating-type and/or finger-type electrodes, wherein the same grating-type and/or finger-type electrode of the first plurality of electrodes and the second plurality of electrodes are formed and facing each other with a cell gap, wherein the first plurality of electrodes and the second plurality of electrodes are composed to generate electric fields in three orthogonal directions, and the electric fields in two of the three orthogonal directions are in-plane electric fields and are substantially parallel to the first substrate, the second substrate and to the liquid crystal layer, while the other electric field of the three orthogonal directions is an out-of-plane electric field and is substantially perpendicular to the first substrate and the second substrate.

To make the above features and advantages of the present disclosure more comprehensible, several embodiments accompanied with drawings are described in detail as follows.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings are included to provide a further understanding of the disclosure, and are incorporated

in and constitute a part of this specification. The drawings illustrate embodiments of the disclosure and, together with the description, serve to explain the principles of the disclosure.

5 FIG. 1 is a schematic cross-sectional view of a liquid crystal pixel element.

FIG. 2A is a schematic three-dimensional view of a liquid crystal pixel element.

10 FIG. 2B is a schematic top view of the liquid crystal pixel element of FIG. 2A.

FIG. 2C is a schematic top view of the liquid crystal pixel element of FIG. 2A.

FIG. 2D is a schematic cross-sectional view of the liquid crystal pixel element of FIG. 2A.

15 FIG. 3A is a schematic three-dimensional view of a liquid crystal pixel element.

FIG. 3B is a schematic top view of the liquid crystal pixel element of FIG. 3A.

20 FIG. 3C is a schematic cross-sectional view of the liquid crystal pixel element of FIG. 3A.

FIG. 4A is a schematic three-dimensional view of a liquid crystal pixel element.

FIG. 4B is a schematic top view of the liquid crystal pixel element of FIG. 4A.

25 FIG. 4C is a schematic cross-sectional view of the liquid crystal pixel element of FIG. 4A.

FIG. 5A is a schematic three-dimensional view of a liquid crystal pixel element.

30 FIG. 5B is a schematic top view of the liquid crystal pixel element of FIG. 5A.

FIG. 5C is a schematic cross-sectional view of the liquid crystal pixel element of FIG. 5A.

FIG. 6 are schematic top-views and cross-sectional views of the liquid crystal pixel elements of FIG. 3A, FIG. 4A and FIG. 5A.

35 FIG. 7A is a schematic top view of a portion of a liquid crystal pixel element.

FIG. 7B is a schematic cross-sectional view of the portion of the liquid crystal pixel element of FIG. 7A.

40 FIG. 8A is a schematic top view of a portion of a liquid crystal pixel element.

FIG. 8B is a schematic cross-sectional view of the portion of the liquid crystal pixel element of FIG. 8A.

45 FIG. 9A is a schematic top view of a portion of a liquid crystal pixel element.

FIG. 9B is a schematic cross-sectional view of the portion of the liquid crystal pixel element of FIG. 9A.

FIG. 10A is a schematic top view of a portion of a liquid crystal pixel element.

50 FIG. 10B is a schematic cross-sectional view of the portion of the liquid crystal pixel element of FIG. 10A.

FIG. 11A is a schematic top view of a portion of a liquid crystal pixel element.

55 FIG. 11B is a schematic cross-sectional view of the portion of the liquid crystal pixel element of FIG. 11A.

FIG. 12 is a schematic top view of a portion of a liquid crystal device.

FIG. 13 is a schematic top view of a portion of a liquid crystal device.

60 FIG. 14 are a schematic top view and cross-sectional views of a portion of a liquid crystal device.

FIG. 15 is a cross-sectional view of a portion of a liquid crystal device.

65 FIG. 16 are a schematic top view and cross-sectional views of a portion of a liquid crystal device.

FIG. 17 are a schematic top view and cross-sectional views of a portion of a liquid crystal device.

FIG. 18 are a schematic top view and cross-sectional views of a portion of a liquid crystal device.

FIG. 19 is a block diagram of a photonic device for THz electromagnetic waves.

DETAILED DESCRIPTION

In the following detailed description, for purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the disclosed embodiments. It will be apparent, however, that one or more embodiments may be practiced without these specific details. In other instances, well-known structures and devices are schematically shown in order to simplify the drawing.

In the following embodiments, wordings used to indicate directions, such as “up,” “down,” “front,” “back,” “left,” and “right”, merely refer to directions in the accompanying drawings. Therefore, the directional wording is used to illustrate rather than limit the disclosure. In the accompanying drawings, each drawing illustrates the general features of the methods, structures, and/or materials used in the specific exemplary embodiments. The drawings should not be construed as definition or limitation to the scope and property coveted by the specific exemplary embodiments. For instance, relative thicknesses and locations of film layers, regions or structures may be reduced or enlarged for clarity.

FIG. 1 is a schematic cross-sectional view of a liquid crystal pixel element 100 according to an embodiment of the invention.

In FIG. 1, the liquid crystal pixel element 100 includes a first substrate 110a and a second substrate 110b. The second substrate 110b is facing the first substrate 110a and is parallel to the first substrate 110a. The first substrate 110a and the second substrate 110b have similar structures and properties. The first substrate 110a and the second substrate 110b are both substrates having uniform thickness in the Z-direction. The first substrate 110a and the second substrate 110b are made of materials transparent to THz frequencies. In some embodiments, a range of the THz frequency is between 0.1 to 10 THz, but is not limited thereto. In some embodiments, the material of the first substrate 110a and the second substrate 110b is glass or plastic, but is not limited thereto.

The liquid crystal pixel element 100 further includes a liquid crystal layer 120 with liquid crystal molecules 122. The liquid crystal layer 120 is disposed between the first substrate 110a and the second substrate 110b in the vertical Z-direction. The liquid crystal layer 120 has a uniform thickness in the Z-direction. In some embodiments, the thickness of the liquid crystal layer 120 is between 50-150 micrometer (μm), preferably 100 μm or less, but is not limited thereto.

The liquid crystal pixel element 100 further includes a plurality of electrodes 130a formed between the first substrate 110a and the liquid crystal layer 120, and a plurality of electrodes 130b formed between the second substrate 110b and the liquid crystal layer 120. The electrodes 130a and the electrodes 130b are separated by a cell gap in the Z-direction, wherein the liquid crystal layer 120 is disposed in the cell gap. An insulating layer 140a and an insulating layer 140b are formed on the electrodes 130a and electrodes 130b respectively to insulate the electrodes 130a and the electrodes 130b and other layers of the liquid crystal pixel elements 100. In some embodiments, the material of the electrodes 130a and 130b is metal or any other conductive

materials, such as copper, aluminum, poly(3,4-ethylenedioxythiophene) polystyrene sulfonate and graphene, but is not limited thereto. In some embodiments, the thickness of the electrodes 130a and 130b is between 100-500 nm, and preferably 200 nm, but is not limited thereto. The width of the electrodes 130a and 130b is between 5-15 μm , and preferably 10 μm , but is not limited thereto. In some embodiments, the thickness of the insulating layers 140a and 140b could be between 200-1000 nm, preferably 500 nm, but is not limited thereto.

The electrodes 130a and the electrodes 130b include grating-type and/or finger-type electrodes. When a voltage difference is applied to the electrodes 130a and the electrodes 130b by a power source controlled by driving modules (not shown), the electrodes 130a and the electrodes 130b together generate electric fields in three orthogonal directions, such as along the X-, Y- and/or Z-directions. The electric fields generated by the electrodes 130a and 130b in two of the three orthogonal directions, such as along the X-direction and the Y-direction, are referred to as in-plane electric fields, and are substantially parallel to the first substrate 110a, the second substrate 110b and the liquid crystal layer 120. The other electric field of the three orthogonal directions, such as along the Z-direction, is referred to as an out-of-plane electric field and is substantially perpendicular to the first substrate 110a and the second substrate 110b.

By applying electric fields in three orthogonal directions, with two in-plane electric fields mutually perpendicular to each other, and one out-of-plane electric field, the liquid crystal molecules 122 in the liquid crystal layer 120 may perform hexdirectional hexa-directional switching between in-plane and out-of-plane orientations.

The liquid crystal pixel element 100 further includes alignment layers 150a and 150b disposed on electrodes 130a and electrodes 130b respectively, and in contact with two opposing sides of liquid crystal layer 120. The alignment layers 150a and 150b are configured to align the liquid crystal molecules 122 to an initial alignment when there are no electric fields in the liquid crystal layer 120 by controlling the pretilt angle and the polar angle of the liquid crystal molecules 122. The pretilt angle is an angle between the long axis of the liquid crystal molecule 122 and the surface of the alignment layer (XY-plane), the azimuthal angle is an angle projected on the XY plane and a fixed axis (for example, along X-direction) in the XY plane perpendicular to Z-direction. In some embodiments, the material for the alignment layers 150a and 150b is polymer such as polyimide, but is not limited thereto.

The liquid crystal pixel element 100 further includes polarizers 160a and 160b disposed on the first substrate 110a and the second substrate 110b respectively. The first polarizer 160a and the second polarizer 160b are configured to polarize the light coming in or out from the liquid crystal layer 120. In some embodiments, the polarizer 160a may be formed between the first substrate 110a and the insulating layer 140a, and the polarizer 160b may be formed between the second substrate 110b and the insulating layer 140b. In some embodiments, the finger-type or strip-type electrodes 130a and 130b are used together as a wire-grid polarizer.

In some embodiments, the polarization directions of the polarizers 160a and 160b are perpendicular or parallel to each other. When a voltage is applied across the liquid crystal layer 120, causing the liquid crystal molecules 122 to twist, this in turn rotates the polarization of light passing through the liquid crystal layer 120. THz light oscillating in

one direction may more easily pass through the liquid crystal layer **120** than light oscillating in another direction. The refractive index (a value for how much slower the light propagates in a material) can be different for light oscillating parallel or perpendicular to the liquid crystal molecules. This is referred to as “optical anisotropy”, which is defined as the difference between the extraordinary refractive index n_e and ordinary refractive index n_o ($\Delta n = n_e - n_o$) and is called “birefringence”.

FIG. 2A is a schematic three-dimensional view of a liquid crystal pixel element. FIG. 2B is a schematic top view of the liquid crystal pixel element of FIG. 2A. FIG. 2C is a schematic top view of the liquid crystal pixel element of FIG. 2A. FIG. 2D is a schematic cross-sectional view of the liquid crystal pixel element of FIG. 2A.

Please refer to FIGS. 2A to 2D. For the purpose of clarity, some elements of liquid crystal pixel element **100** are omitted.

As shown in FIG. 2A, the first plurality of electrodes **130a** and the second plurality of electrodes **130b** are presented. The first plurality of electrodes **130a** includes a pair electrodes **132a**, a pair of electrodes **134a**, and an electrode **136a**, which are all formed on the same level of the first substrate **110a**. The second plurality of electrodes **130b** includes a pair electrodes **132b**, a pair of electrodes **134b**, and an electrode **136b**, which are all formed on the same level of the second substrate **110b**. The first plurality of electrodes **130a** and the second plurality of electrodes **130b** are formed and facing each other with the same arrangements. The electrodes **132a**, **132b**, **134a**, and **134b** are finger-type electrodes. The electrodes **136a** and **136b** are grating-type electrodes.

Referring to FIG. 2A and FIG. 2B, the pair of electrodes **132a** are formed on the first substrate **110a**. The electrodes **132a**, which are finger-type electrodes, are parallel to each other. Each of the electrodes **132a** has a strip shape, with the long axis of each of the electrodes **132a** perpendicular to the X-direction. In some embodiments, the electrodes **132a** may have other shapes, which is not limited thereto. When applying a voltage difference between the electrodes **132a**, the pair of electrodes **132a** generates an in-plane electric field substantially parallel to the first substrate **110a** and the liquid crystal layer **120**. The direction of the in-plane electric field generated by the electrodes **132a** may be along the positive or negative X-direction, depending on the direction of the voltage applied to the electrodes **132a**. The electric field generated along the X-direction reorients the liquid crystal molecules **122** in the liquid crystal layer **120** along the X-direction. The pair of electrodes **132b** formed on the second substrate **110b** has properties similar to the pair of electrodes **132a**, which is not repeated hereof.

Referring to FIG. 2A and FIG. 2B, the pair of electrodes **134a** are formed on the first substrate **110a**. The electrodes **134a**, which are finger-type electrodes, are parallel to each other. Each of the electrodes **134a** has a strip shape, with the long axis of each of the electrodes **134a** perpendicular to the Y-direction. In some embodiments, the electrodes **134a** may have other shapes, which is not limited thereto. When applying a voltage difference between the electrodes **134a**, the pair of electrodes **134a** generates an in-plane electric field substantially parallel to the first substrate **110a** and the liquid crystal layer **120**. The direction of the in-plane electric field generated by the electrodes **134a** may be along the positive or negative Y-direction, depending on the direction of the voltage applied to the electrodes **134a**. The electric field generated along the Y-direction reorients the liquid crystal molecules **122** in the liquid crystal layer **120** along

the Y-direction. The pair of electrodes **134b** formed on the second substrate **110b** has properties similar to the pair of electrodes **134a**, which is not repeated hereof.

Referring to FIG. 2A and FIG. 2B, the electrode **136a** is formed on the first substrate **110a** and the electrode **136b** is formed on the second substrate **110b**. As shown in FIG. 2A and FIG. 2B, the electrodes **136a** and **136b** are grating-type electrodes. In some embodiments, the electrodes **136a** and **136b** may have other shapes, which is not limited thereto. The directions of the grating-type electrodes **136a** and **136b** are both extending along the Y-direction. When applying a voltage difference between the electrodes **136a** and **136b**, the electrodes **136a** and **136b** together generate an out-of-plane electric field substantially perpendicular to the first substrate **110a**, the second substrate **110b** and the liquid crystal layer **120**. The direction of the out-of-plane electric field may be along the positive or negative Z-direction, depending on the direction of the voltage applied to the electrodes **136a** and **136b**. In some embodiments, the electric field generated along the Z-direction reorients the liquid crystal molecules **122** in the liquid crystal layer **120** along the Z-direction.

Referring to FIG. 2B and FIG. 2D, when the voltage is not applied to the electrodes **132a**, **132b**, **134a**, **134b**, **136a** and/or **136b**, there is no electric field generated in the liquid crystal layer **120**. Therefore, the liquid crystal molecules **122** are in their initial alignment. In some embodiments, the initial alignment of the liquid crystal molecules **122** is in-plane, which the long axis of the liquid crystal molecules **122** are parallel to the first substrate **110a** and the second substrate **110b**. In some embodiments, the initial alignment of the liquid crystal molecule **122** is nearly perpendicular to the extending direction of the grating-type electrode **136a**. In other words, the angle between the long axis of the liquid crystal molecule **122** and the extending direction of the electrode **136a** is nearly perpendicular. Referring to FIG. 2B, the extending direction of the electrode **136a** is along the Y-direction. In some embodiments, the angle between the long axis of the liquid crystal molecule **122** and the extending direction of the electrode **136a** is between 85-95 degrees, which is nearly the direction of the X-direction, as shown in FIG. 2D, but the initial orientation angle is not limited thereto.

Referring to FIG. 2B, the electrodes **132a** and electrodes **134a** are configured to generate in-plane electric fields. As shown in FIG. 2B, a distance between the two electrodes **132a** is defined as $d1$, and a distance between the two electrodes **134a** is defined as $d2$. In some embodiments, a ratio of the distance $d1$ between the two electrodes **132a** and the distance $d2$ between the two electrodes **134a**, $d1/d2$, is substantially equal to 1. In some embodiments, the ratio $d1/d2$ is between 0.9 and 1.1. Since the distance $d1$ between the two electrodes **132a** and the distance $d2$ between the two electrodes **134a** are substantially the same, when applying similar voltage difference to the electrodes **132a** and **134a**, the electric field generated by the electrodes **132a** and the electric field generated by the electrodes **134a** may be substantially the same, so the two in-plane electric fields in the liquid crystal layer **120** may have more similar electric field strength.

Referring to FIG. 2B, the initial alignment of the liquid crystal molecules **122** is along the X-direction. In some embodiments, the distance $d2$ between the electrodes **134a**, which generate the in-plane electric field perpendicular to the initial alignment of the liquid crystal molecules **122**, is shorter than the distance $d1$ between the electrodes **132a**, which generate the in-plane electric field perpendicular to

the initial alignment of the liquid crystal molecules **122**, which is $d2/d1 < 1$, or $d1/d2 > 1$. The electrodes **132a** generate the in-plane electric field along the X-direction, which is parallel to the initial alignment of the liquid crystal molecules **122**. The electrodes **134a** generate the in-plane electric field along the Y-direction, which is perpendicular to the initial alignment of the liquid crystal molecules **122**. When the distance **d2** between the electrodes **134a** is shorter than the distance **d1** between the electrodes **132a**, the strength of the electric field generated by the electrodes **134a** will be stronger than the strength of the electric field generated by the electrodes **132a**, which is easier to orient the liquid crystal molecules **122** along the direction of the electric field generated by the electrodes **134a**, which is perpendicular to the initial alignment of the liquid crystal molecules **122**.

Referring to FIG. 2C, in some embodiments, the extending direction of the electrode **136a** is along the Y-direction. The initial alignment of the liquid crystal molecules **122** is in-plane, which the long axis of the liquid crystal molecules **122** are parallel to the first substrate **110a** and the second substrate **110b**. In some embodiments, the initial alignment of the liquid crystal molecule **122** is nearly 45 degrees from the extending direction of the electrode **136a**. In other words, the angle between the long axis of the liquid crystal molecule **122** and the extending direction of the electrode **136a** is nearly 45 degrees. In some embodiments, the angle between the long axis of the liquid crystal molecule **122** and the extending direction of the electrode **136a** is between 40-50 degrees, but is not limited thereto.

FIG. 3A is a schematic three-dimensional view of a liquid crystal pixel element. FIG. 3B is a schematic top view of the liquid crystal pixel element of FIG. 3A. FIG. 3C is a schematic cross-sectional view of the liquid crystal pixel element of FIG. 3A.

Please refer to FIG. 3A, FIG. 3B, and FIG. 3C. In this embodiment, a power source **138** is connected to the pair of electrodes **132a** on the first substrate **110a**, and the pair of electrodes **132b** on the second substrate **110b**. When applying a voltage difference between the electrodes **132a**, the pair of electrodes **132a** generates an in-plane electric field substantially parallel to the first substrate **110a** and the liquid crystal layer **120**. The electric field generated by the electrodes **132a** may be along the positive or negative X-direction which reorients the liquid crystal molecules **122** in the liquid crystal layer **120** along the same direction. Similarly, when applying a voltage difference between the electrodes **132b**, the pair of electrodes **132b** generates an in-plane electric field substantially parallel to the second substrate **110b** and the liquid crystal layer **120**. The electric field generated by the electrodes **132b** is along the positive or negative X-direction which also aligns the liquid crystal molecules **122** in the liquid crystal layer **120** along the same direction.

As a result, by applying a voltage difference to the pair of electrodes **132a** and **132b**, the liquid crystal molecules **122** in the liquid crystal layer **120** are reoriented along the generated electric fields, which is along the positive or negative X-direction. In general, the average orientation direction of the liquid crystal molecules **122** is along the X-direction.

FIG. 4A is a schematic three-dimensional view of a liquid crystal pixel element. FIG. 4B is a schematic top view of the liquid crystal pixel element of FIG. 4A. FIG. 4C is a schematic cross-sectional view of the liquid crystal pixel element of FIG. 4A.

Please refer to FIG. 4A, FIG. 4B, and FIG. 4C. In this embodiment, a power source **138** is connected to the pair of

electrodes **134a** on the first substrate **110a**, and the pair of electrodes **134b** on the second substrate **110b**. When applying a voltage difference between the electrodes **134a**, the pair of electrodes **134a** generates an in-plane electric field substantially parallel to the first substrate **110a** and the liquid crystal layer **120**. The electric field generated by the pair of electrodes **134a** is perpendicular to the electric field generated by the electrodes **132a**. The electric field generated by the electrodes **134a** may be along the positive or negative Y-direction which reorients the liquid crystal molecules **122** in the liquid crystal layer **120** along the same direction. Similarly, when applying a voltage difference between the electrodes **134b**, the pair of electrodes **134b** generates an in-plane electric field substantially parallel to the second substrate **110b** and the liquid crystal layer **120**. The electric field generated by the electrodes **134b** is along the positive or negative Y-direction which also aligns the liquid crystal molecules **122** in the liquid crystal layer **120** along the same direction.

As a result, by applying a voltage difference to the pair of electrodes **134a** and **134b**, the liquid crystal molecules **122** in the liquid crystal layer **120** are reoriented along the generated electric fields, which is along the positive or negative Y-direction. In general, the average orientation direction of the liquid crystal molecules **122** is along the positive or negative Y-direction.

FIG. 5A is a schematic three-dimensional view of a liquid crystal pixel element. FIG. 5B is a schematic top view of the liquid crystal pixel element of FIG. 5A. FIG. 5C is a schematic cross-sectional view of the liquid crystal pixel element of FIG. 5A.

Please refer to FIG. 5A, FIG. 5B, and FIG. 5C. In this embodiment, a power source **138** is connected to the electrode **136a** on the first substrate **110a**, and the electrode **136b** on the second substrate **110b**. When applying a voltage difference between the electrode **136a** and the electrode **136b**, the electrode **136a** and the electrode **136b** generates an out-of-plane electric field substantially perpendicular to the first substrate **110a**, the second substrate **110b** and the liquid crystal layer **120**. The electric field generated by the electrode **136a** and the electrode **136b** is perpendicular to the electric field generated by the pair of electrodes **132a** and perpendicular to the electric field generated by the pair of electrodes **134a**. The electric field generated by the electrode **136a** and the electrode **136b** may be along the positive or negative Z-direction which reorients the liquid crystal molecules **122** in the liquid crystal layer **120** along the same direction.

As a result, by applying a voltage difference to the electrode **136a** and the electrode **136b**, the liquid crystal molecules **122** in the liquid crystal layer **120** are reoriented along the generated electric fields, which is along the positive or negative Z-direction. In general, the average orientation direction of the liquid crystal molecules **122** is along the positive or negative Z-direction.

As a result, by applying voltage differences to the electrodes **132a**, **132b**, **134a**, **134b**, **136a**, and/or **136b** on the first substrate **110a** and the second substrate **110b**, electric fields along three orthogonal directions (positive or negative X-direction, positive or negative Y-direction, and positive or negative Z-direction) may be generated to reorient the liquid crystal molecules **122** in the liquid crystal layer along the desired directions. As shown in FIG. 6, the orientation of the liquid crystal molecules **122** between X-, Y- and Z-directions may also be switched by applying proper voltage difference to the corresponding electrodes. With different orientation of the liquid crystal molecules, the phases of the

incoming THz waves incident the liquid crystal pixel element may be retarded to the desired phase.

In the previous discussions, the liquid crystal molecules **122** with positive dielectric anisotropy ($\Delta\epsilon > 0$) are used. However, when liquid crystal molecules **122** with negative dielectric anisotropy ($\Delta\epsilon < 0$) are used, when applying the electric field to the liquid crystal layer, orientations of the liquid crystal molecules are 90 degrees different from those liquid crystal molecules with positive dielectric anisotropy ($\Delta\epsilon > 0$).

As shown in FIG. 2A to 5C, the thickness of the liquid crystal layer **120** is between 50-150 μm , and preferably 100 μm or less, but is not limited to thereto. In some embodiments, the liquid crystal pixel element **100** become more effective when the thickness of the liquid crystal layer **120** is less than 100 μm . Even less thickness of the liquid crystal layer **120** is preferable in terms of low-loss phase shifters. Furthermore, for the purpose of low-loss phase shifters, the material of the substrates **110a** and **110b** of the liquid crystal pixel element **100** may be low-loss materials such as fused quartz, silica, lithium niobate, and others, which are not limited thereto. By using low-loss substrate materials in the liquid crystal pixel element, the overall thickness of the liquid crystal pixel element **100** may be further reduced. In some embodiments, the disclosed liquid crystal devices can be combined with azimuthally rotatable birefringent substrates such as quartz, silica, lithium niobate, which are not limited thereto. The birefringent substrates compensate phase shifts, which enables reducing the thickness of the liquid crystal layer in the disclosed liquid crystal device while maintaining the maximum phase shift as a phase shifter.

In other inventions, changes in the orientational direction of liquid crystal molecules are limited to a value of approximately 90 degrees or less, which are typically achieved in-plane or between an in-plane direction and an out-of-plane direction. However, the liquid crystal pixel element **100**, as shown in FIGS. 3A to 5C, enables creating three 90-degree changes in the orientational directions of liquid crystal molecules **122** in space, which are achieved in XY, XZ, and YZ planes, depending on the electric fields applied to the liquid crystal layer. As a result, three pairs of bidirectional 90-degree switching are realized. Therefore, by combining a pair of polarizers **160a** and **160b**, the range of phase change accompanying the orientations of the liquid crystal molecules **122** becomes nonlinearly large as compared with the conventional techniques. Further, each switching in each 90-degree orientational direction are bidirectionally governed by electric fields, indicating that all responses of orientational changes are tunable and faster than those in conventional techniques.

The electrodes on the substrates may have various arrangements to suit various requirements. In FIG. 7A to FIG. 11B, various arrangements of the electrodes are presented. In these figures, since the arrangements of the electrodes **132a**, **134a**, and **136a** on the first substrate **110a** and the second substrate **110b** are the same, only the arrangements of the electrodes **132a**, **134a**, and **136a** on the first substrate **110a** is presented and discussed below.

FIG. 7A is a schematic top view of a portion of a liquid crystal pixel element. FIG. 7B is a schematic cross-sectional view of the portion of the liquid crystal pixel element of FIG. 7A. For the purpose of clarity, only the elements formed on the first substrate **110a** are presented. The electrodes formed on the second substrate **110b** are arranged similarly. Referring to FIG. 7A, from the top view, the arrangements of electrodes **132a**, **134a**, and **136a** is the same as shown in

FIG. 2B. However, as shown in FIG. 7B, only the electrodes **132a** are formed on the substrate **110a**. The electrodes **132a** are covered with an insulating layer **140a**. The electrodes **134a** and **136a** are formed on the insulating layer **140a**. The electrodes **134a** and **136a** are covered with an insulating layer **142a**. In other words, the electrodes **134a** and **136a** are formed on a same plane, but on a plane different from the plane which the electrodes **132a** are formed. By arranging the electrodes in different planes, the wiring to the electrodes may be easier, and the shape of the electrodes may be more flexible since more space are available in one plane. In some embodiments, the thickness of the insulating layers **140a** and **142a** is 200-1000 nm, preferably 500 nm, but is not limited thereto. In some embodiments, the thickness of the electrodes **132a**, **134a**, and **136a** is 100-500 nm, preferably 200 nm, but is not limited thereto. The width of the electrodes **130a** and **130b** is between 5-15 μm , and preferably but is not limited thereto.

FIG. 8A is a schematic top view of a portion of a liquid crystal pixel element. FIG. 8B is a schematic cross-sectional view of the portion of the liquid crystal pixel element of FIG. 8A. Referring to FIG. 8A, from the top view, the arrangement of electrodes **132a**, **134a**, and **136a** is the same as shown in FIG. 7A. However, as shown in FIG. 8B, only the electrode **136a** is formed on the substrate **110a**. The electrode **136a** is covered with an insulating layer **140a**. The electrodes **132a** are formed on the insulating layer **140a**. The electrodes **132a** are covered with an insulating layer **142a**. The electrodes **134a** are formed on the insulating layer **142a**. The electrodes **136a** are further covered with an insulating layer **144a**. In other words, the electrodes **132a**, **134a** and **136a** are each formed on a different plane. In some embodiments, the electrodes **132a**, **134a** and **136a** may be formed on layers different from what is shown in FIG. 8B, which is not limited thereto. By arranging the electrodes in different planes, the wiring to the electrodes may be easier, and the shape of the electrodes may be more flexible since more space are available in one plane. In some embodiments, the thickness of the insulating layers **140a** and **142a** is 200-1000 nm, preferably 500 nm, but is not limited thereto. In some embodiments, the thickness of the electrodes **132a**, **134a**, and **136a** is 100-500 nm, preferably 200 nm, but is not limited thereto. The width of the electrodes **130a** and **130b** is between 5-15 μm , and preferably 10 μm , but is not limited thereto.

FIG. 9A is a schematic top view of a portion of a liquid crystal pixel element. FIG. 9B is a schematic cross-sectional view of the portion of the liquid crystal pixel element of FIG. 9A. The arrangements of the electrodes **132a** and **134a** in FIG. 9A and FIG. 9B are similar to the arrangement of the electrodes **132a** and **134a** in FIG. 8A. The differences in FIG. 9A and FIG. 9B are that the electrode **136a** extends over the top surface of the first substrate **110a** below the electrodes **132a** and **134a**. With similar arrangement of the electrode **136b** formed on the second substrate **110b** (not shown), the electrode **136a** and **136b** may form a more uniform electric field along the Z-direction, so the out-of-plane electric field generated in the liquid crystal layer **120** may be more uniform.

FIG. 10A is a schematic top view of a portion of a liquid crystal pixel element. FIG. 10B is a schematic cross-sectional view of the portion of the liquid crystal pixel element of FIG. 10A. The arrangements of the electrodes **132a** and **134a** in FIG. 10A and FIG. 10B are similar to the arrangements of the electrodes **132a** and **134a** in FIG. 9A and FIG. 9B. The difference in FIG. 10A and FIG. 10B is that, instead of a grating-type electrode, the electrode **136a** is now a

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plurality of finger-type electrodes extending along the Y-direction. In some embodiments, each of the finger-type electrodes has a same width in the X-direction. In some embodiments, the gaps between the finger-type electrodes are the same. With similar arrangement of the electrode **136b** formed on the second substrate **110b** (not shown), the electrode **136a** and **136b** may form a periodically varying electric field along the Z-direction.

FIG. **11A** is a schematic top view of a portion of a liquid crystal pixel element. FIG. **11B** is a schematic cross-sectional view of the portion of the liquid crystal pixel element of FIG. **11A**. The arrangements of the electrodes **132a** and **134a** in FIG. **11A** and FIG. **11B** are similar to the arrangements of the electrodes **132a** and **134a** in FIG. **10A** and FIG. **10B**. The difference in FIG. **11A** and FIG. **11B** is that the finger-type electrodes **136a** are now shifted along the X-direction such that from the top view, the electrodes **132a** and the electrodes **136a** are now overlapped, instead of not overlapping each other as shown in FIG. **10A** and FIG. **10B**.

With various arrangement of the electrodes, a variety of electric fields in the liquid crystal layer **120** may be generated according to the desired purpose.

FIG. **12** is a schematic top view of a portion of a liquid crystal device **200a**. For the purpose of clarity, only the electrodes on the first substrate **110a** are presented. The electrodes formed on the second substrate **110b** are arranged similarly. The liquid crystal device **200a** is formed by an array of liquid crystal pixel elements **100**. In the liquid crystal device **200a**, the electrodes **132a** are shared with the neighboring liquid crystal pixel elements in the X-direction, and the electrodes **134a** are shared with the neighboring liquid crystal pixel elements in the Y-direction. The electrode **136a** of the liquid crystal pixel element **100** is not shared by neighboring liquid crystal pixel elements.

As shown in FIG. **12**, an array of the liquid crystal pixel elements **100** in the liquid crystal device **200a** enables enlarging the area for beam shaping with phase shift. Even if a single liquid crystal pixel element may be too small for THz beam, forming a liquid crystal device using arrays of the liquid crystal pixel elements of this disclosure enables enlarging the area for THz beam exposure.

FIG. **13** is a schematic top view of a portion of another liquid crystal device **200b**. For the purpose of clarity, only the electrodes formed on the first substrate **110a** are presented. The electrodes formed on the second substrate **110b** are arranged similarly. The arrangement of the electrodes **132a** and **134a** are similar to the arrangement shown in FIG. **12**. The difference is that the electrode **136a** in FIG. **12** is now merged with the electrode **136a** in the neighboring liquid crystal pixel elements along the Y-direction to form a new electrode **137a**. As shown in FIG. **13**, the electrode **137a** is now shared by several liquid crystal pixel elements along the Y-direction. The number of liquid crystal pixel elements which share an electrode **137a** depends on the desired purpose, which is not limited thereto. In some embodiments, the electrode **137a** may extend along the X-direction.

FIG. **14** are a schematic top view and cross-sectional views of a portion of a liquid crystal device **200c**. For the purpose of clarity, only the electrodes formed on the first substrate **110a** are presented. The electrodes formed on the second substrate **110b** are arranged similarly. The liquid crystal device **200c** shown in FIG. **14** is similar to the liquid crystal device **200a** shown in FIG. **12**. The difference is that, in FIG. **14**, the liquid crystal device **200c** further includes driving modules **162a**, **164a** and **166a** connecting to the electrodes **132a**, **134a** and **136a** respectively. The driving

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modules **162a**, **164a** and **166a** control the electrodes **132a**, **134a** and **136a** to generate the electric fields in the three orthogonal directions. In the cross-section view along the line AA', the electrode **136a** is formed on the substrate **110a**, and is covered with an insulating layer **140a**. The electrodes **132a** are formed on the insulating layer **140a**, and is covered with an insulating layer **142a**. The driving module **164a** is formed on the insulating layer **142a**. In the cross-section view along the line BB', the driving module **166a** is formed on the substrate **110a** and connects with the electrode **136a**. The driving module **162a** is formed on the insulating layer **140a**. The electrodes **134a** are formed on the insulating layer **142a**. In some embodiments, the thickness of the insulating layers **140a** and **142a** is 200-1000 nm, preferably 500 nm, but is not limited thereto. In some embodiments, the thickness of the electrodes **132a**, **134a**, and **136a** is 100-500 nm, preferably 200 nm, but is not limited thereto. The width of the electrodes **130a** and **130b** is between 5-15 μm , and preferably 10 μm , but is not limited thereto.

With the arrangement shown in FIG. **14**, the driving module **162a**, **164a** and **166a** may supply a voltage difference to electrodes **132a**, **134a**, and **136a** respectively, which may generate the electric field along the desired direction in the liquid crystal layer.

To operate the arrays of the liquid crystal pixel elements in the liquid crystal device **200c**, each liquid crystal element is provided with the same potential via the electrodes, such as electrodes **132a**, **134a**, and **136a**, such that uniform liquid crystal orientation is achieved throughout the entire array of pixels. Driving modules **162a**, **164a**, **166a** which provide such uniform electric signals, are much simpler than those in liquid crystal displays. Overlapping an electrode with another electrode via an insulating layer works as a capacitor, which can be added to the capacitor formed by liquid crystal layer in the liquid crystal pixel element. When each element is operated via a thin film transistor (not shown), the added capacitor from the layered electrodes has an advantage in holding voltage characteristics in the liquid crystal pixel element. When holding voltage characteristics is good, various types of liquid crystals with different properties, such as large dielectric anisotropy, low resistivity, low absorption loss may be used in the liquid crystal layer.

FIG. **15** is a cross-sectional view of a portion of a liquid crystal device **200d**. The liquid crystal device **200d** has a first substrate **110a** with the structure shown in the cross-section of the liquid crystal device **200c** along line AA' in FIG. **14**. The liquid crystal device **200d** has a second substrate **110b** facing the first substrate **110a** with the same structure of the first substrate **110a**. The first substrate **110a** and the second substrate **110b** are separated by a cell gap. The cell gap is a distance between the top surface of the insulating layer **144a** and the top surface of the insulating layer **144b**. In some embodiments, a thickness of the cell gap, t , is 50-150 μm , and preferably 100 μm or less, but is not limited thereto.

FIG. **16** are a schematic top view and cross-sectional views of a portion of a liquid crystal device **200e**. The liquid crystal device **200e** shown in FIG. **16** is similar to the liquid crystal device **200c** shown in FIG. **14**. The difference is that, in FIG. **16**, the horizontal finger-type electrodes **132a** and the vertical finger-type electrodes **134a** are connected as electrodes **132a'**, as shown in FIG. **16**. The electrodes **132a'** are connected with the driving module **164a**. As shown in the cross-sectional views along lines AA' and BB', the electrodes **132a'** and the driving module **164a** are formed on the insulating layer **140a**, and are covered by the insulating layer **142a**. Compare to the liquid crystal device **200c** shown

in FIG. 14, the number of insulating layers is reduced from 3 to 2, which simplifies the overall structure of the liquid crystal device 200e.

However, since the vertical and horizontal finger-type electrodes 134a and 132a are connected as the electrodes 132a', the electric field generated by the electrodes 132a' is not completely along the X-direction or the Y-direction. As a result, the range of the orientation of the liquid crystal molecules becomes narrower in the liquid crystal device 200, and the liquid crystal device 200e does not have exact hexa-directional switching as the liquid crystal device 200c. In some embodiments the x and y dimensions of each pixel element is approximately the same.

FIG. 17 are a schematic top view and cross-sectional views of a portion of a liquid crystal device 200f. For the purpose of clarity, only the electrodes formed on the first substrate 110a are presented. The electrodes formed on the second substrate 110b are arranged similarly. The liquid crystal device 200f shown in FIG. 17 is similar to the liquid crystal device 200c shown in FIG. 14. The difference is that, in FIG. 17, the electrodes 136a are replaced with the electrodes 137a as shown in FIG. 13. The driving module 166a is now connected with the electrodes 137a, which extends through several liquid crystal pixel elements along the Y-direction. With this arrangement, the driving module 166a may control the electric field in Z-direction for several liquid crystal pixel elements at the same time.

FIG. 18 are a schematic top view and cross-sectional views of a portion of a liquid crystal device 200g. The liquid crystal device 200g shown in FIG. 18 is similar to the liquid crystal device 200f shown in FIG. 17. The difference is that, in FIG. 18, the horizontal finger-type electrodes 132a and the vertical finger-type electrodes 134a are connected as electrodes 134a', as shown in FIG. 18. The electrodes 134a' are connected with the driving module 162a. As shown in the cross-sectional views along lines AA' and BB', the electrodes 134a' and the driving module 162a are formed on the insulating layer 140a, and are covered by the insulating layer 142a. Compare to the liquid crystal device 200f shown in FIG. 17, the number of insulating layers is reduced from 3 to 2, which simplifies the overall structure of the liquid crystal device 200f.

FIG. 19 is a block diagram of a photonic device for THz electromagnetic waves. As shown in FIG. 19, a photonic device 10 used for THz electromagnetic waves is presented. In some embodiments, the photonic device 10 is a polarizer, a filter, a phase shifter, or a modulator, or is a broadband wireless communication system, a security surveillance system, a medical imaging system, or a materials characterization system, which is not limited thereto. The photonic device 10 includes a liquid crystal device 200, which includes a plurality of liquid crystal pixel elements 100. In some embodiments, the liquid crystal device 200 includes the liquid crystal devices 200a, 200b, 200c, 200d, and/or 200e, described in this application, but is not limited thereto. With the three orthogonal directions of the electric fields in the liquid crystal pixel elements 100, the liquid crystal molecules in the liquid crystal pixel elements 100 may rotate to any directions according to the applied electric fields, which are suited for applications for THz electromagnetic waves applications.

The disclosed structures set forth above enable continuously switching of the orientation of the LC molecules between the initial, intrinsic in-plane, and out-of-plane states, thereby providing a wider range of phase shifts while maintaining a rapid response. Furthermore, mutual switching between the three orientation states of the LC molecules

becomes possible using the three orthogonal electric fields generated by three pairs of electrodes. In other words, the disclosed structures effectively allow hexa-directional switching between the initial, intrinsic in-plane, and out-of-plane states. In principle, utilizing the three LC orientation states broadens the variations in phase shifts. Furthermore, switching between three LC orientation states by applying electric fields maintains a faster response time. The range of phase shifts afforded by the novel LC switching mode for THz devices such as phase shifters can potentially be further improved by optimizing some device and material parameters, including even larger retardation using LCs with greater birefringence.

The liquid crystal device disclosed here may have wide applications, such as integrated into a THz antenna arrays, or integrated into THz photonic crystals.

It will be apparent to those skilled in the art that various modifications and variations can be made to the disclosed embodiments. It is intended that the specification and examples be considered as exemplary only, with a true scope of the present disclosure being indicated by the following claims and their equivalents.

What is claimed is:

1. A liquid crystal device comprising:

a single or a plurality of pixel elements, each pixel element comprising:

a first substrate,

a second substrate facing the first substrate and parallel to the first substrate,

a liquid crystal layer disposed between the first substrate and the second substrate,

a first plurality of electrodes formed between the first substrate and the liquid crystal layer, wherein the first plurality of electrodes is grating-type and/or finger-type electrodes,

a second plurality of electrodes formed between the second substrate and the liquid crystal layer, wherein the second plurality of electrodes, is grating-type and/or finger-type electrodes, wherein the same grating-type and/or finger-type electrode of the first plurality of electrodes and the second plurality of electrodes are formed and facing each other with a cell gap,

wherein the first plurality of electrodes and the second plurality of electrodes are composed to generate electric fields in three orthogonal directions, and the electric fields in two of the three orthogonal directions are in-plane electric fields and are substantially parallel to the first substrate, the second substrate and to the liquid crystal layer, while the other electric field of the three orthogonal directions is an out-of-plane electric field and is substantially perpendicular to the first substrate and the second substrate.

2. The liquid crystal device according to claim 1, wherein an initial alignment of liquid crystal molecules in the liquid crystal layer is nearly perpendicular from an extending direction of one of the grating-type and/or finger-type electrodes of the first plurality of electrodes and the second plurality of electrodes.

3. The liquid crystal device according to claim 2, wherein the initial alignment of the liquid crystal molecules in the liquid crystal layer is 40 to 50 degrees from the extending direction of one of the grating-type and/or finger-type electrodes of the first plurality of electrodes and the second plurality of electrodes.

4. The liquid crystal device according to claim 1, wherein an initial alignment of liquid crystal molecules of the liquid crystal layer is 85 to 95 degrees from an

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- extending direction of one of the grating-type and/or finger-type electrodes of the first plurality of electrodes and the second plurality of electrodes.
5. The liquid crystal device according to claim 1, wherein the liquid crystal device further comprises:
- a first alignment layer disposed between the first plurality of electrodes and the liquid crystal layer, and
 - a second alignment layer disposed between the second plurality of electrodes and the liquid crystal layer,
- wherein the first alignment layer and the second alignment layer are configured to align liquid crystal molecules in the liquid crystal layer to an initial alignment.
6. The liquid crystal device according to claim 1, wherein a ratio of a distance between a first pair of electrodes of the first plurality of electrodes that generate a first in-plane electric field and a distance between a second pair of electrodes of the first plurality of electrodes that generate a second in-plane electric field is substantially equal to one.
7. The liquid crystal device according to claim 6, wherein the ratio of the distance between the first pair of electrodes of the first plurality of electrodes that generate the first in-plane electric field and the distance between the second pair of electrodes of the first plurality of electrodes that generate the second in-plane electric field is between 0.9 to 1.1.
8. The liquid crystal device according to claim 1, wherein a distance between a first pair of electrodes of the first plurality of electrodes that generate a first in-plane electric field along a direction perpendicular to an initial alignment of liquid crystals of the liquid crystal layer is shorter than a distance between a second pair of electrodes of the first plurality of electrodes that generate a second in-plane electric field along a direction parallel to the initial alignment of the liquid crystals of the liquid crystal layer.
9. The liquid crystal device according to claim 1, wherein electrodes of the first plurality of electrodes that generate a first in-plane electric field, electrodes of the first plurality of electrodes that generate a second in-plane electric field perpendicular to the first in-plane electric field, and electrodes of the first plurality of

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- electrodes that generates an out-of-plane electric field are formed on a same level parallel to the first substrate.
10. The liquid crystal device according to claim 1, wherein electrodes of the first plurality of electrodes that generate a first in-plane electric field, electrodes of the first plurality of electrodes that generate a second in-plane electric field perpendicular to the first in-plane electric field, and electrodes of the first plurality of electrodes that generates an out-of-plane electric field are at different levels parallel to the first substrate.
11. The liquid crystal device according to claim 1, further comprising:
- a first polarizer, disposed on one side of the liquid crystal layer; and
 - a second polarizer, disposed on the other side of the liquid crystal layer,
- wherein the first polarizer and the second polarizer are configured to polarize the light coming in or out from the liquid crystal layer.
12. The liquid crystal device according to claim 1, further comprising:
- a plurality of driving modules, connecting to the first plurality of electrodes and the second plurality of electrodes to control the first plurality of electrodes and the second plurality of electrodes to generate the electric field in the three orthogonal directions.
13. A system for THz electromagnetic waves, comprising: a liquid crystal device according to claim 1.
14. The liquid crystal device according to claim 1, wherein a thickness of the cell gap is between 50-150 μm .
15. The liquid crystal device according to claim 1, wherein each pixel element of the plurality of pixel elements has the same electric signal.
16. The liquid crystal device according to claim 1, wherein the liquid crystal layer is subjected to the electric fields in the three orthogonal directions generated by the first plurality of electrodes and the second plurality of electrodes, and a phase of an incident electromagnetic wave is changed due to a reorientation of the liquid crystal layer changes in respond to the electric fields.

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