



US012542375B2

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

(10) **Patent No.:** **US 12,542,375 B2**
(45) **Date of Patent:** **Feb. 3, 2026**

(54) **ELECTRONICALLY RECONFIGURABLE
POLARIZATION-ROTATING PHASE
SHIFTER**

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(71) Applicant: **Wisconsin Alumni Research
Foundation**, Madison, WI (US)

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(US)

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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 87 days.

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Covell & Tummino LLP

(21) Appl. No.: **18/432,839**

(22) Filed: **Feb. 5, 2024**

(57) **ABSTRACT**

(65) **Prior Publication Data**

US 2025/0253547 A1 Aug. 7, 2025

An antenna element includes a first impedance structure, a
second impedance structure, and a polarization rotating
element. The first impedance structure includes a first dielec-
tric slab and a first conducting pattern layer mounted on the
first dielectric slab. The second impedance structure
includes a second dielectric slab and a second conducting
pattern layer mounted on the second dielectric slab. The
polarization rotating element includes a third dielectric slab,
a third conducting pattern layer, a first switch, a fourth
conducting pattern layer, and a second switch. The third
conducting pattern layer is mounted between the third
dielectric slab and the first dielectric slab and forms a first
dipole dependent on a position of the first switch. The fourth
conducting pattern layer is mounted between the third
dielectric slab and the second dielectric slab and forms a
second dipole dependent on a position of the second switch.

(51) **Int. Cl.**
H01Q 21/24 (2006.01)
H01Q 1/38 (2006.01)

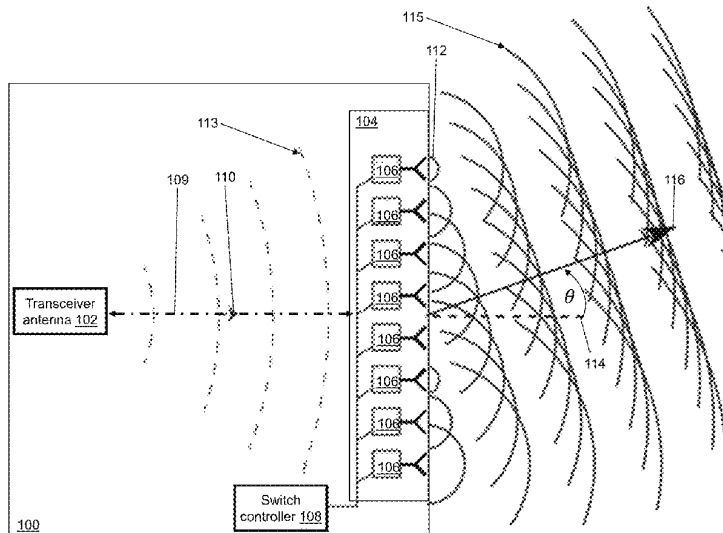
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(52) **U.S. Cl.**
CPC **H01Q 21/24** (2013.01); **H01Q 1/38**
(2013.01); **H01Q 9/0407** (2013.01); **H01Q**
21/065 (2013.01)

(58) **Field of Classification Search**
CPC H01Q 21/24; H01Q 1/38; H01Q 9/0407;
H01Q 21/065

See application file for complete search history.

20 Claims, 63 Drawing Sheets



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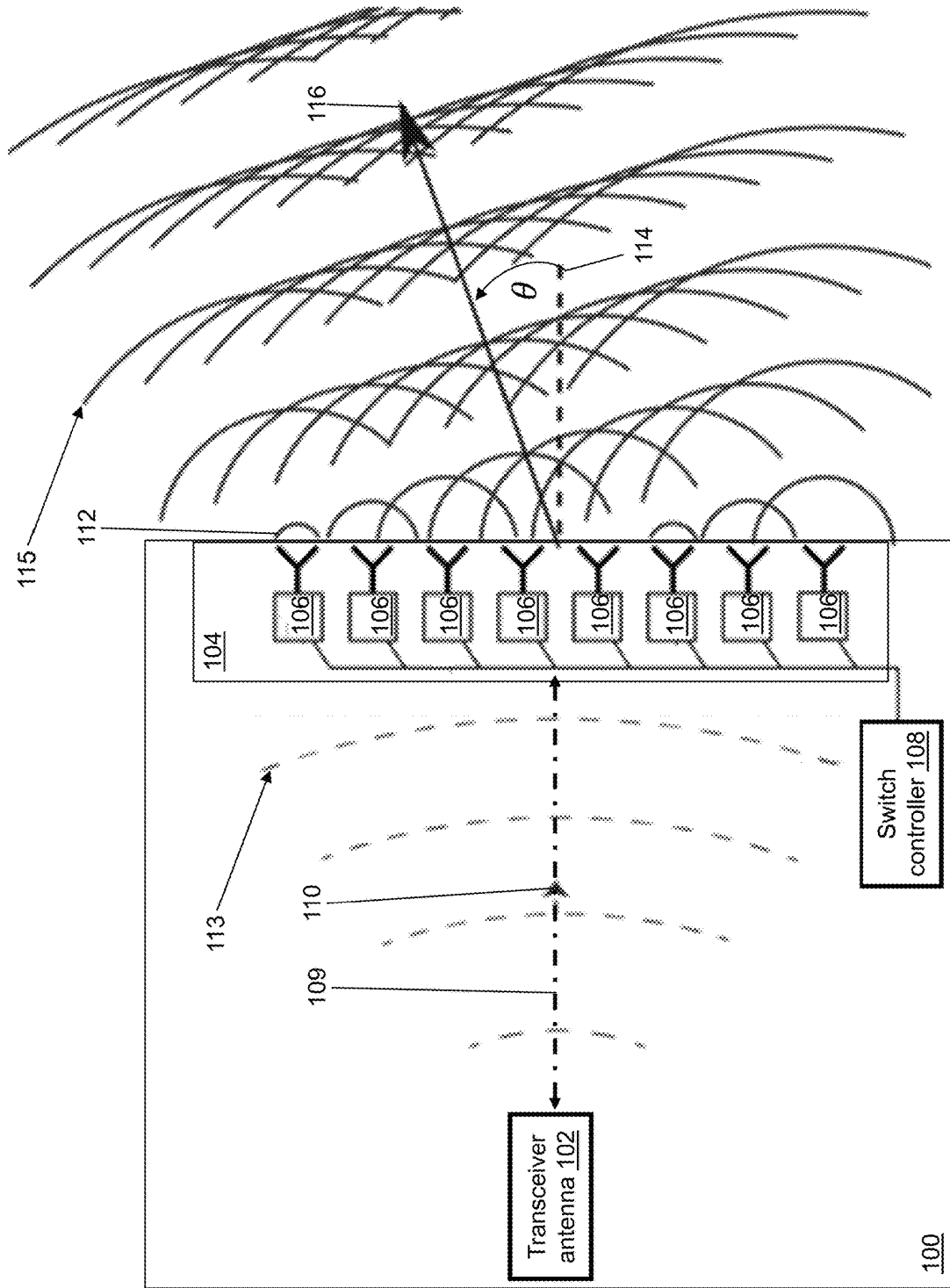


FIG. 1

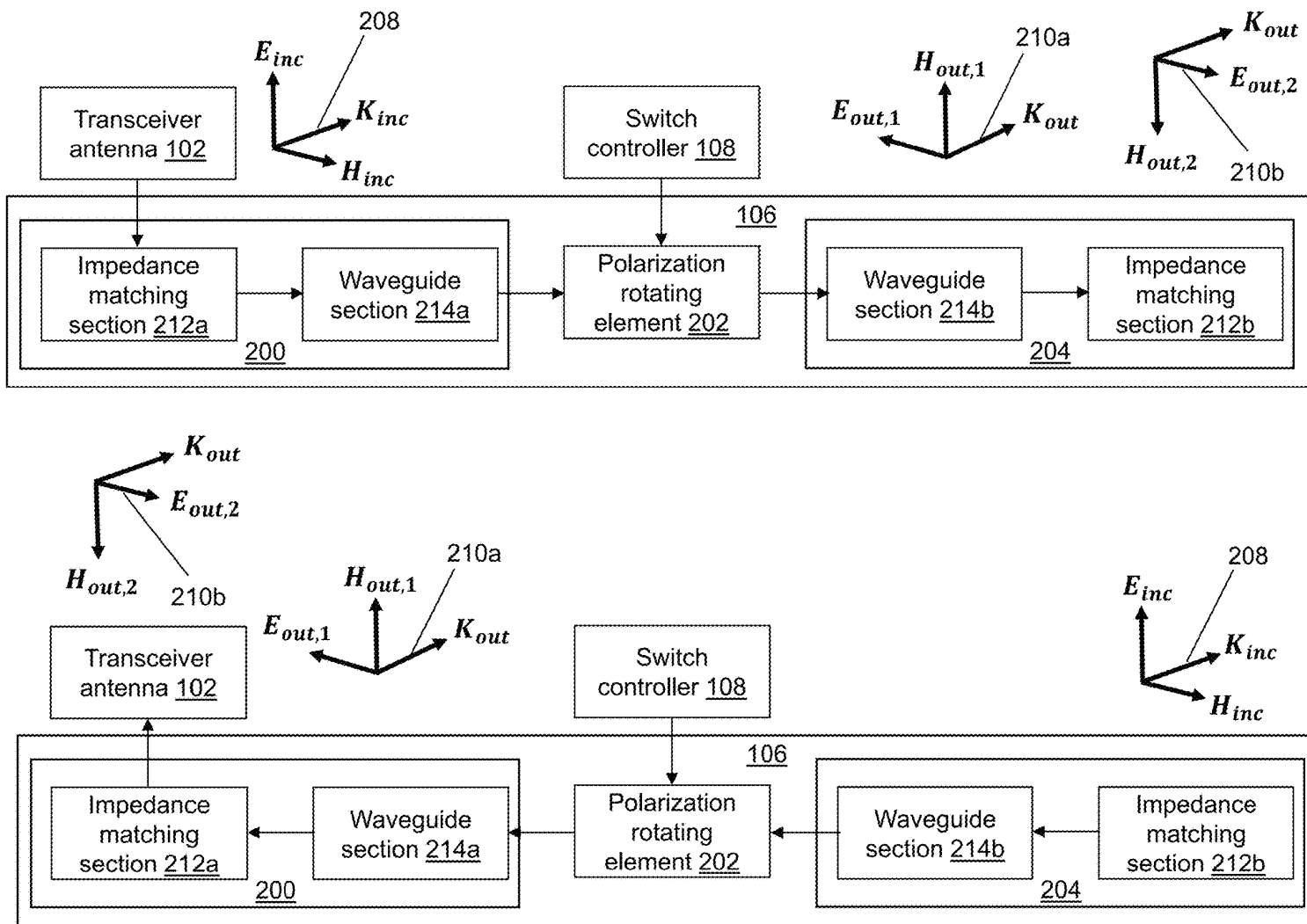


FIG. 2

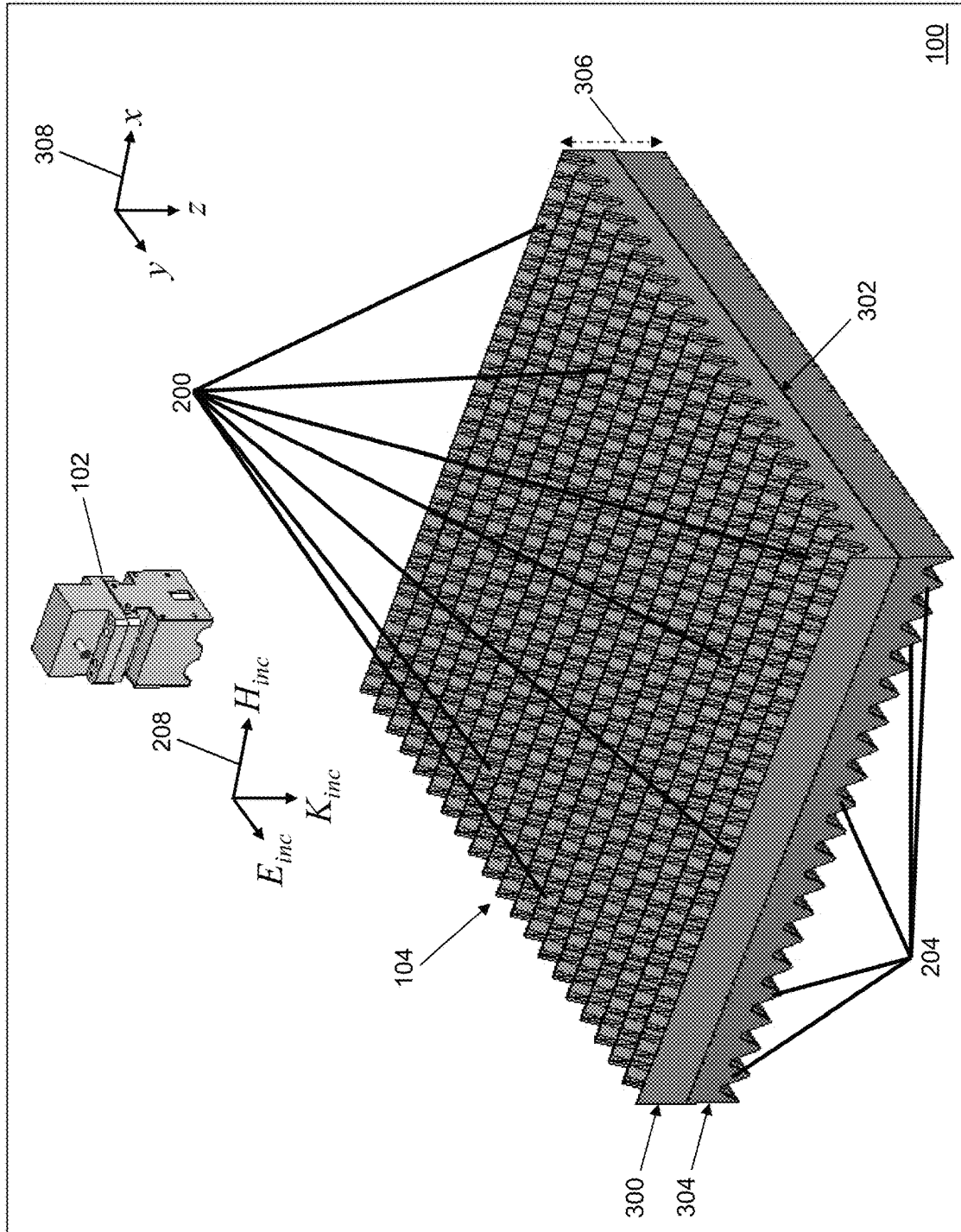
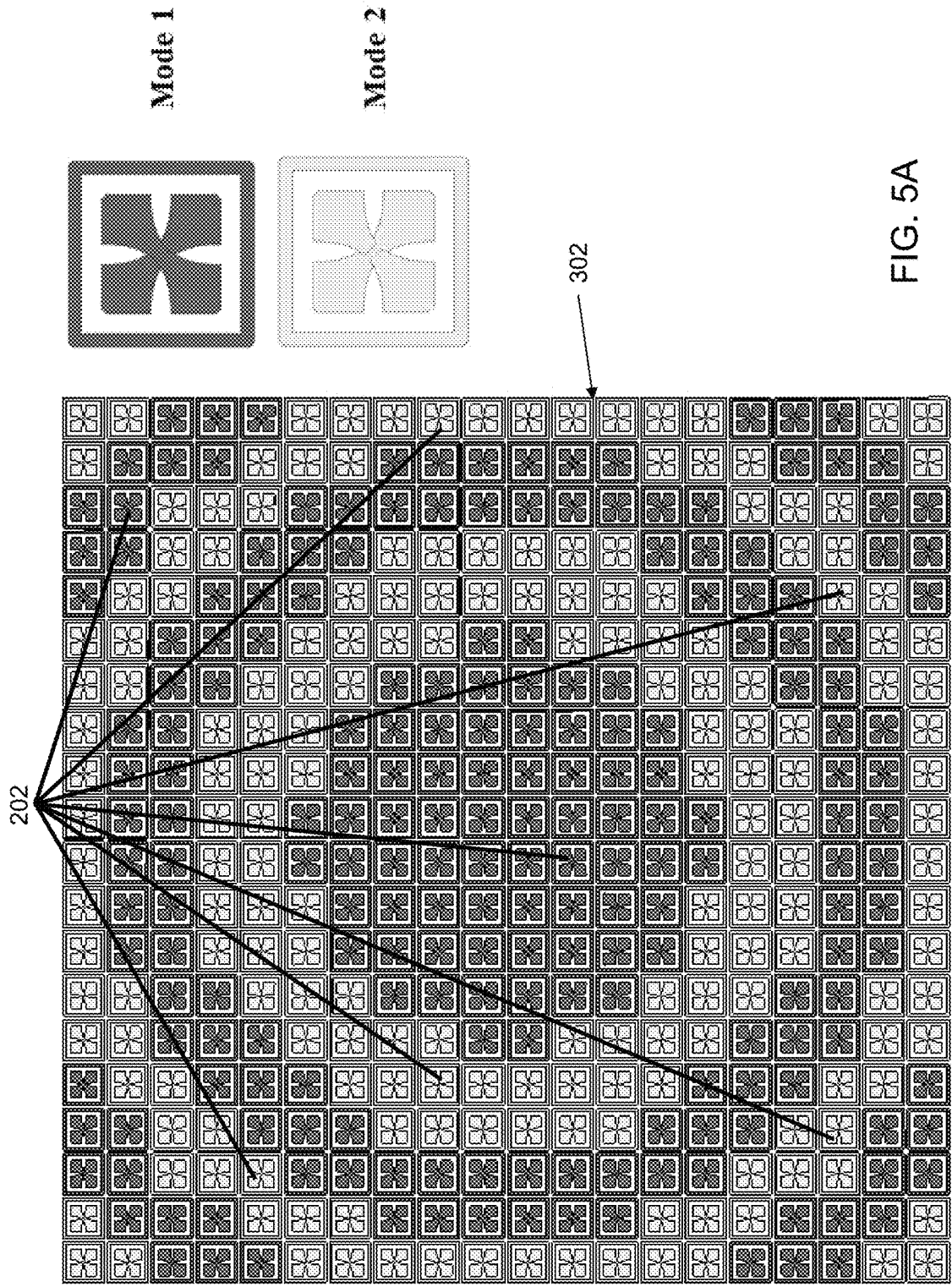


FIG. 3



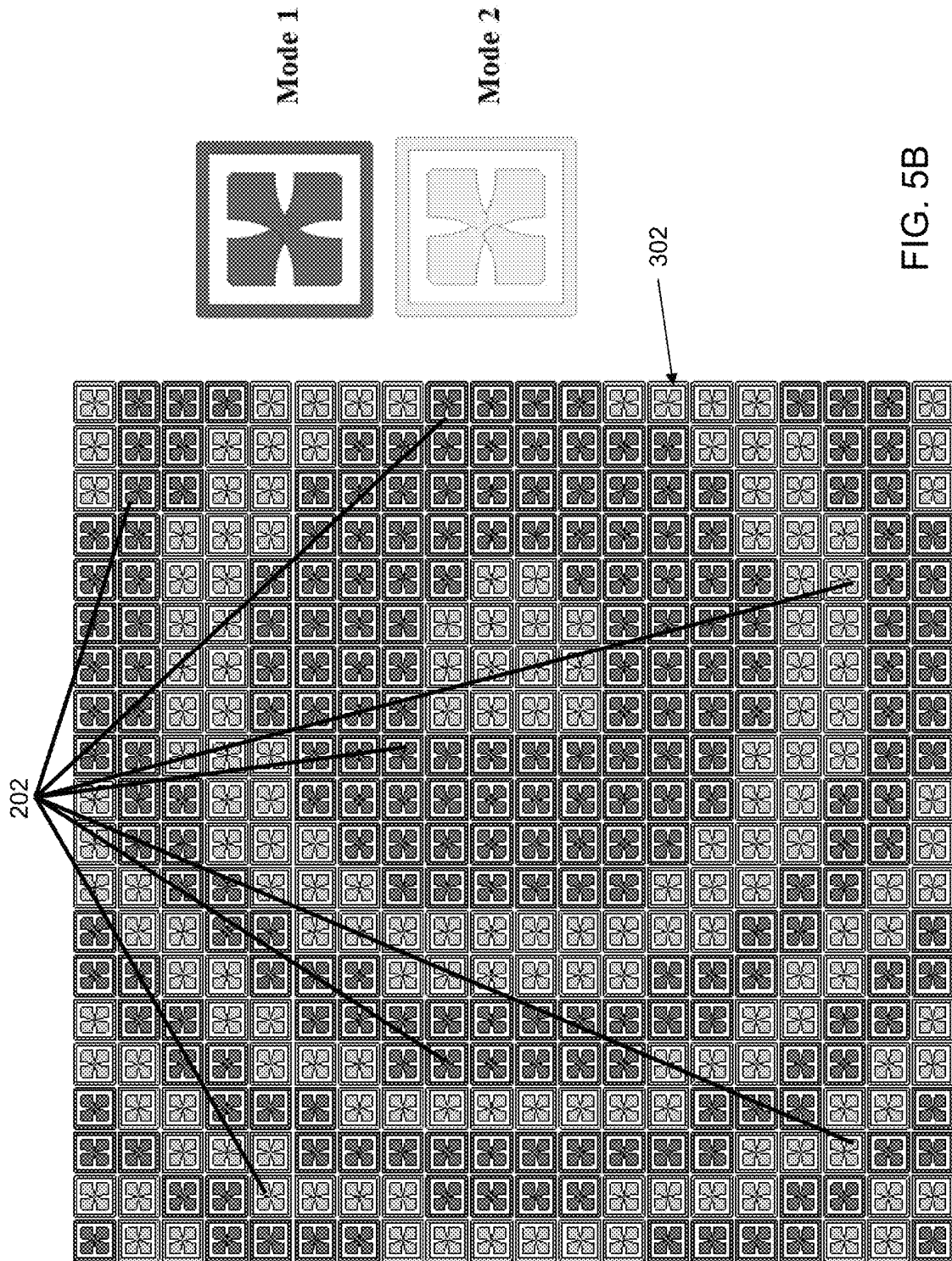


FIG. 5B

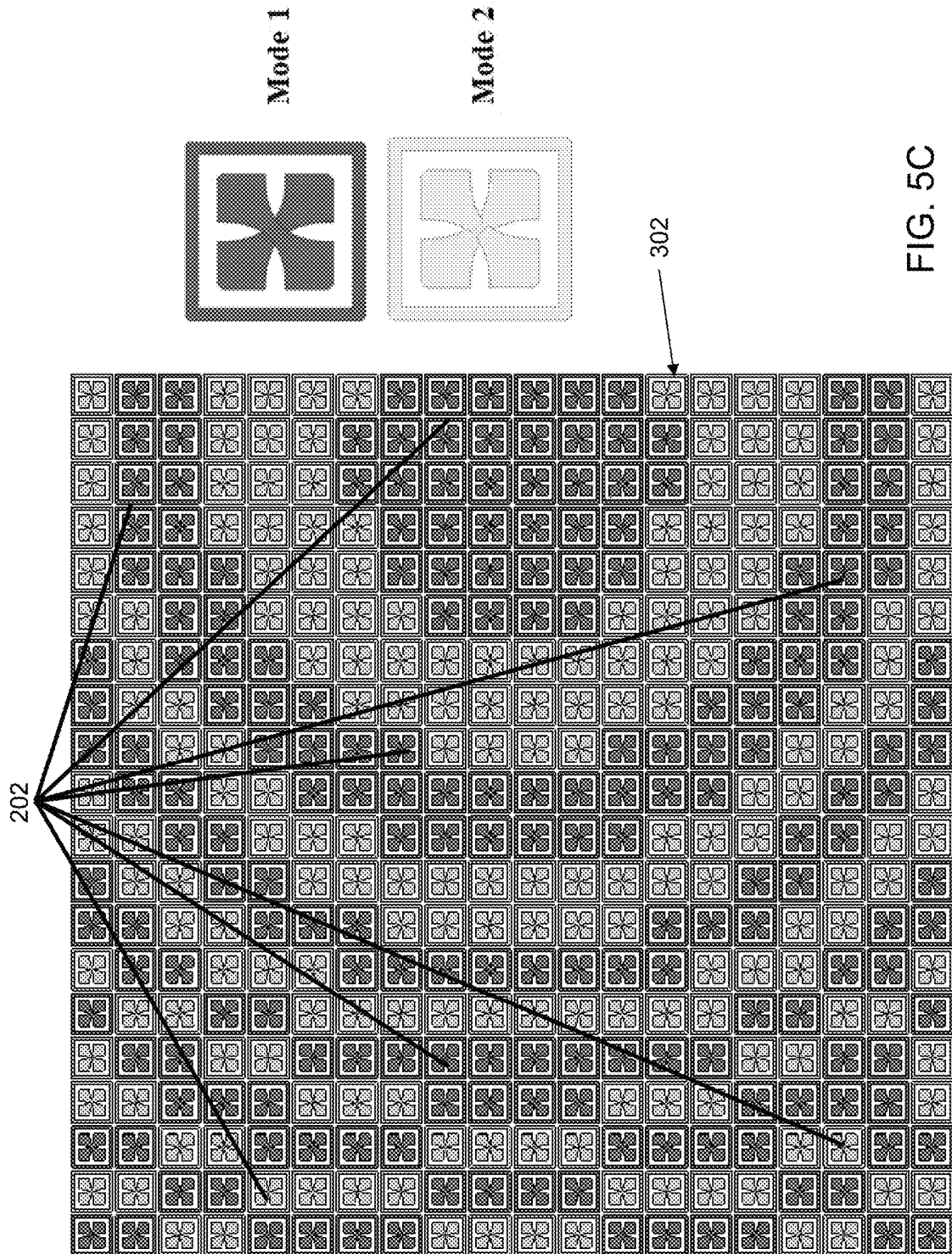


FIG. 5C

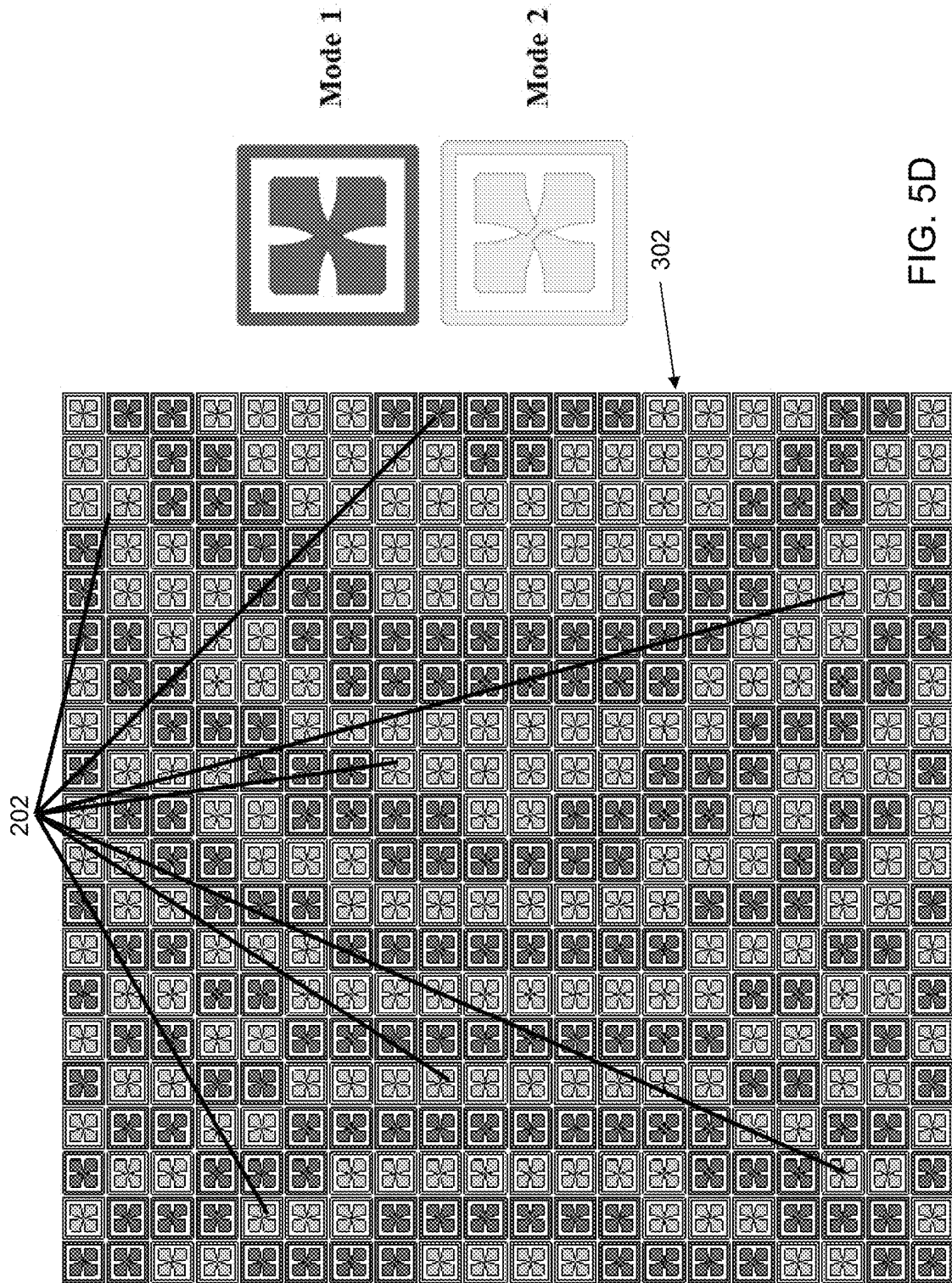


FIG. 5D

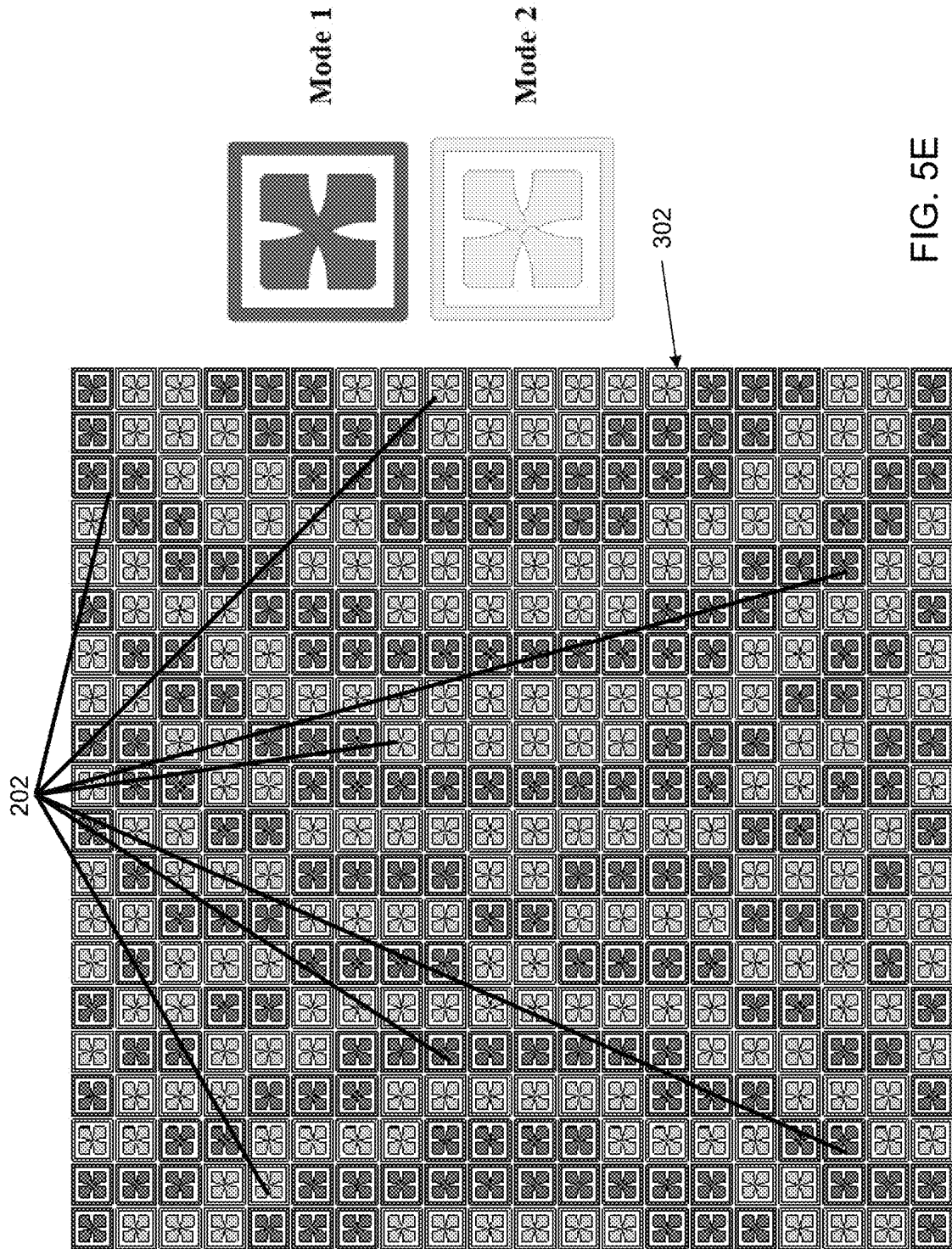


FIG. 5E

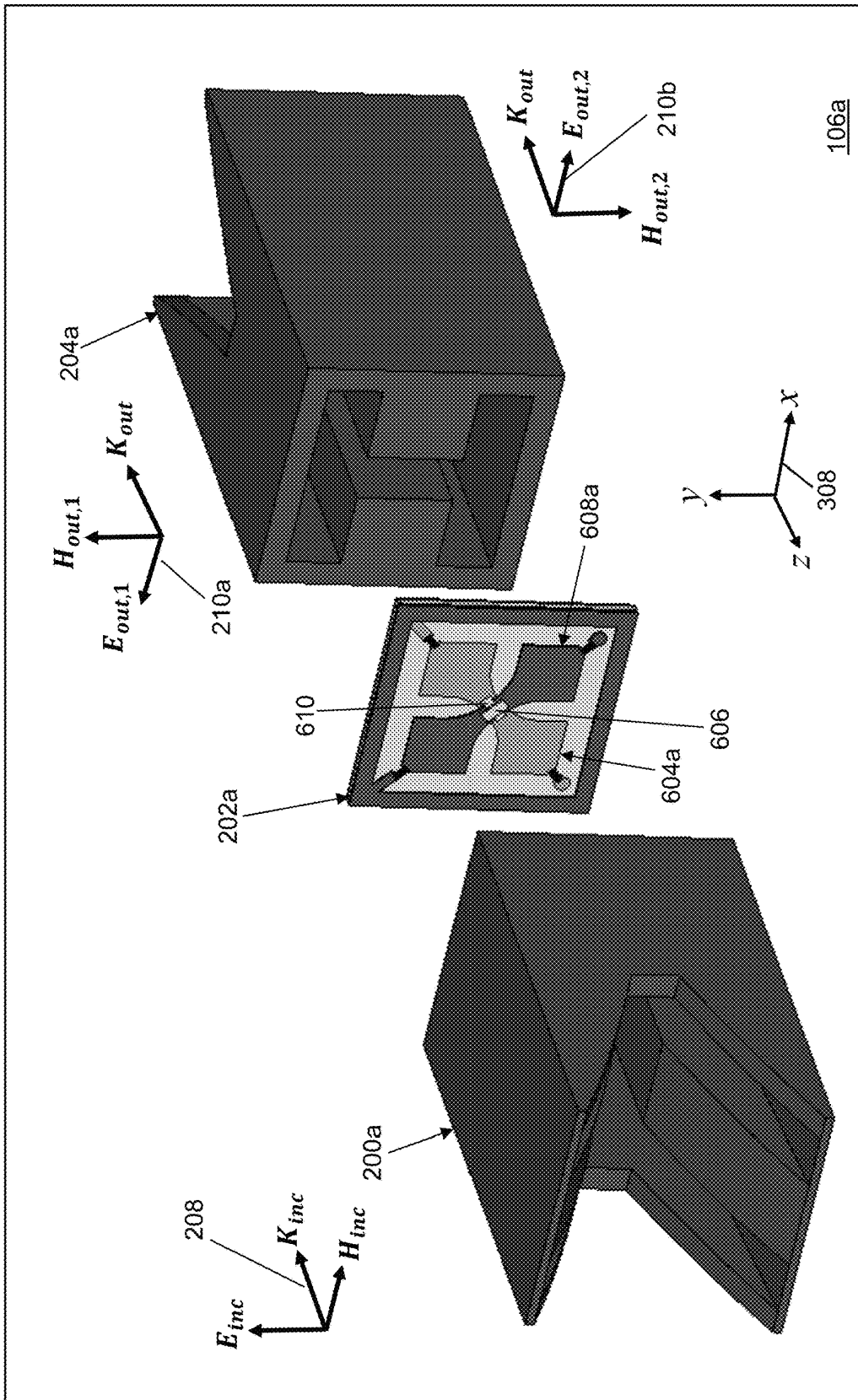
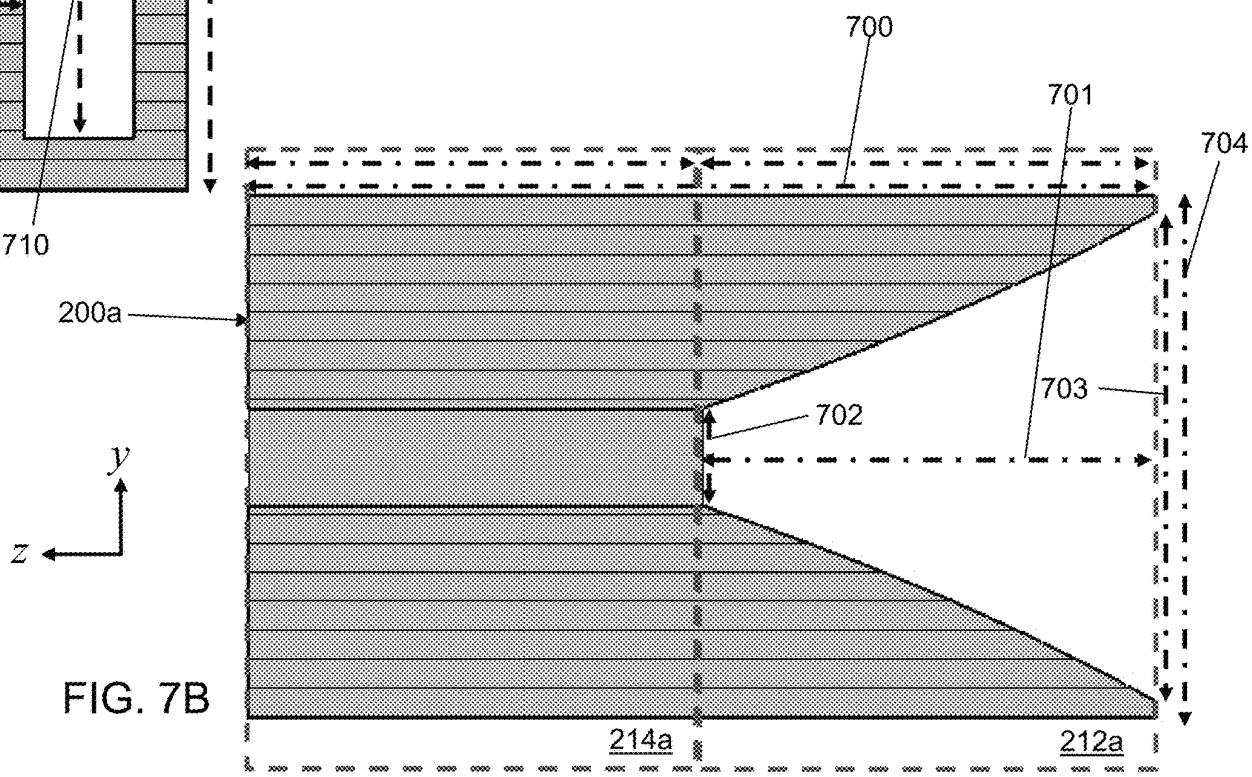
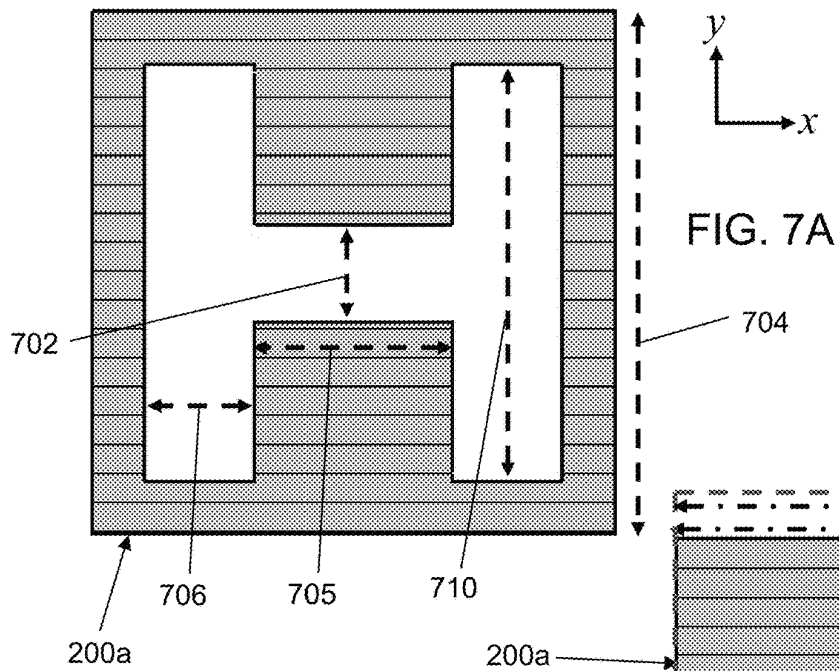
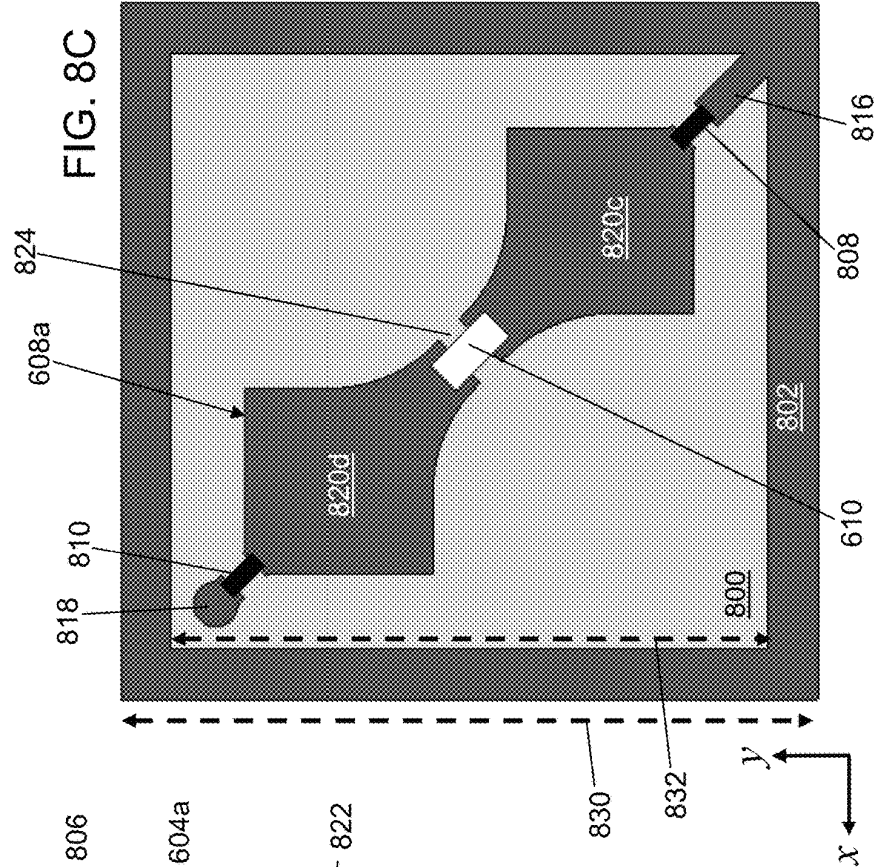
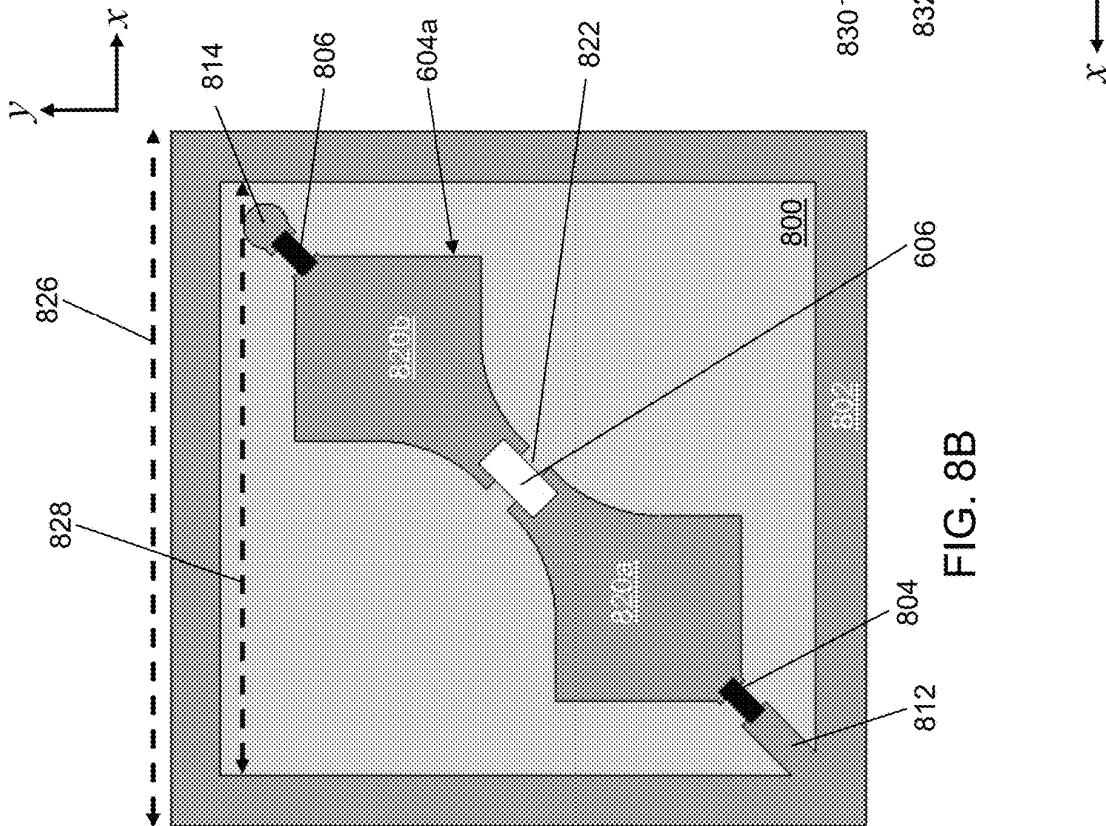


FIG. 6





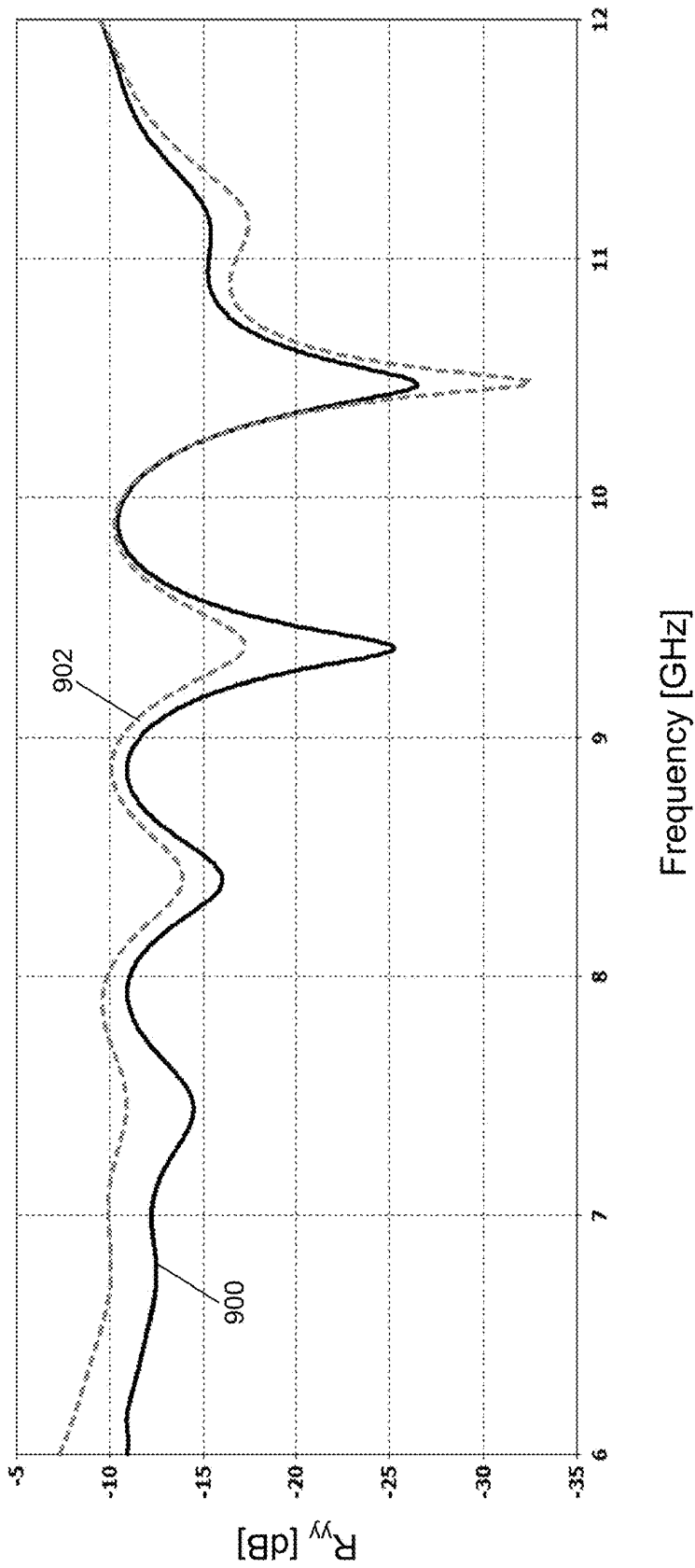


FIG. 9A

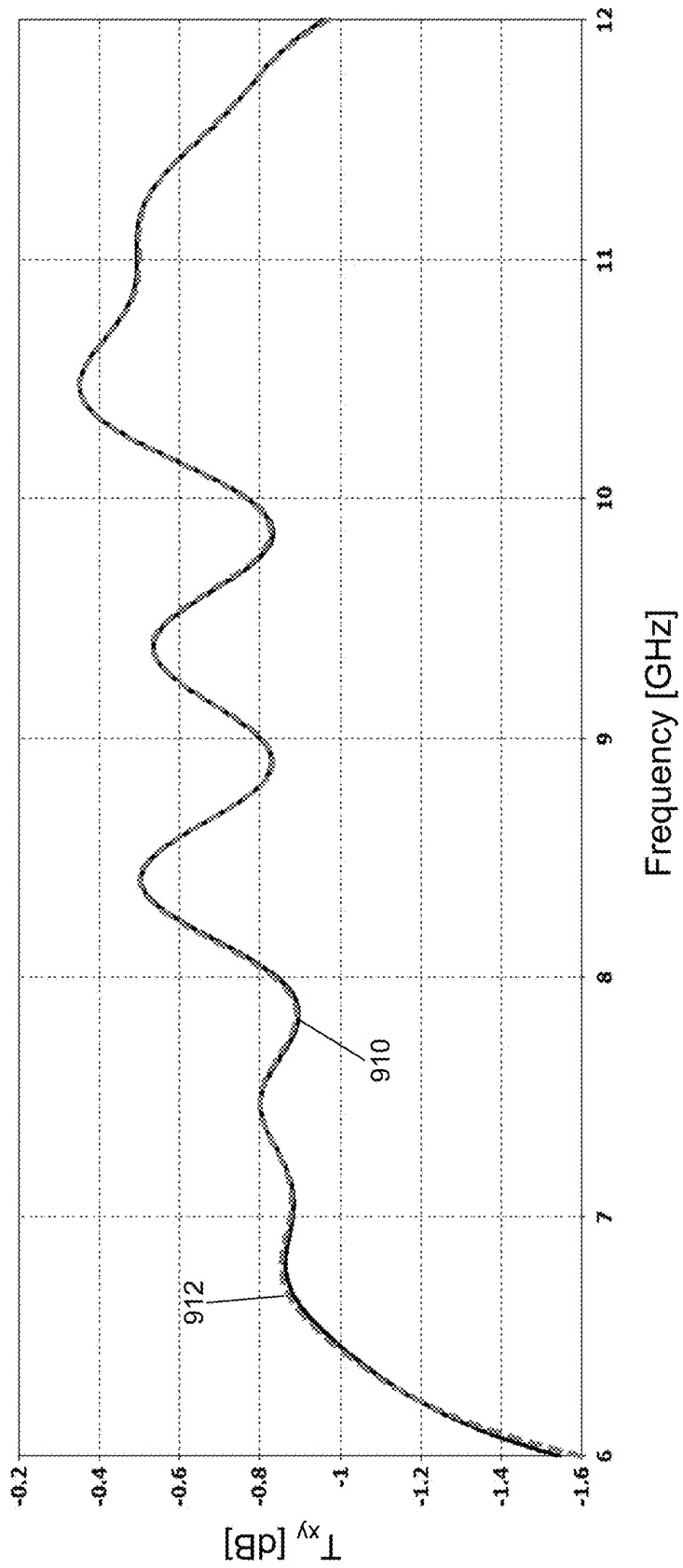


FIG. 9B

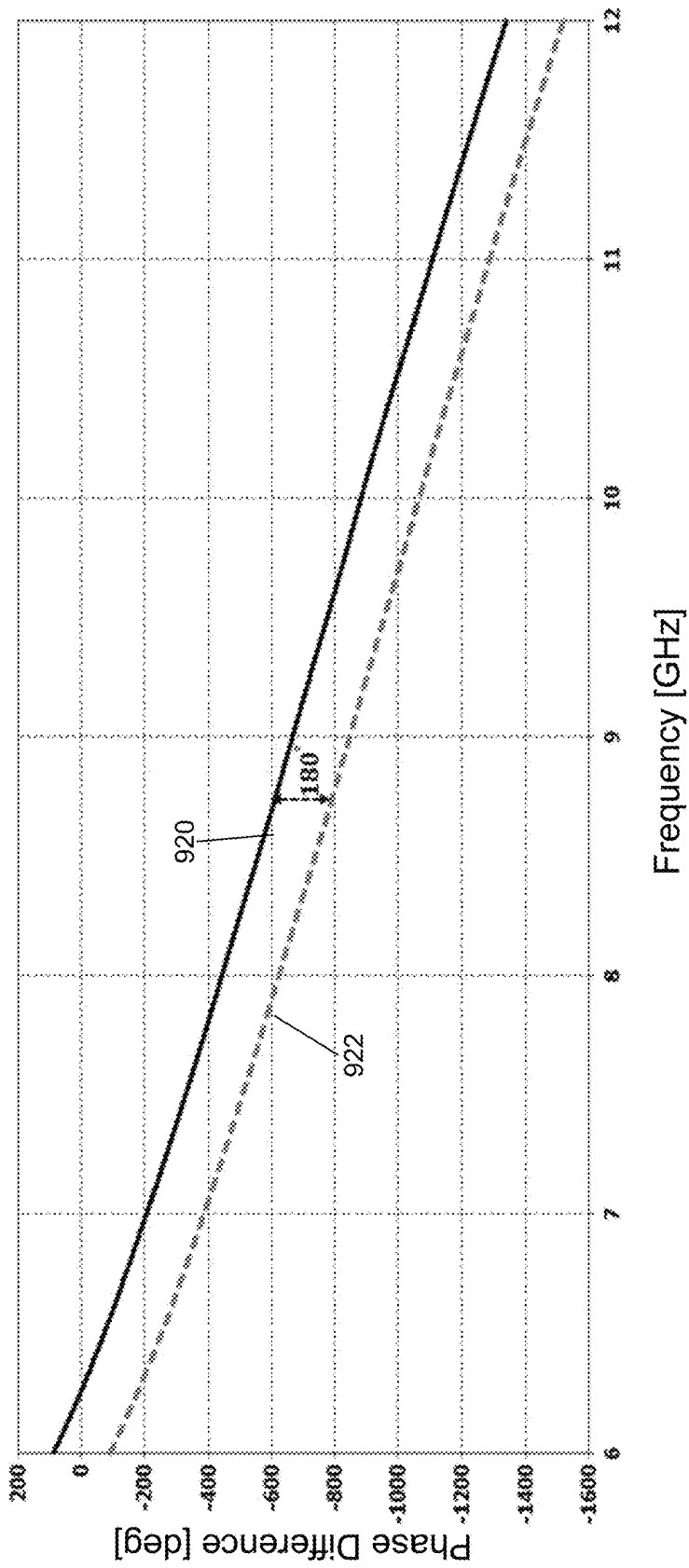


FIG. 9C

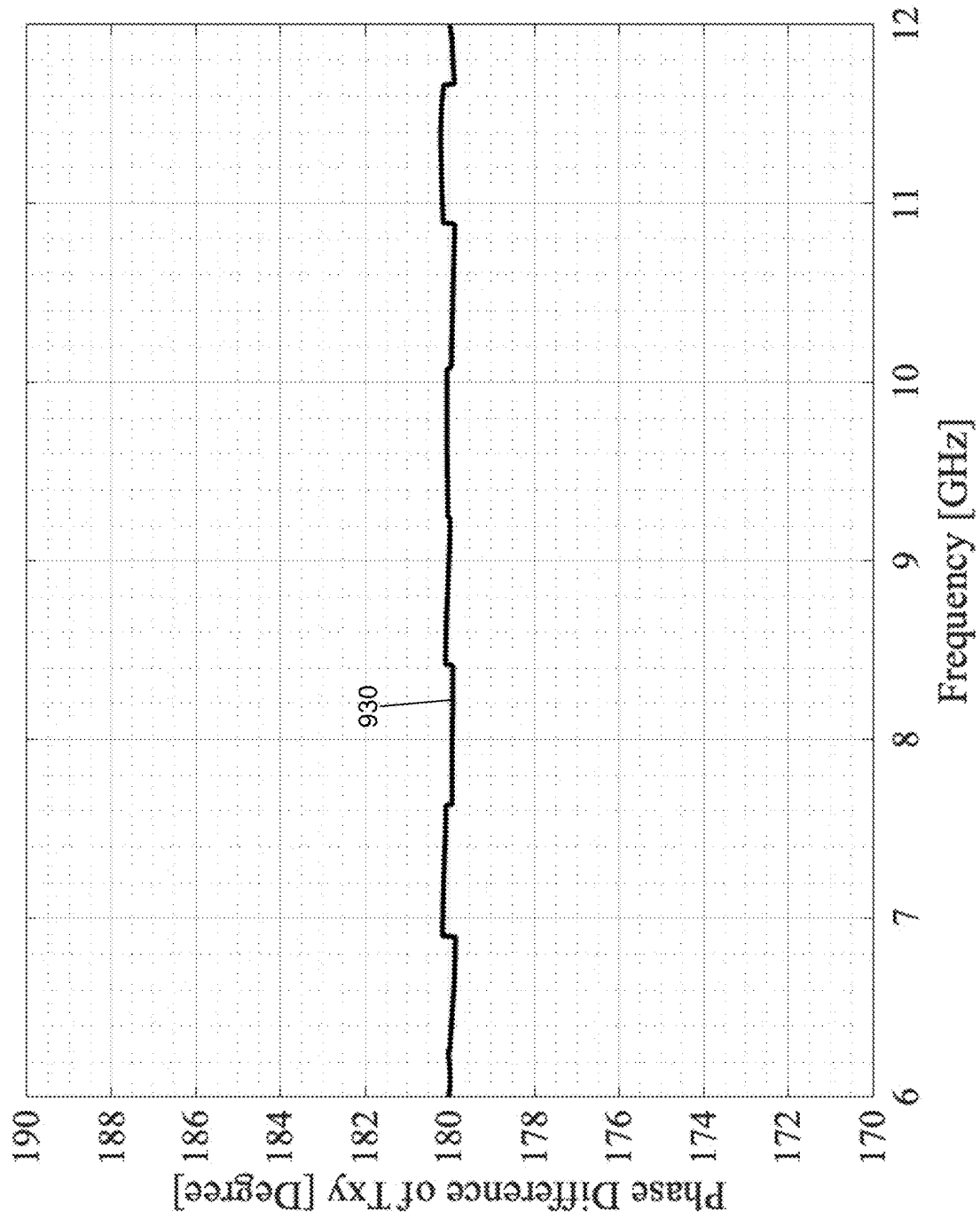


FIG. 9D

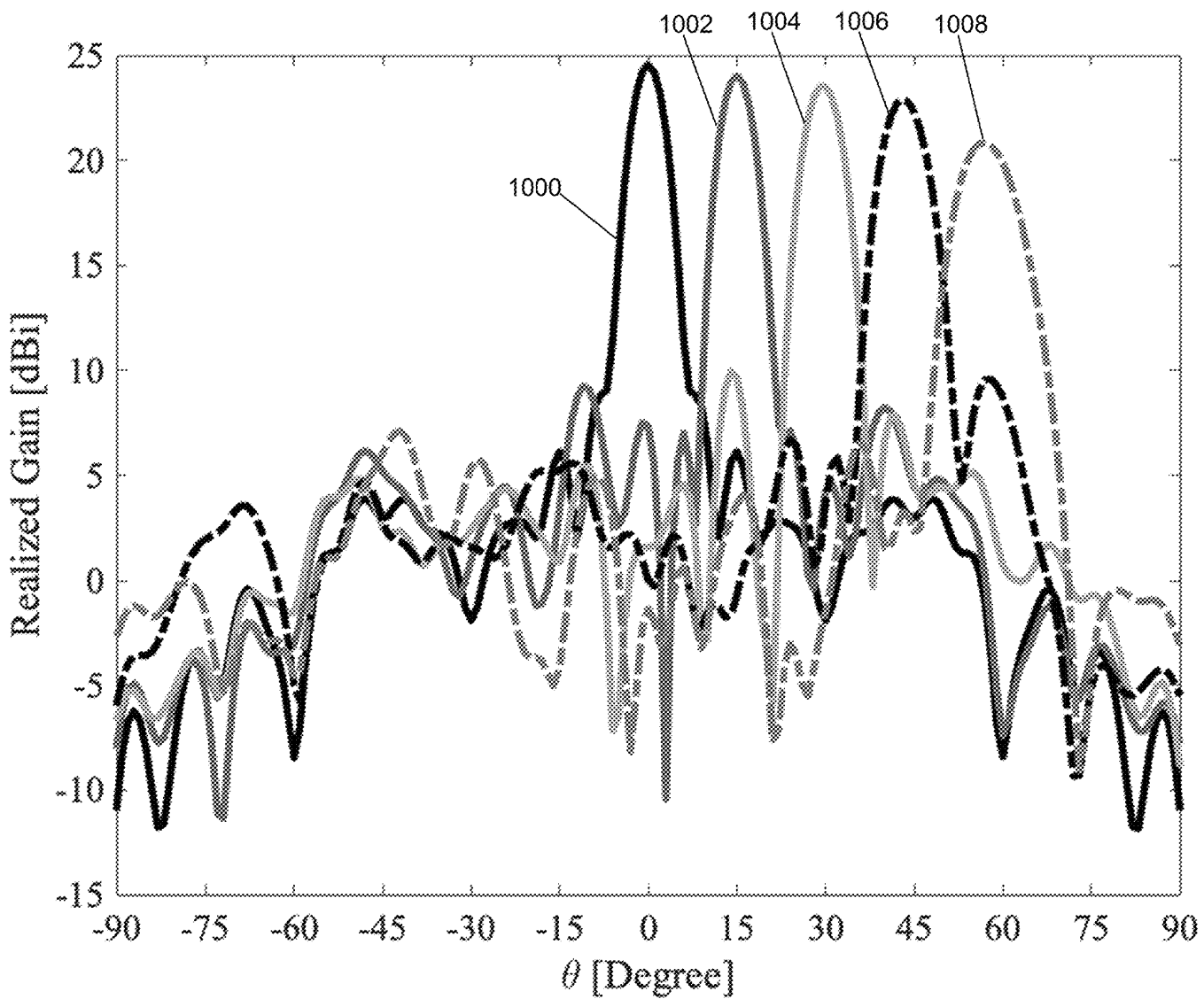


FIG. 10

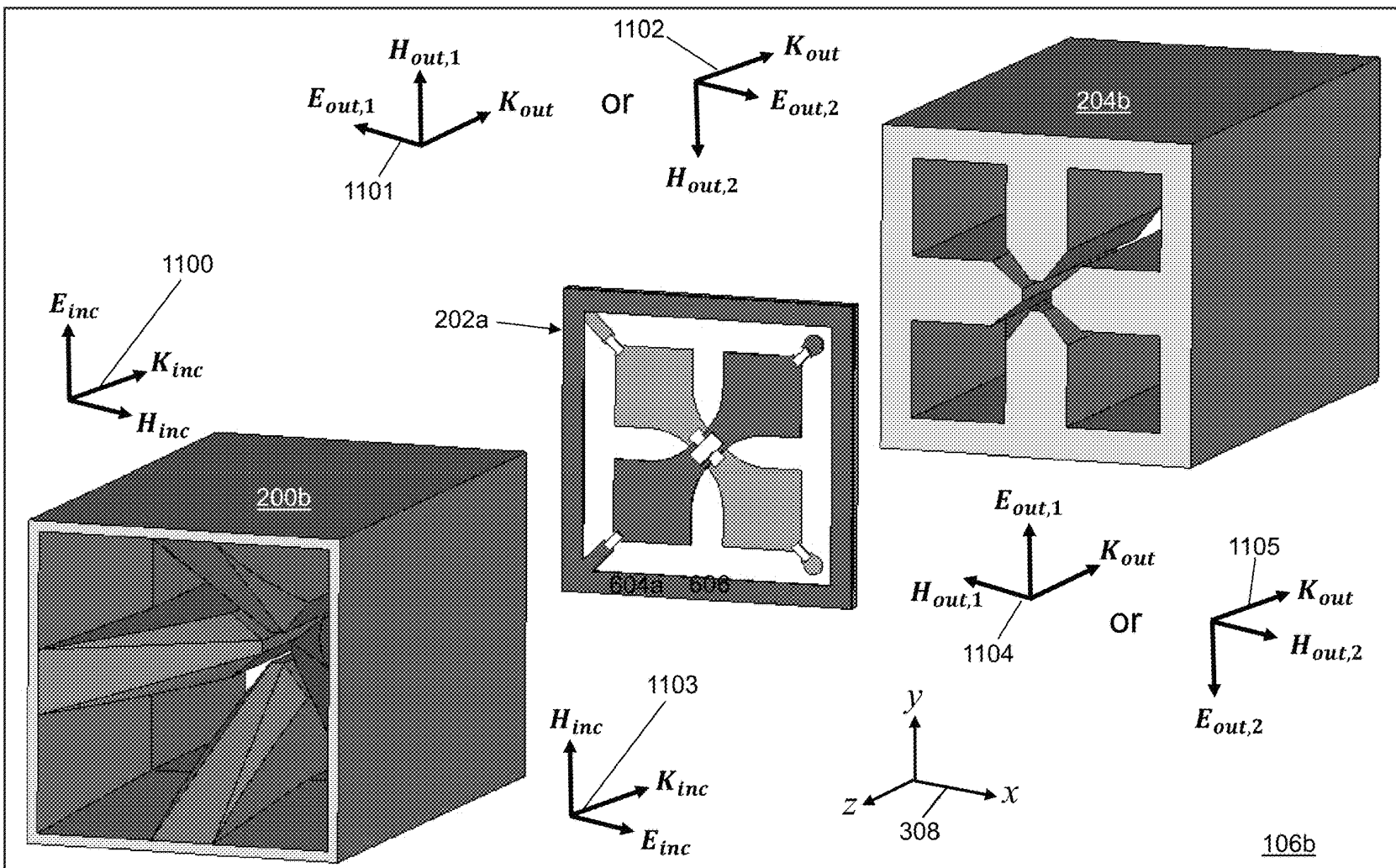


FIG. 11A

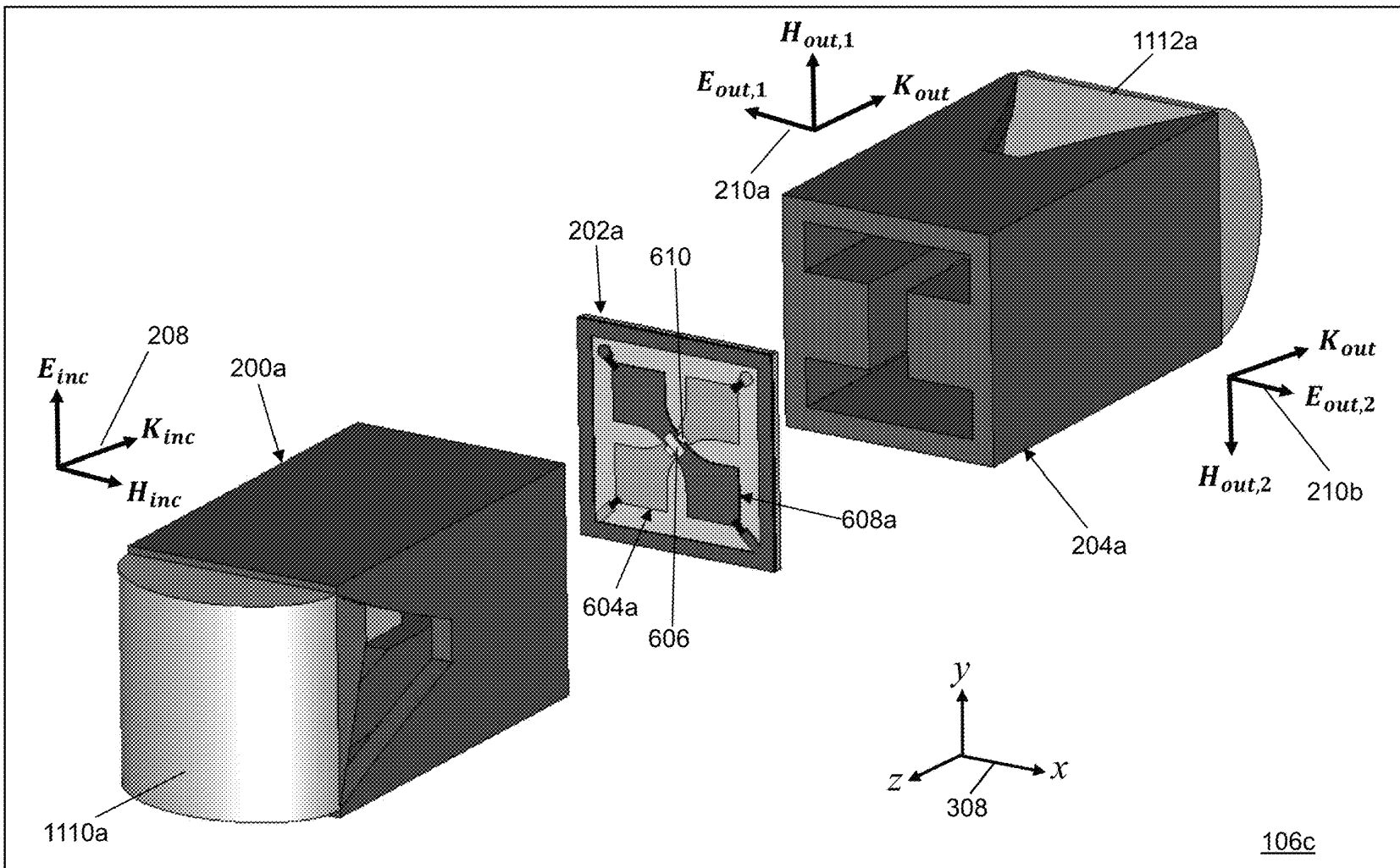
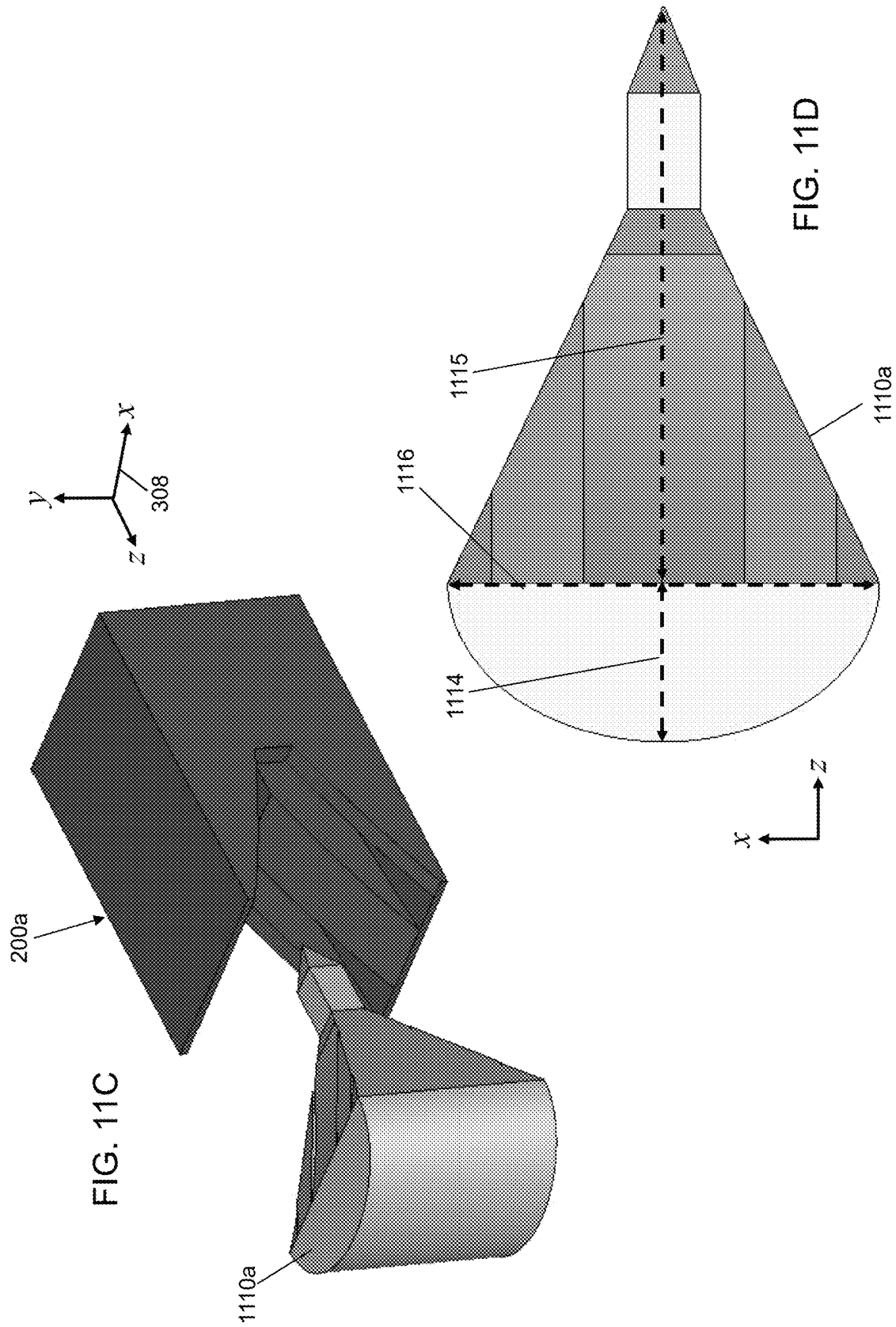


FIG. 11B



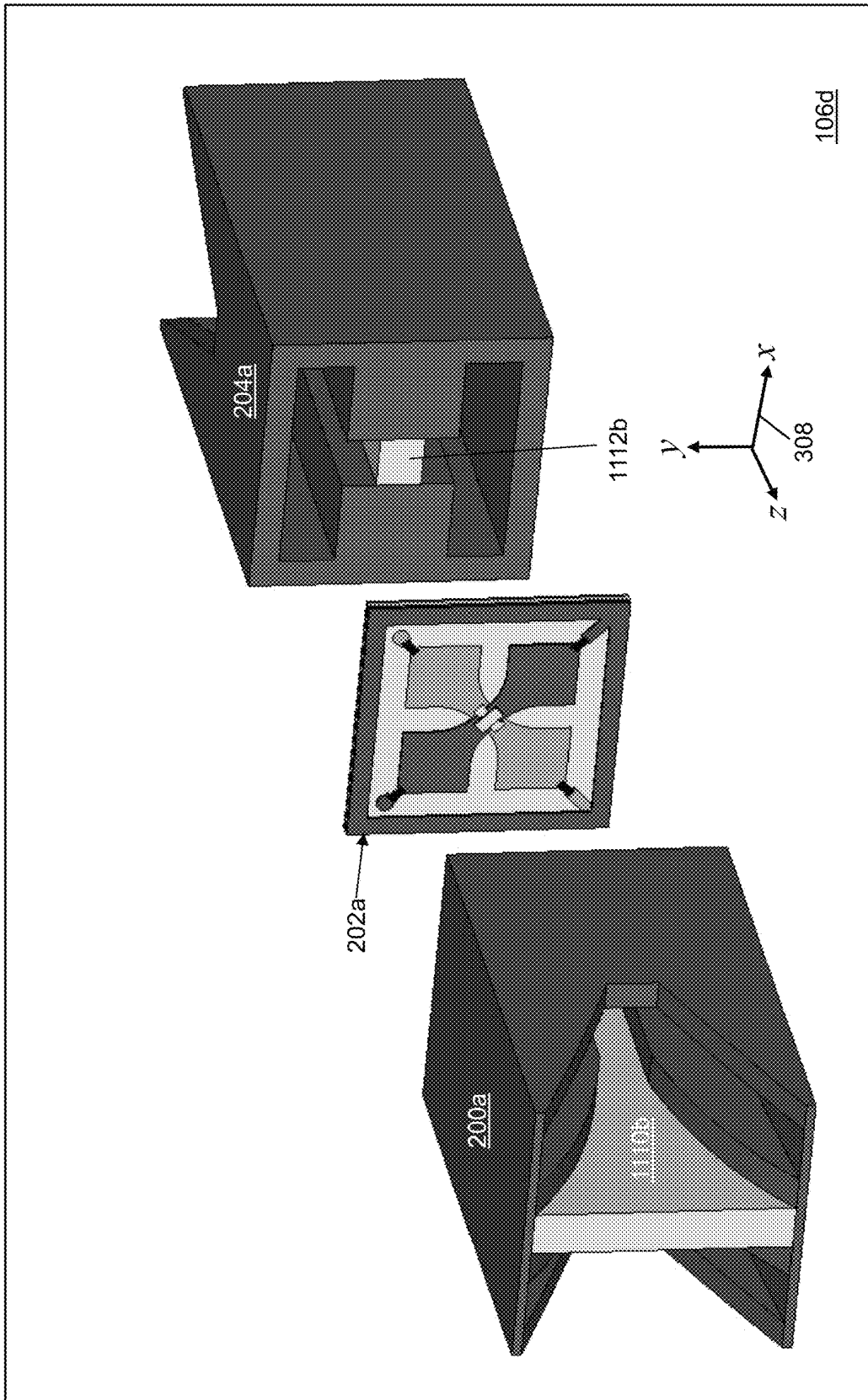


FIG. 11E

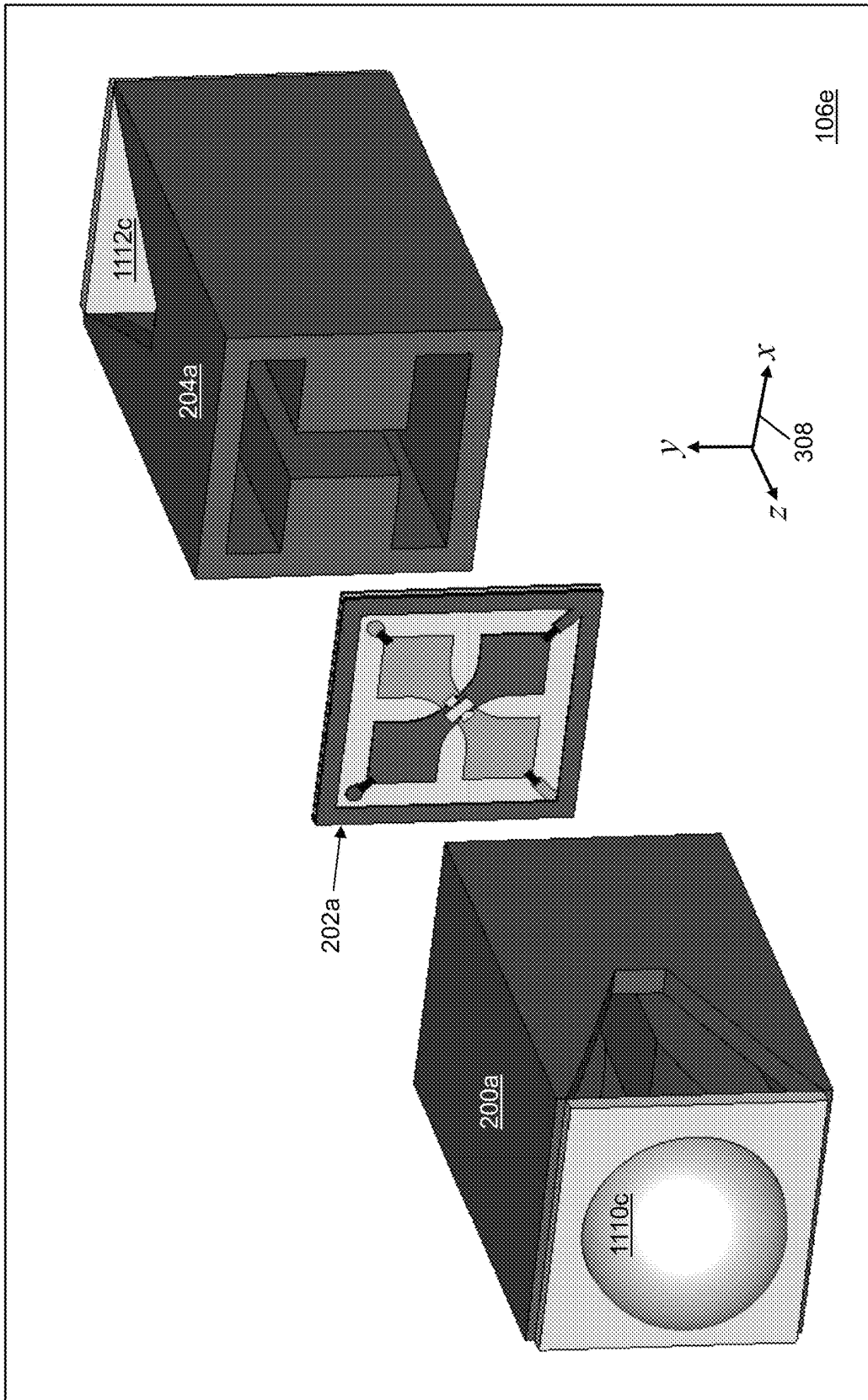


FIG. 11F

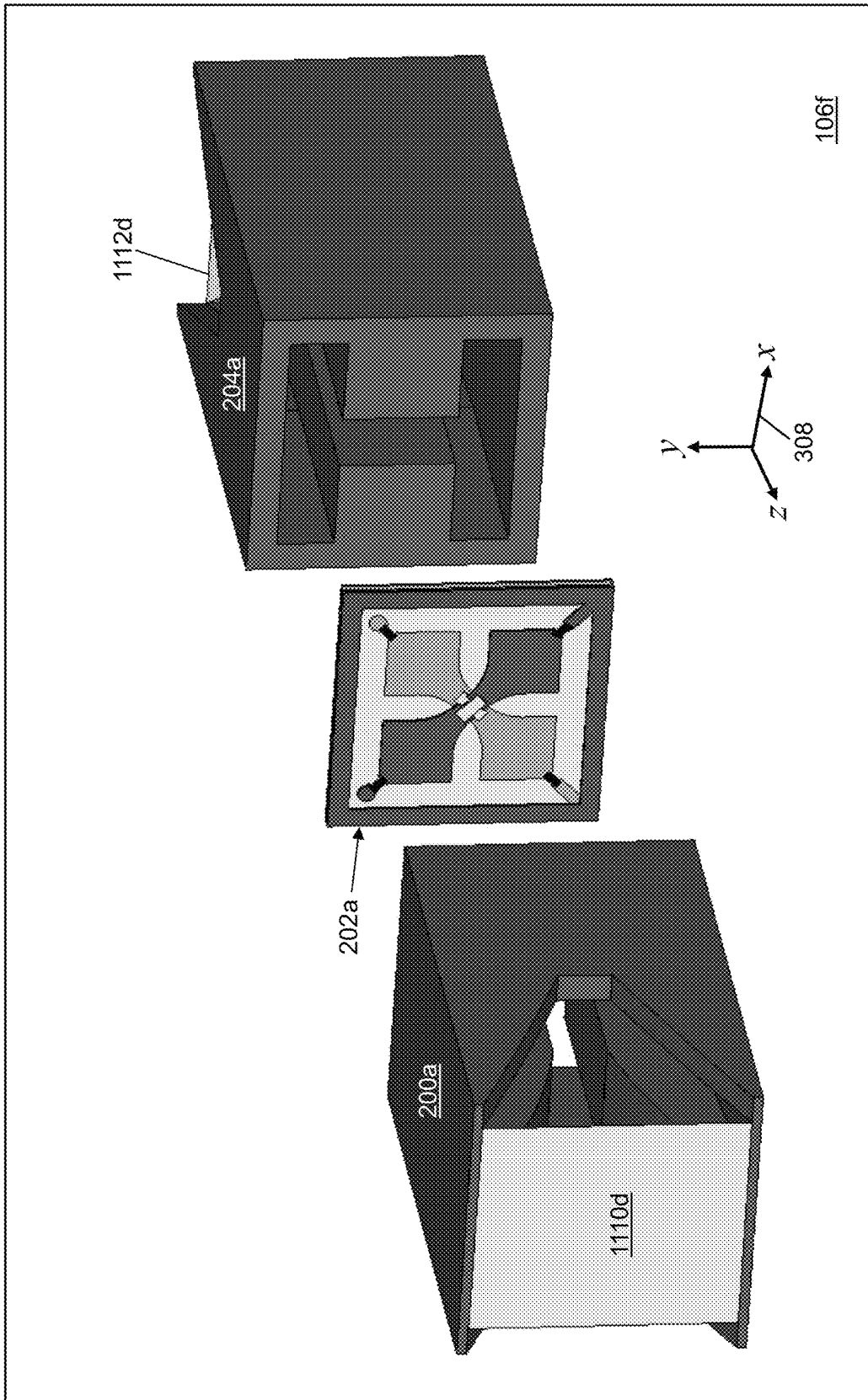


FIG. 11G

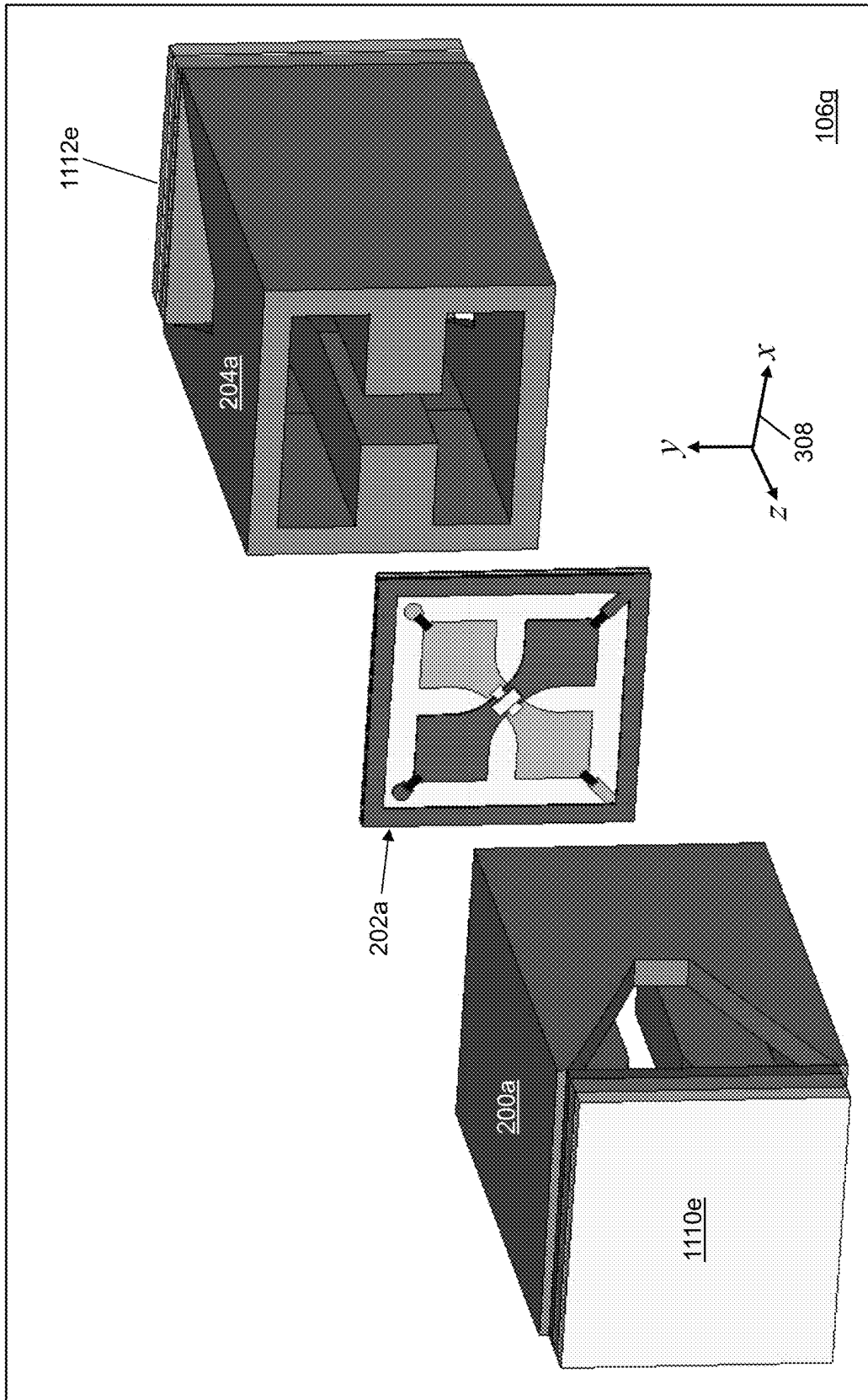


FIG. 11H

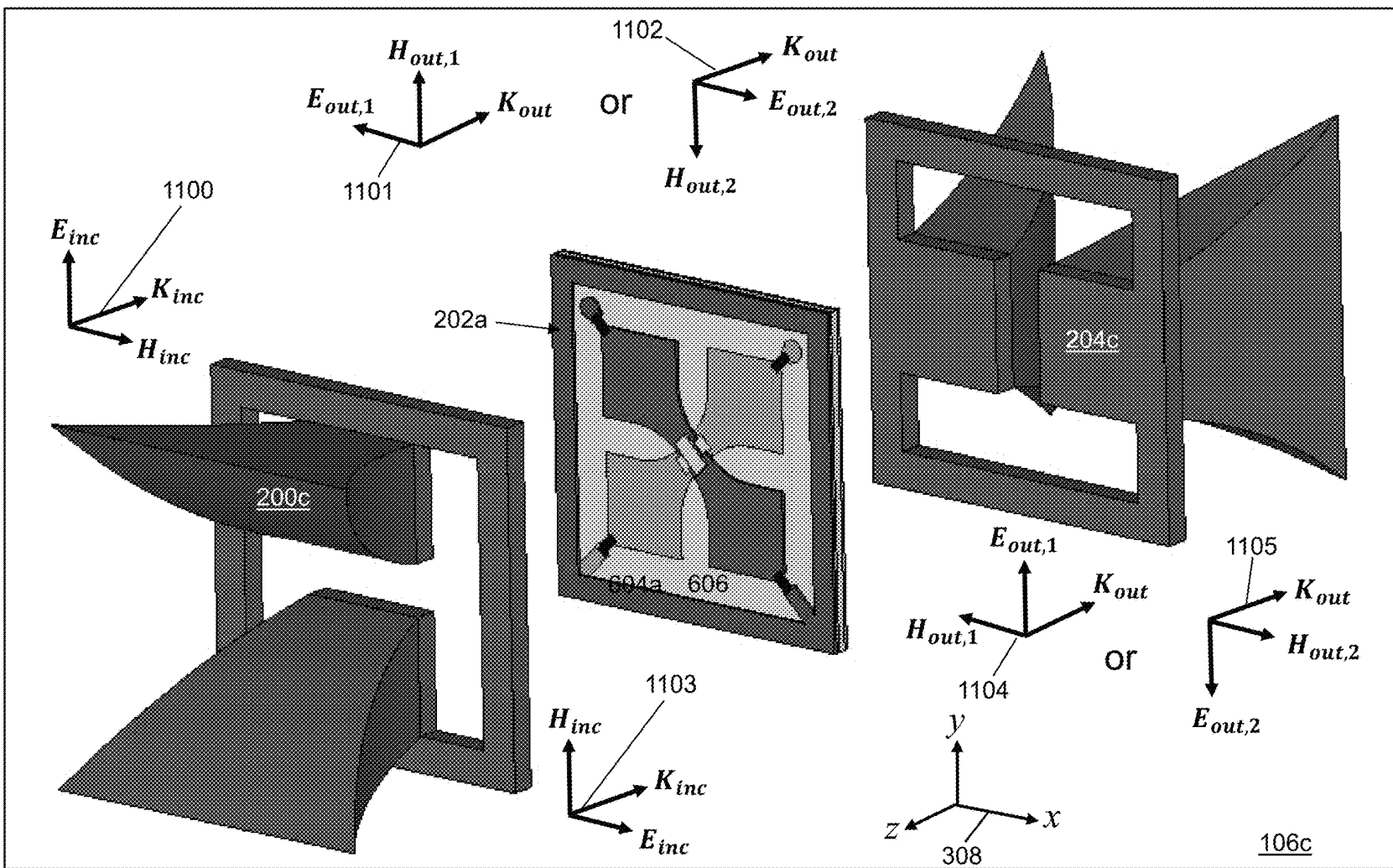
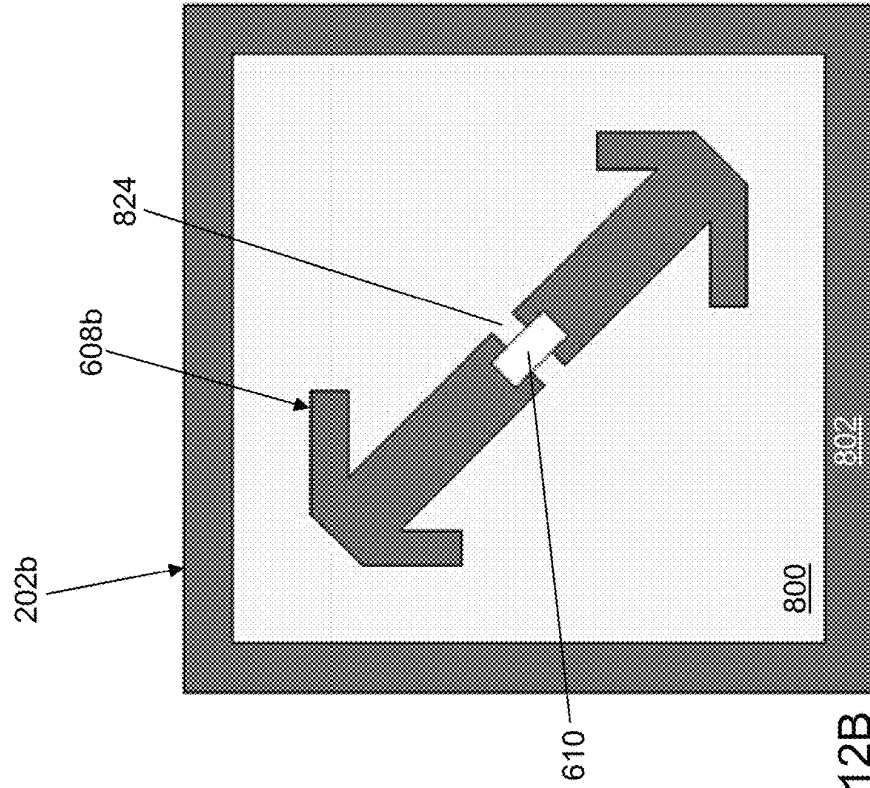
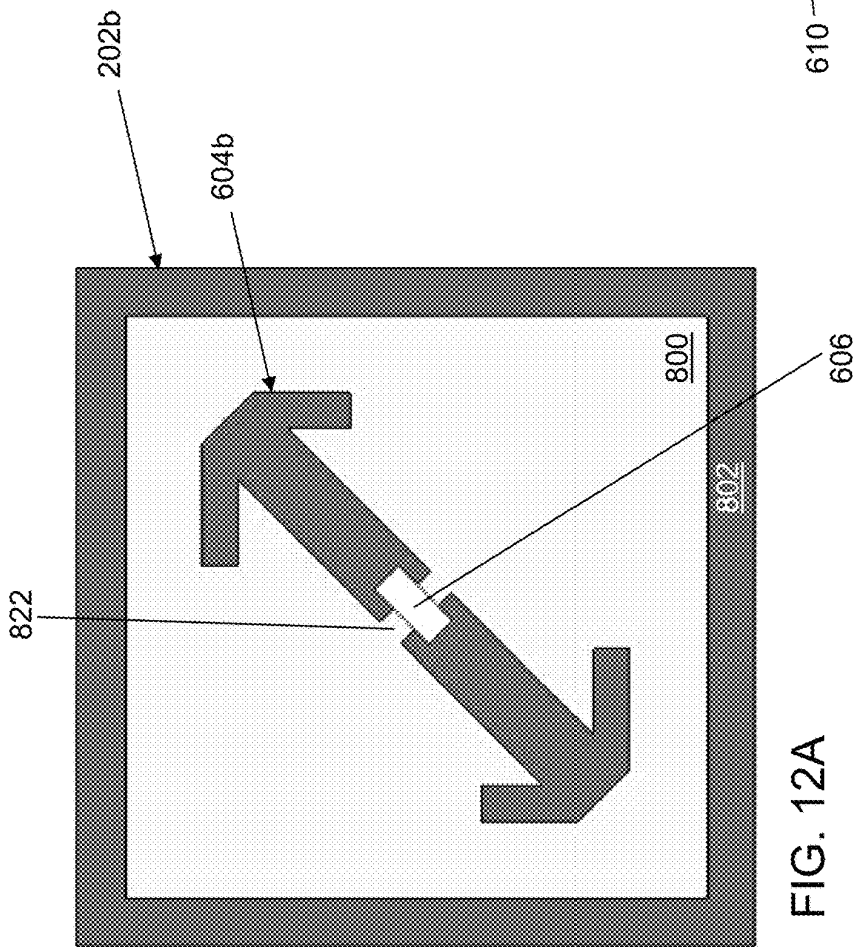


FIG. 11I



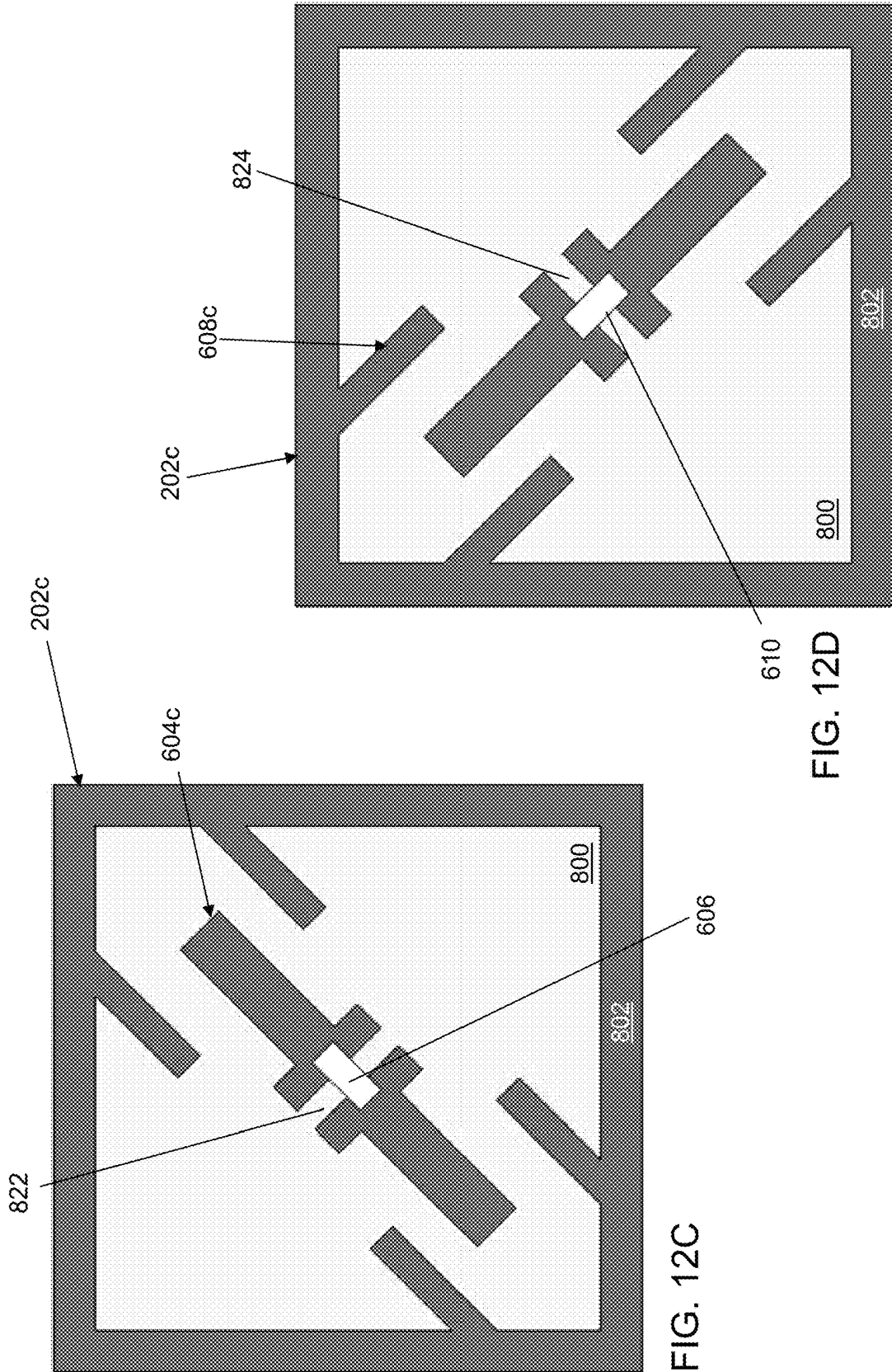


FIG. 12C

FIG. 12D

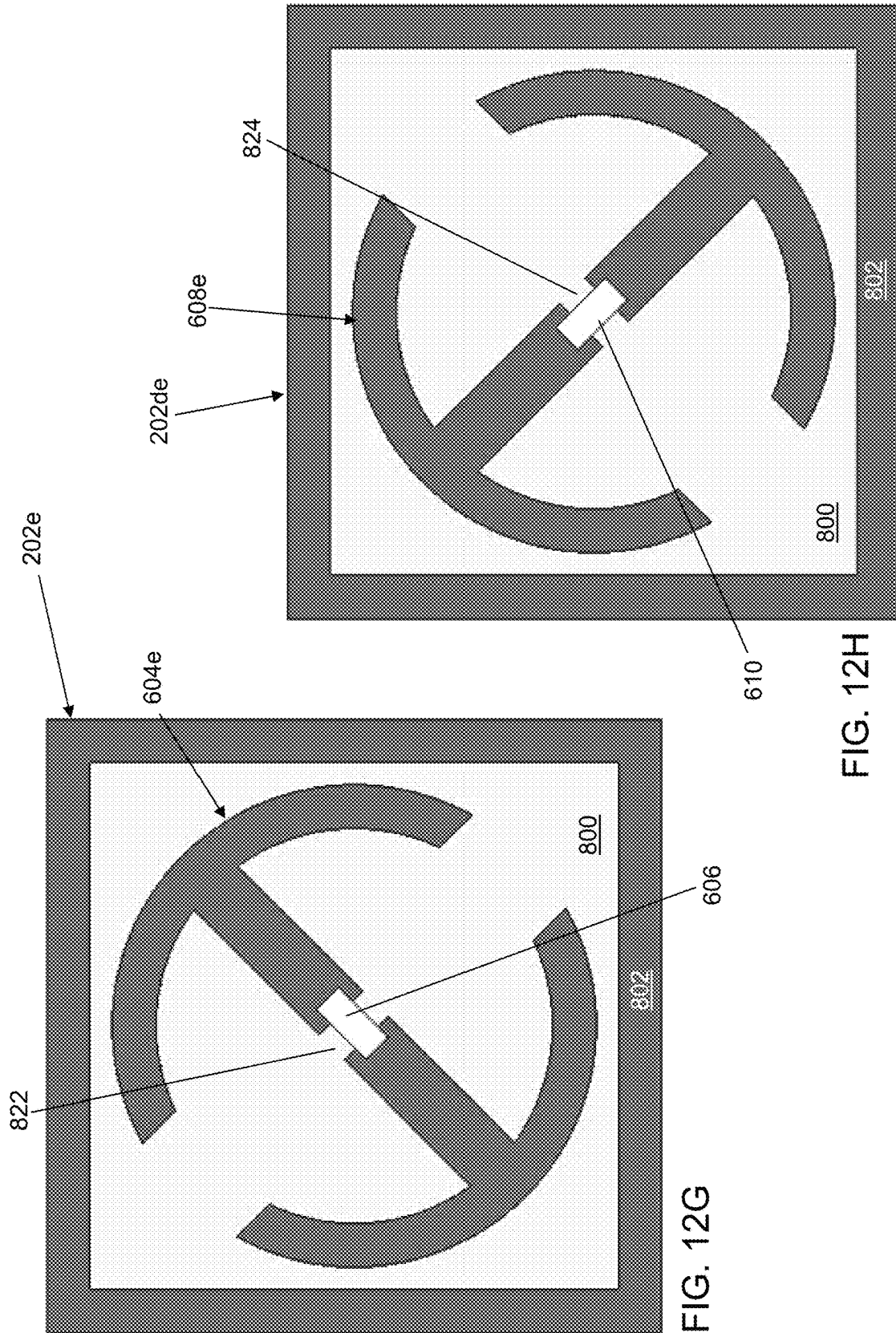


FIG. 12G

FIG. 12H

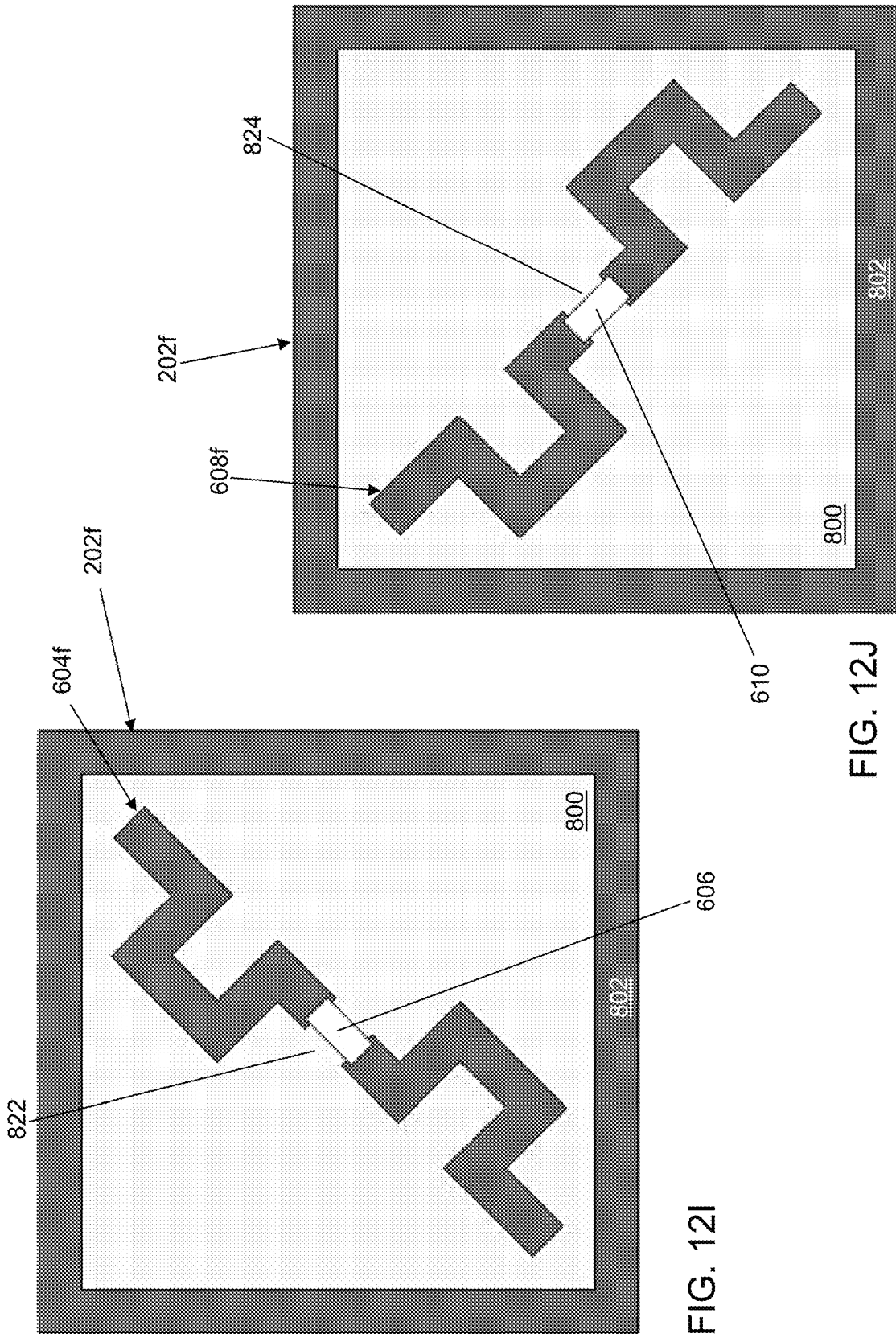


FIG. 12I

FIG. 12J

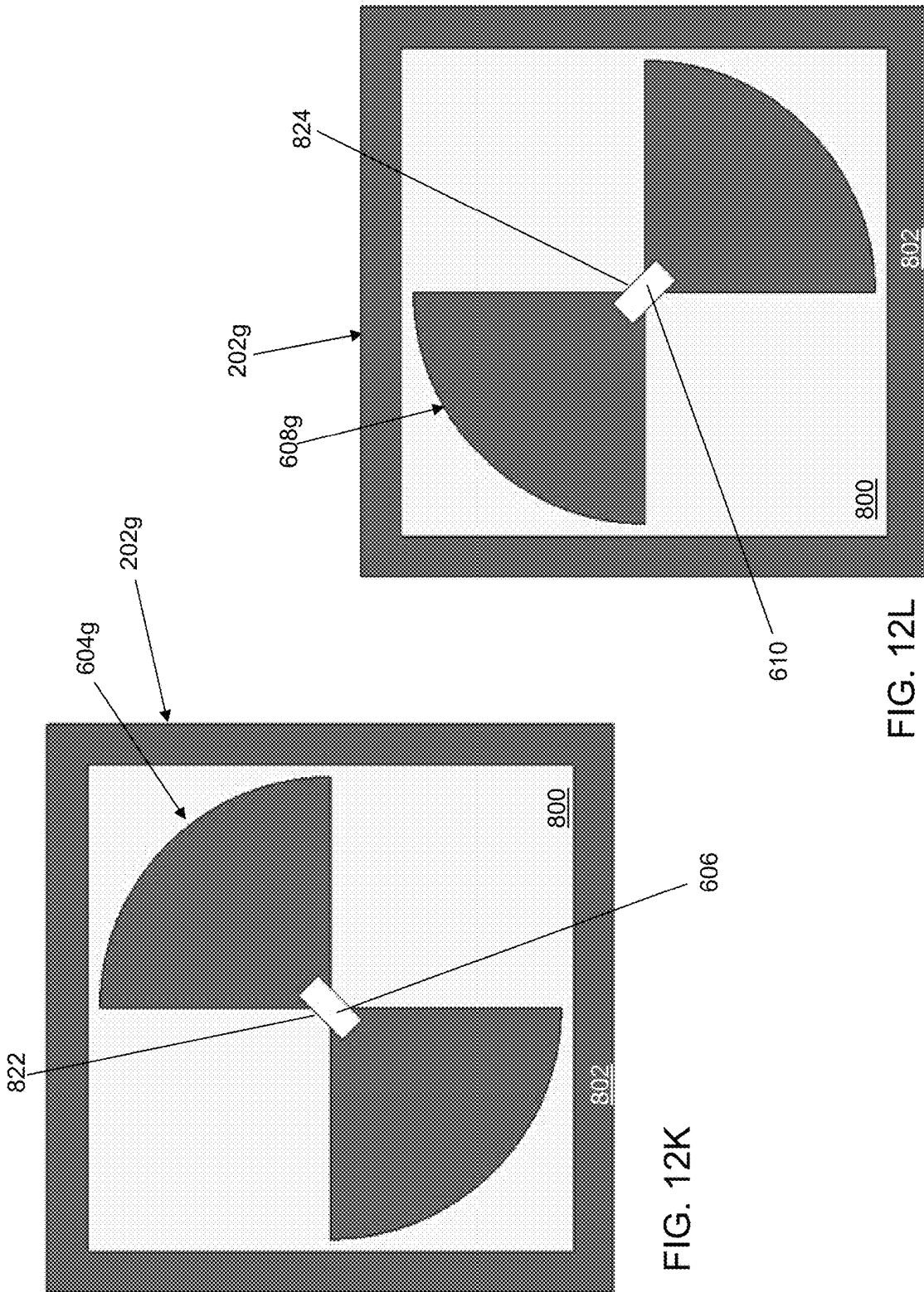


FIG. 12K

FIG. 12L

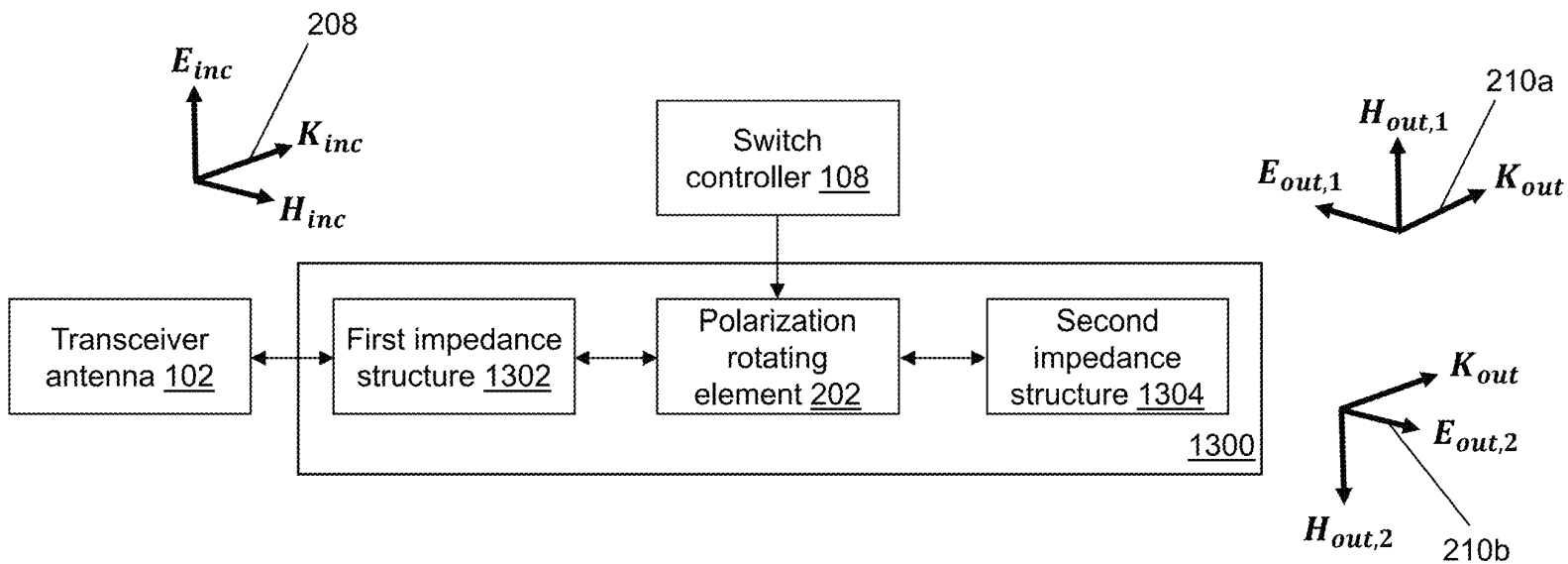


FIG. 13

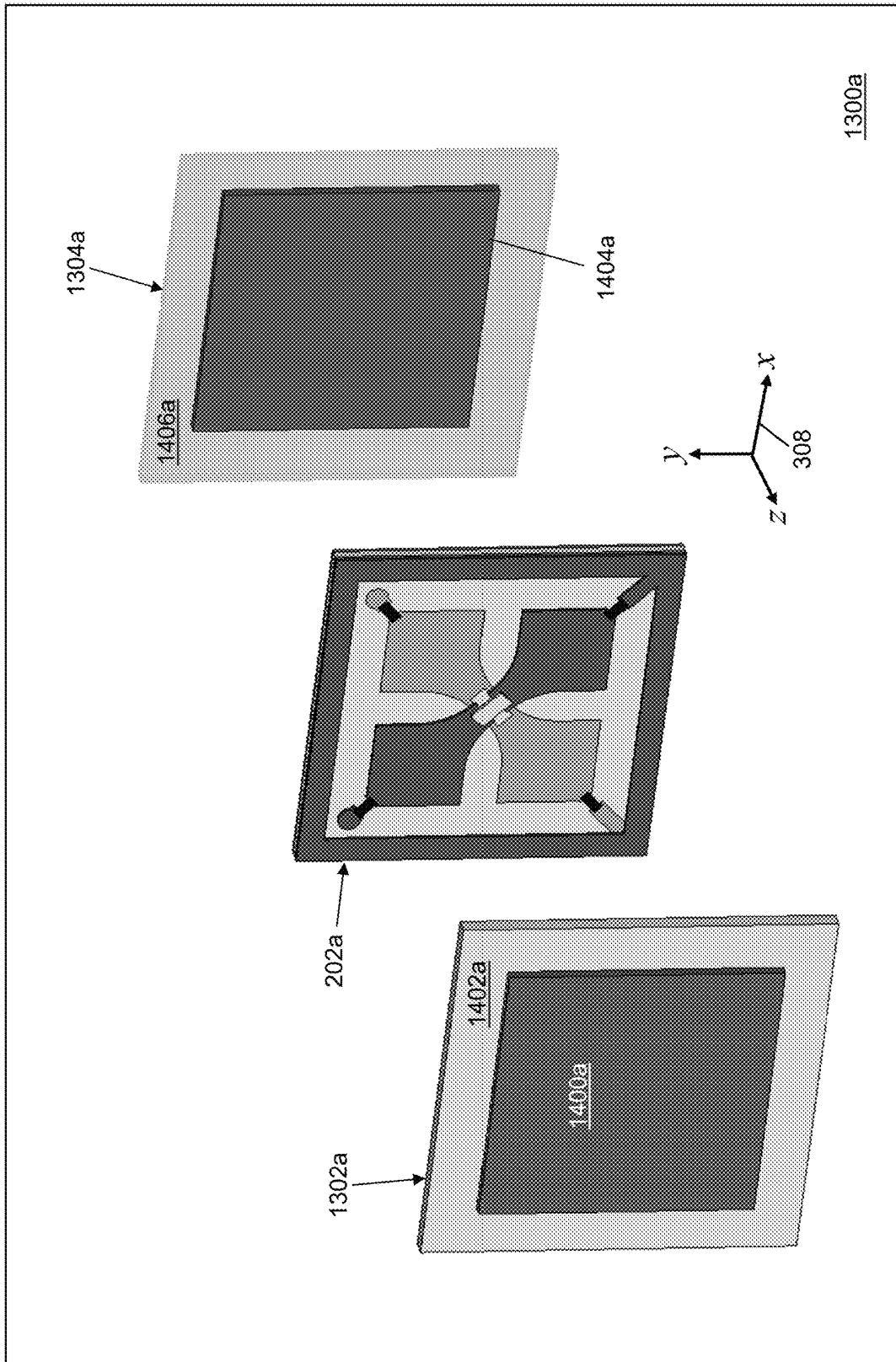
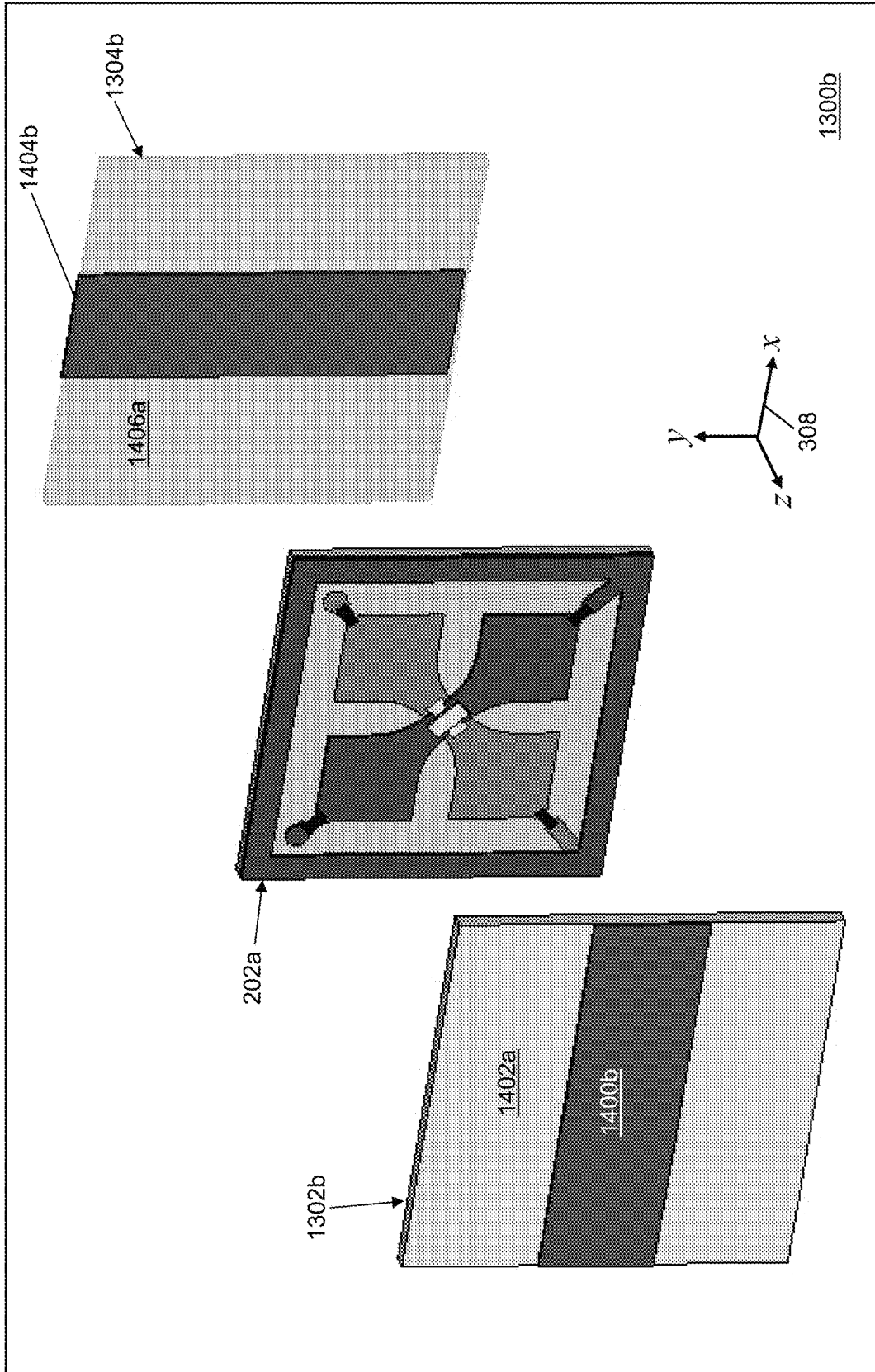


FIG. 14A



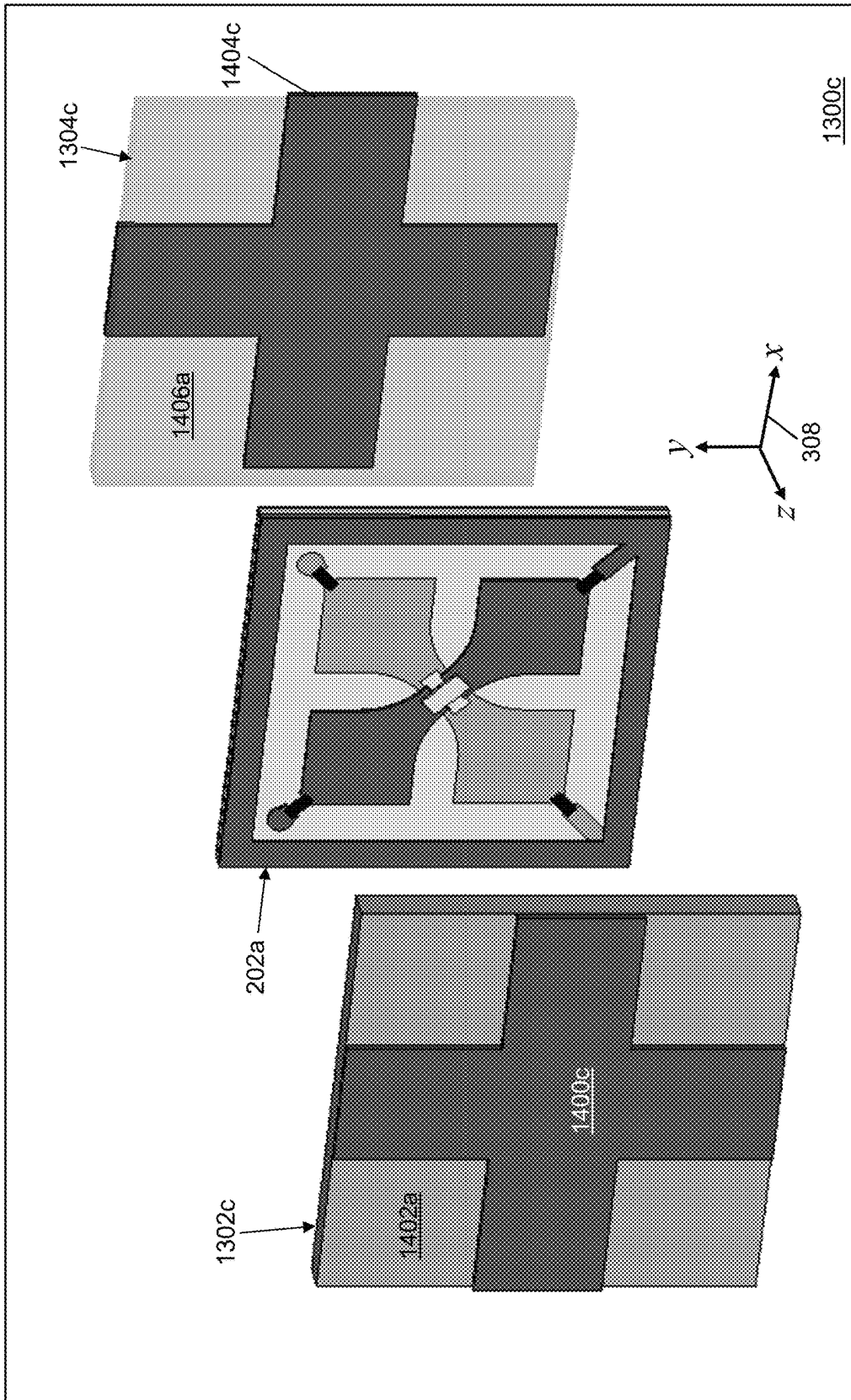


FIG. 14C

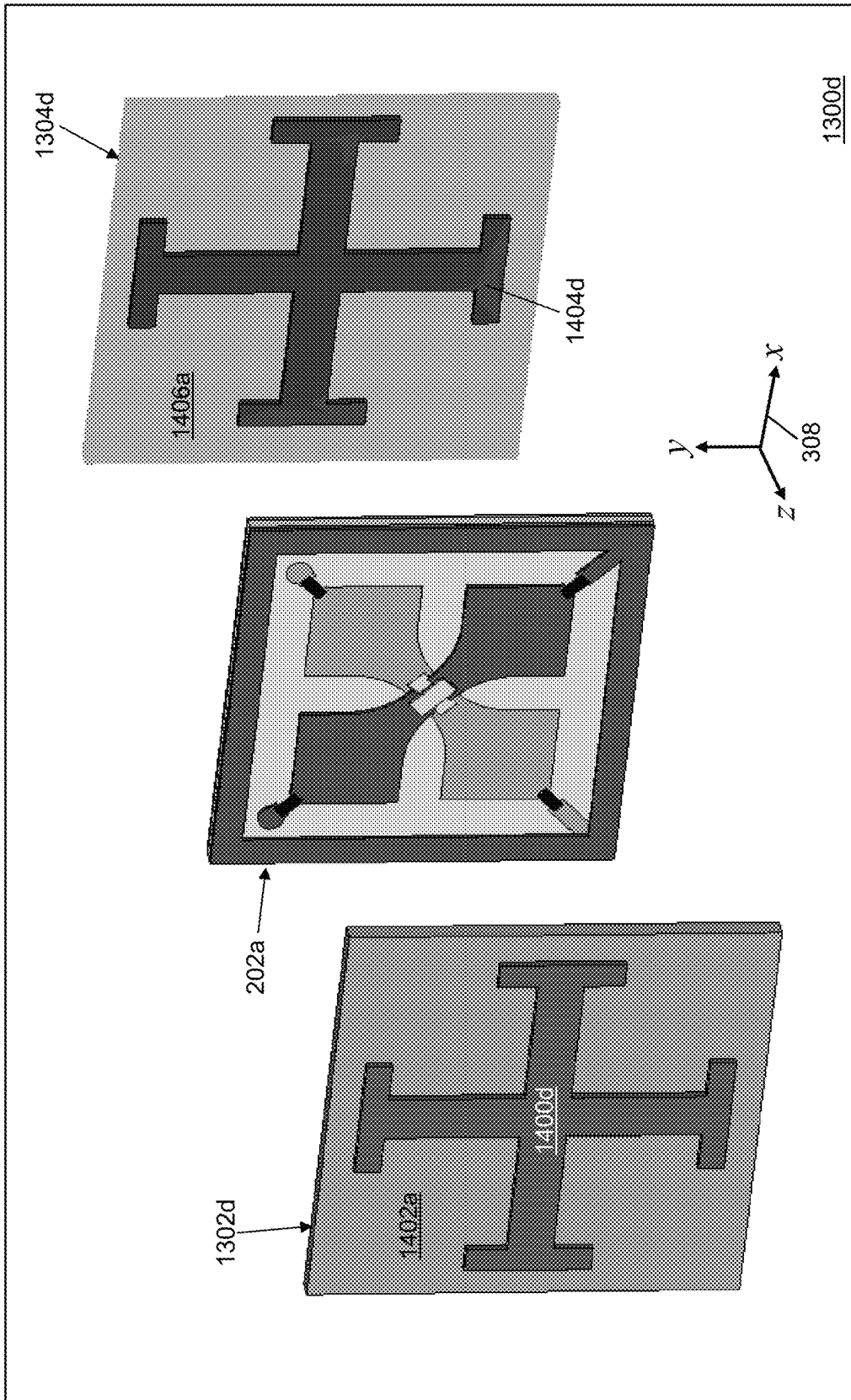


FIG. 14D

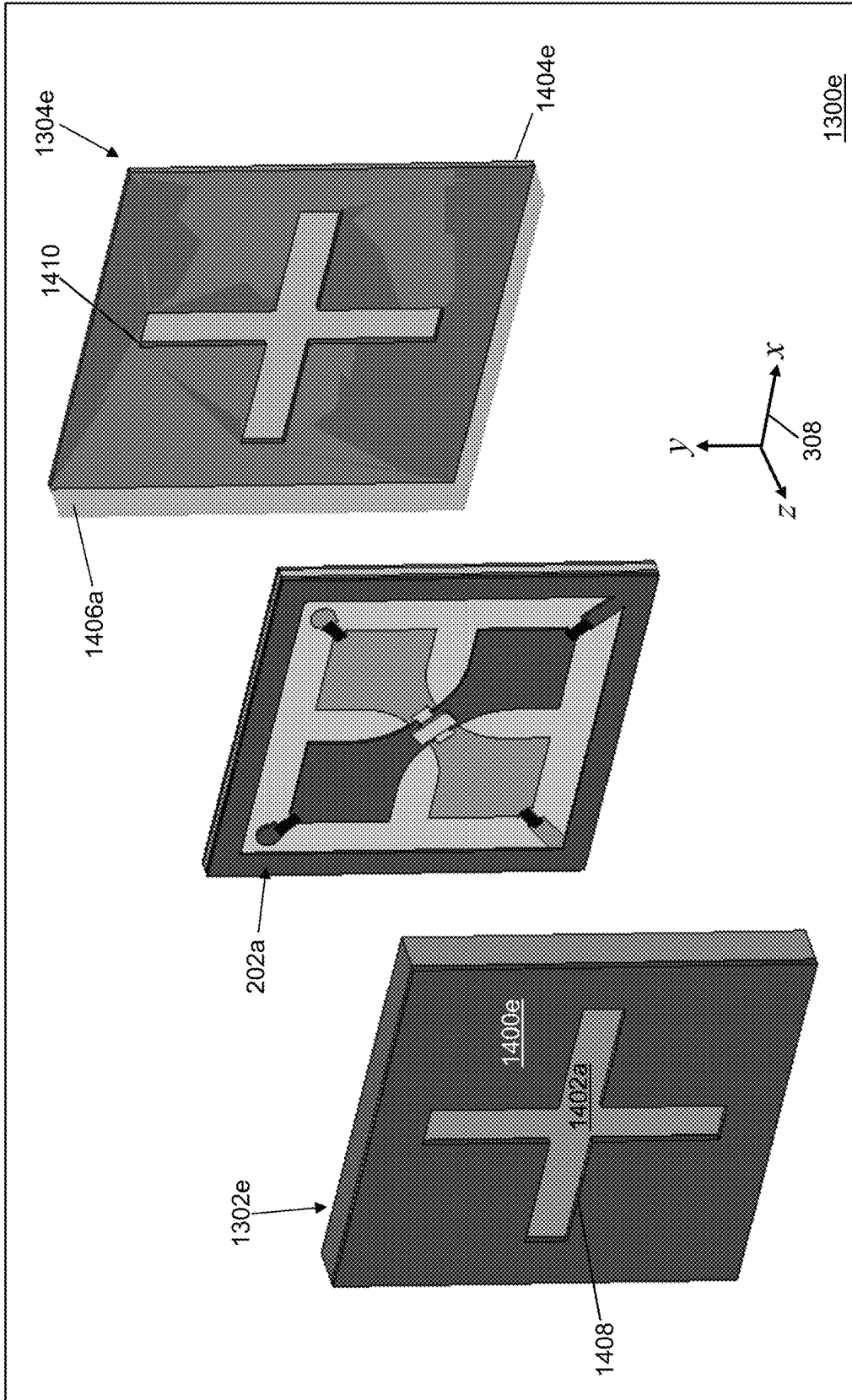


FIG. 14E

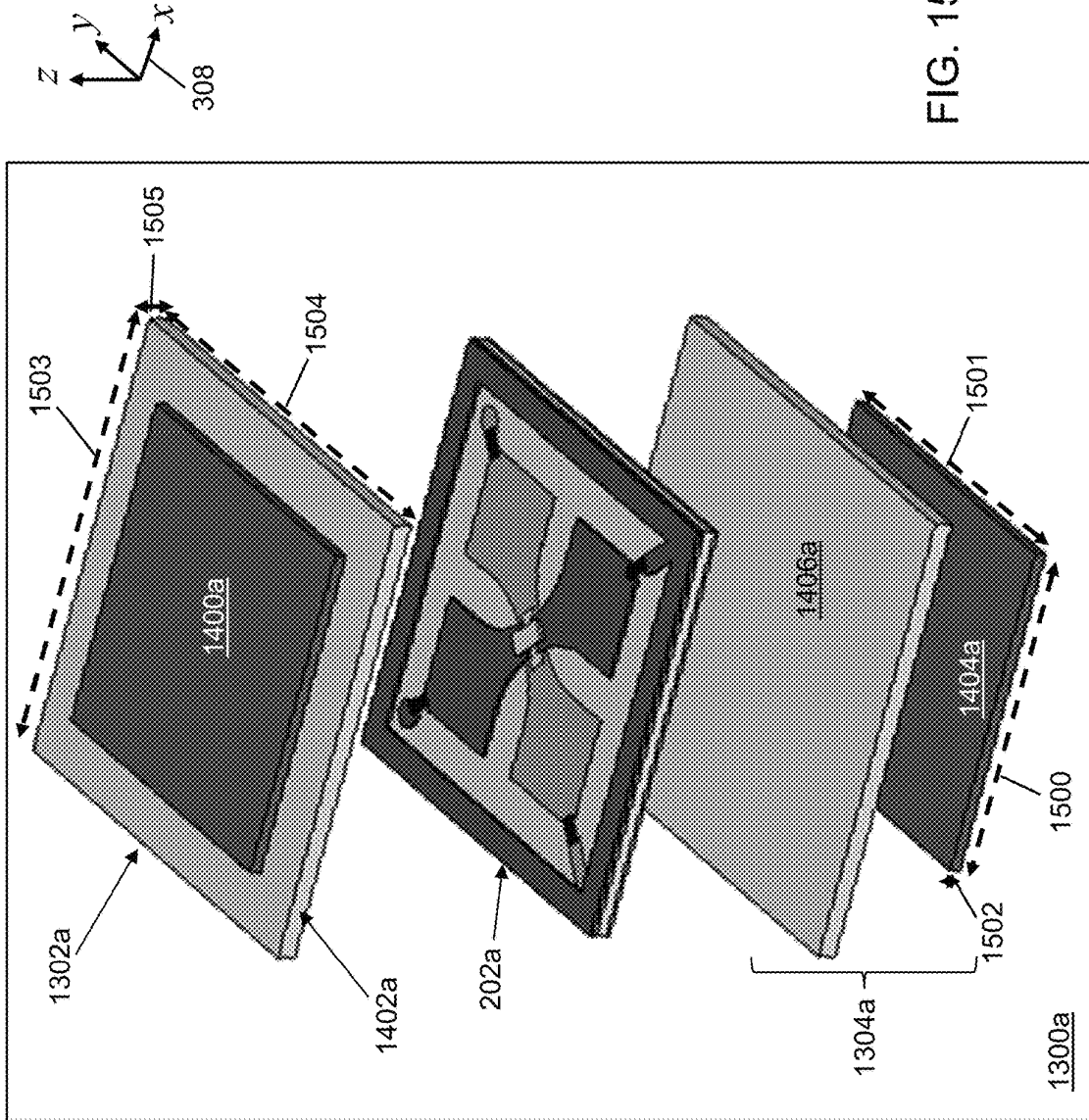


FIG. 15A

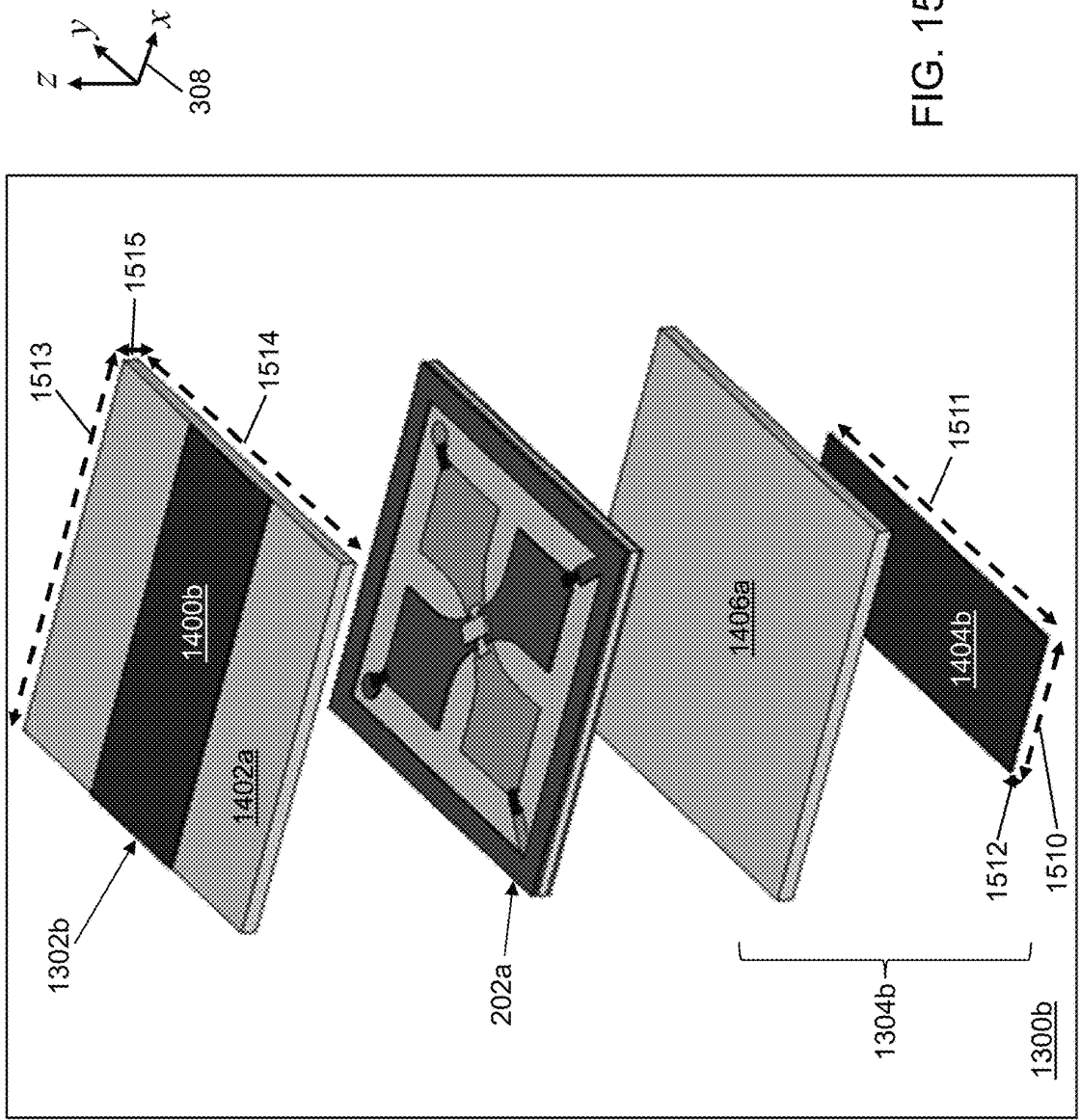


FIG. 15B

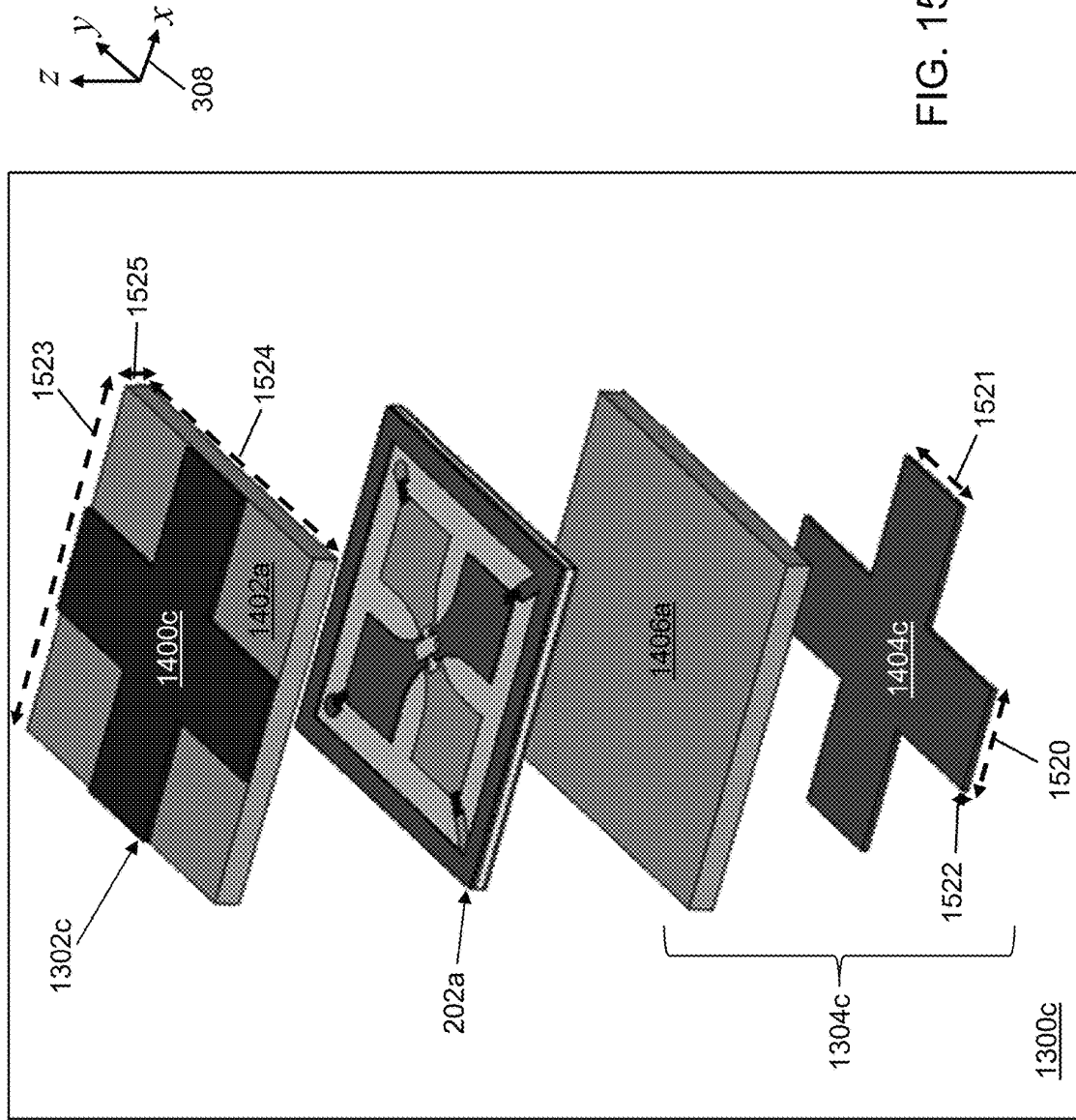


FIG. 15C

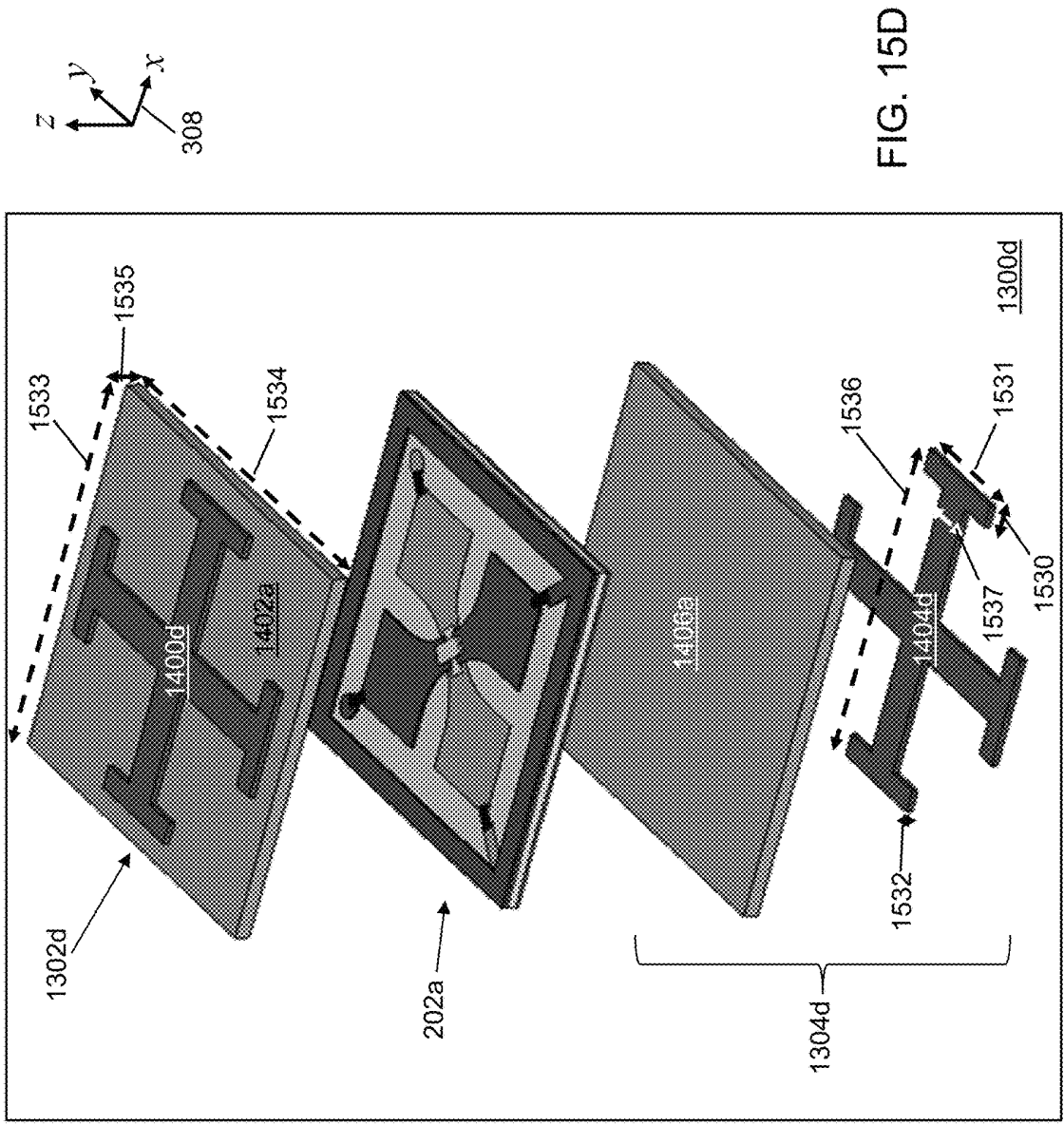


FIG. 15D

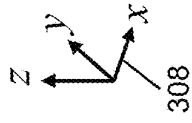
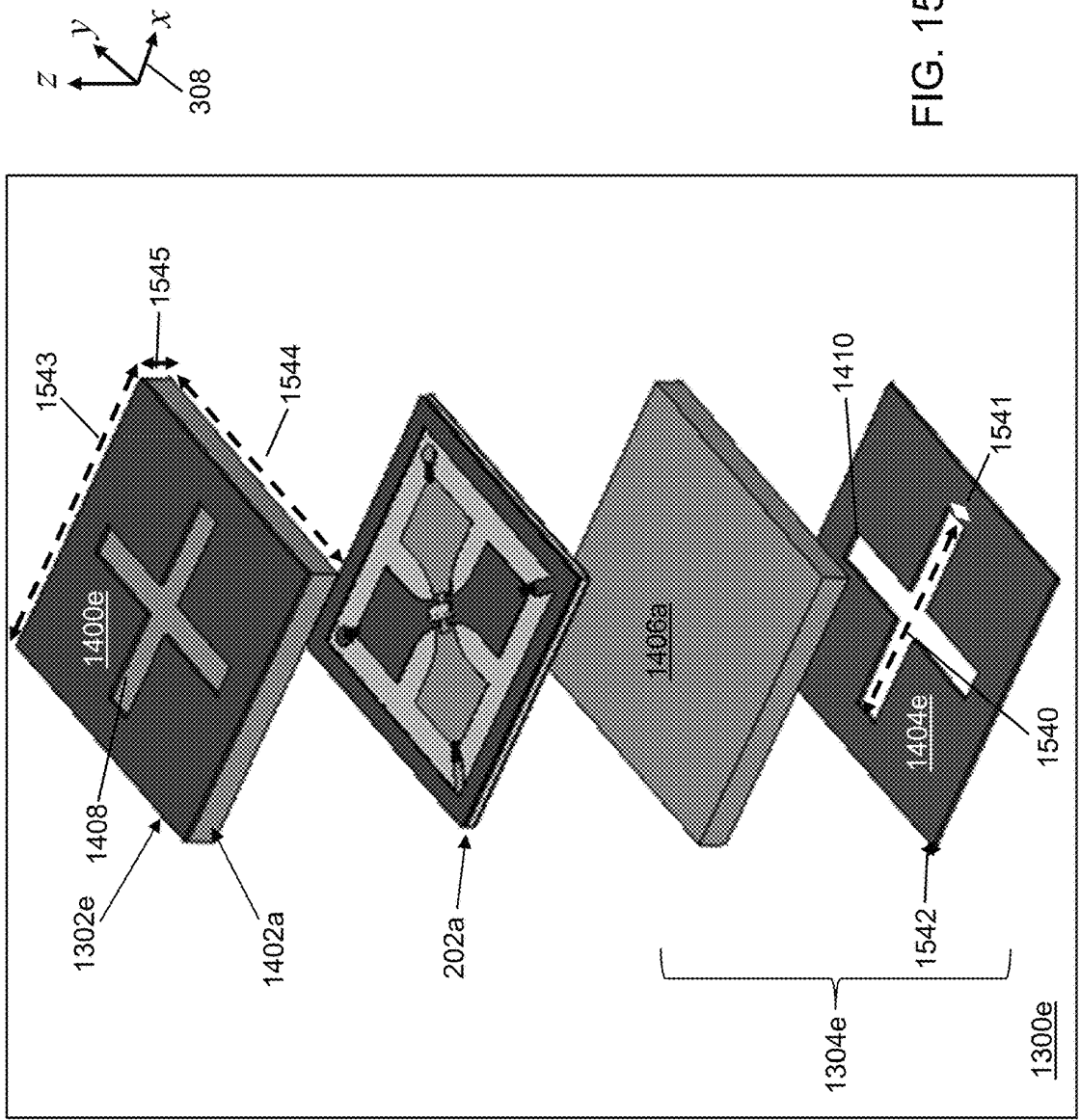


FIG. 15E

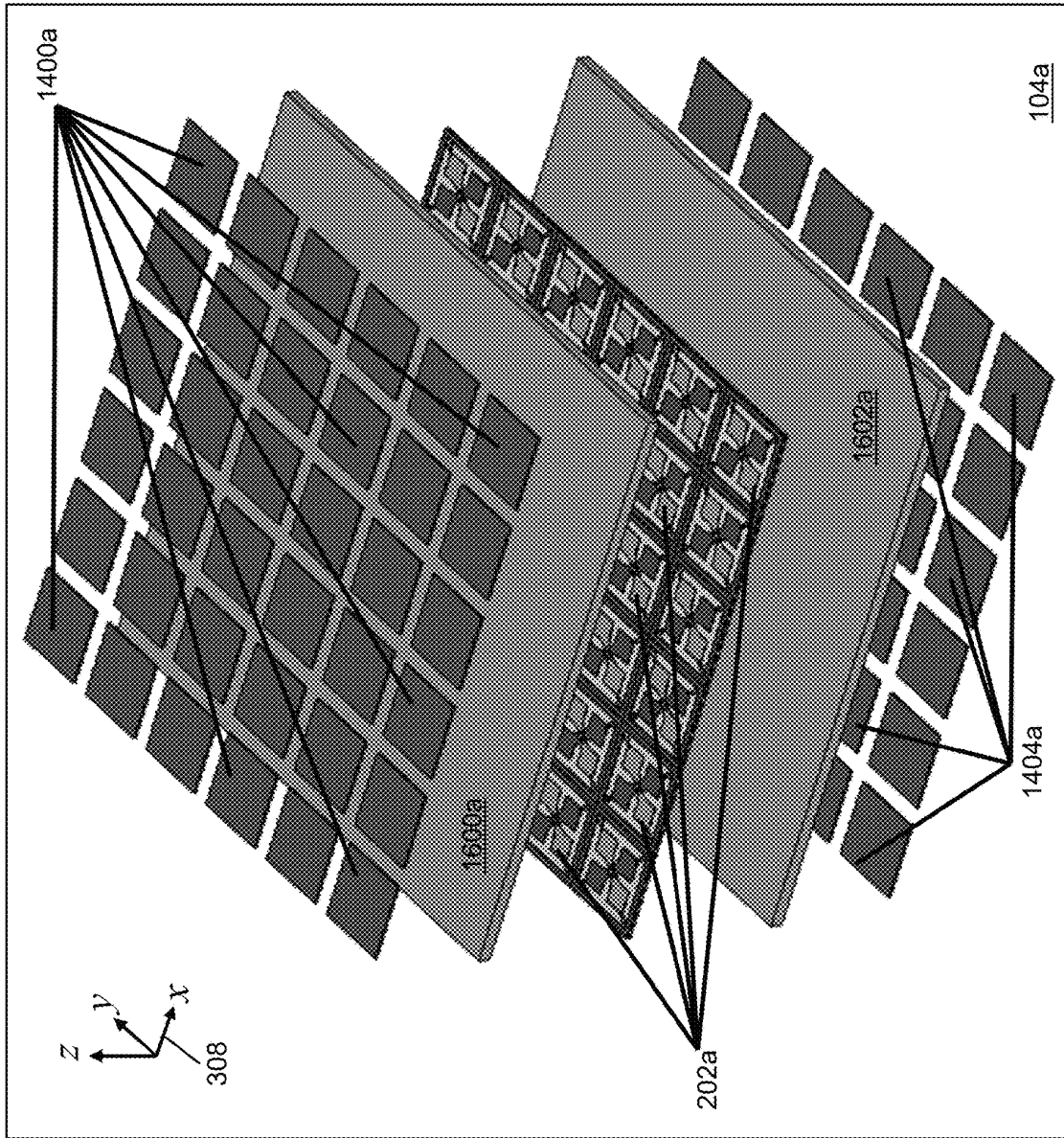


FIG. 16A

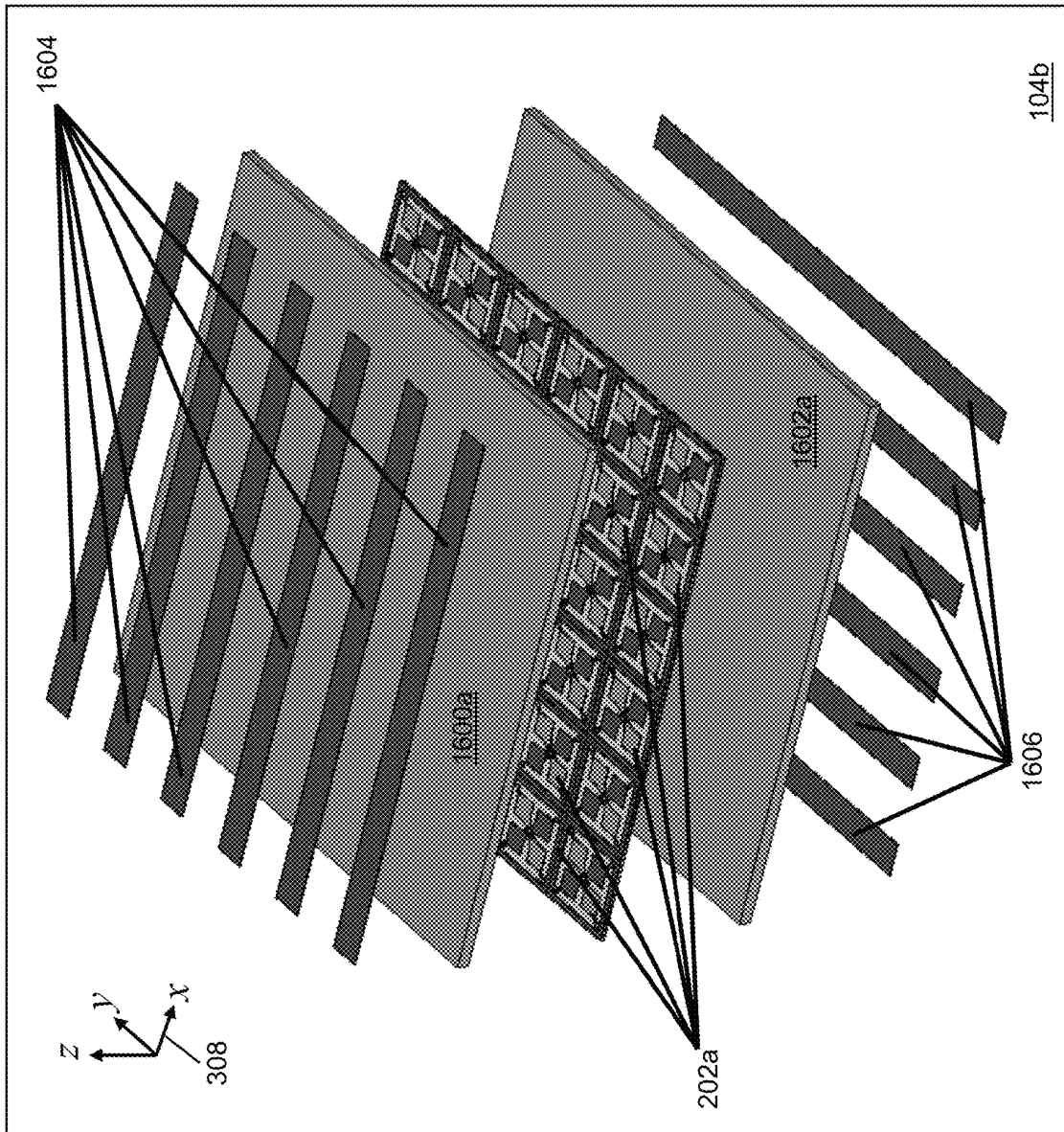
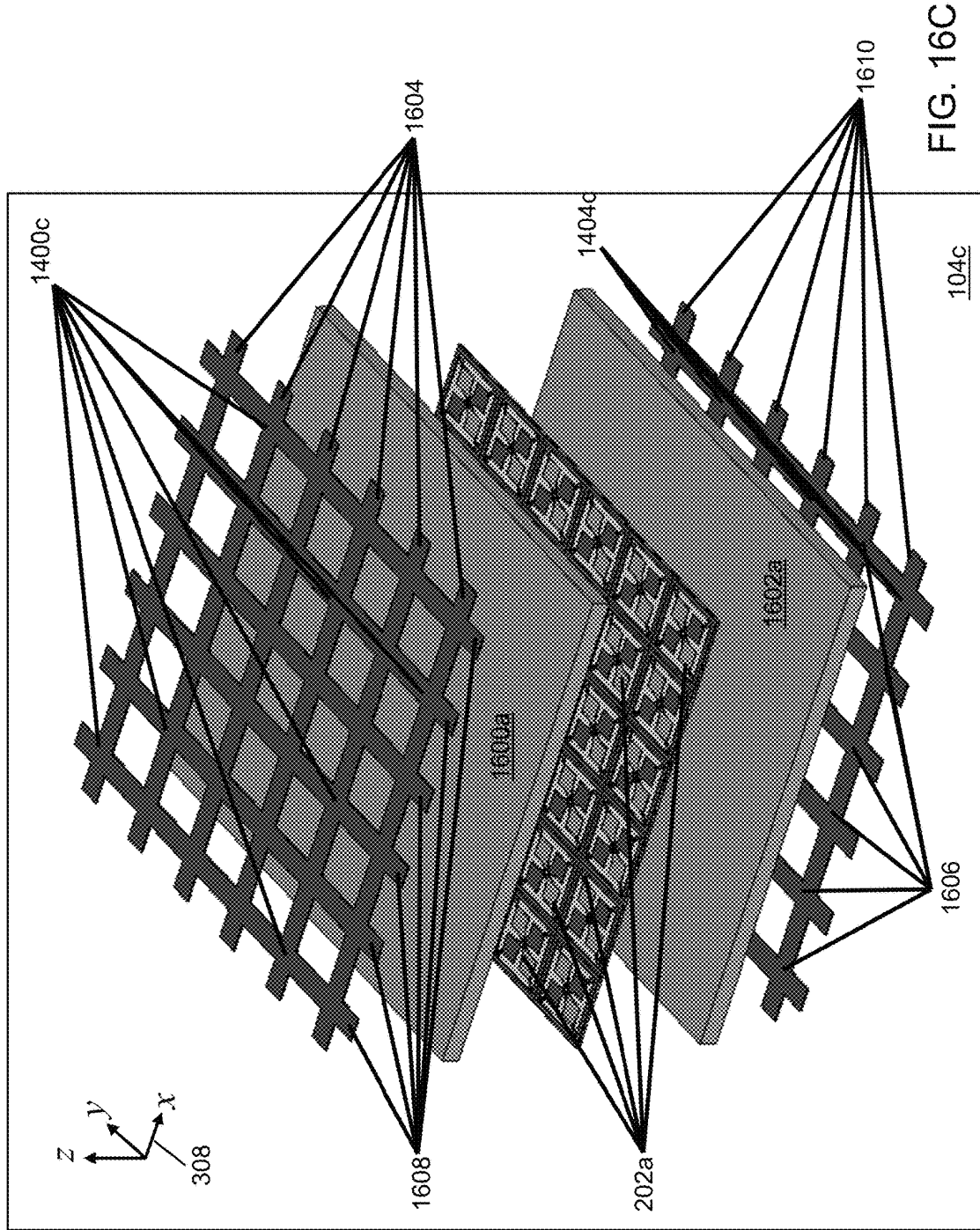


FIG. 16B



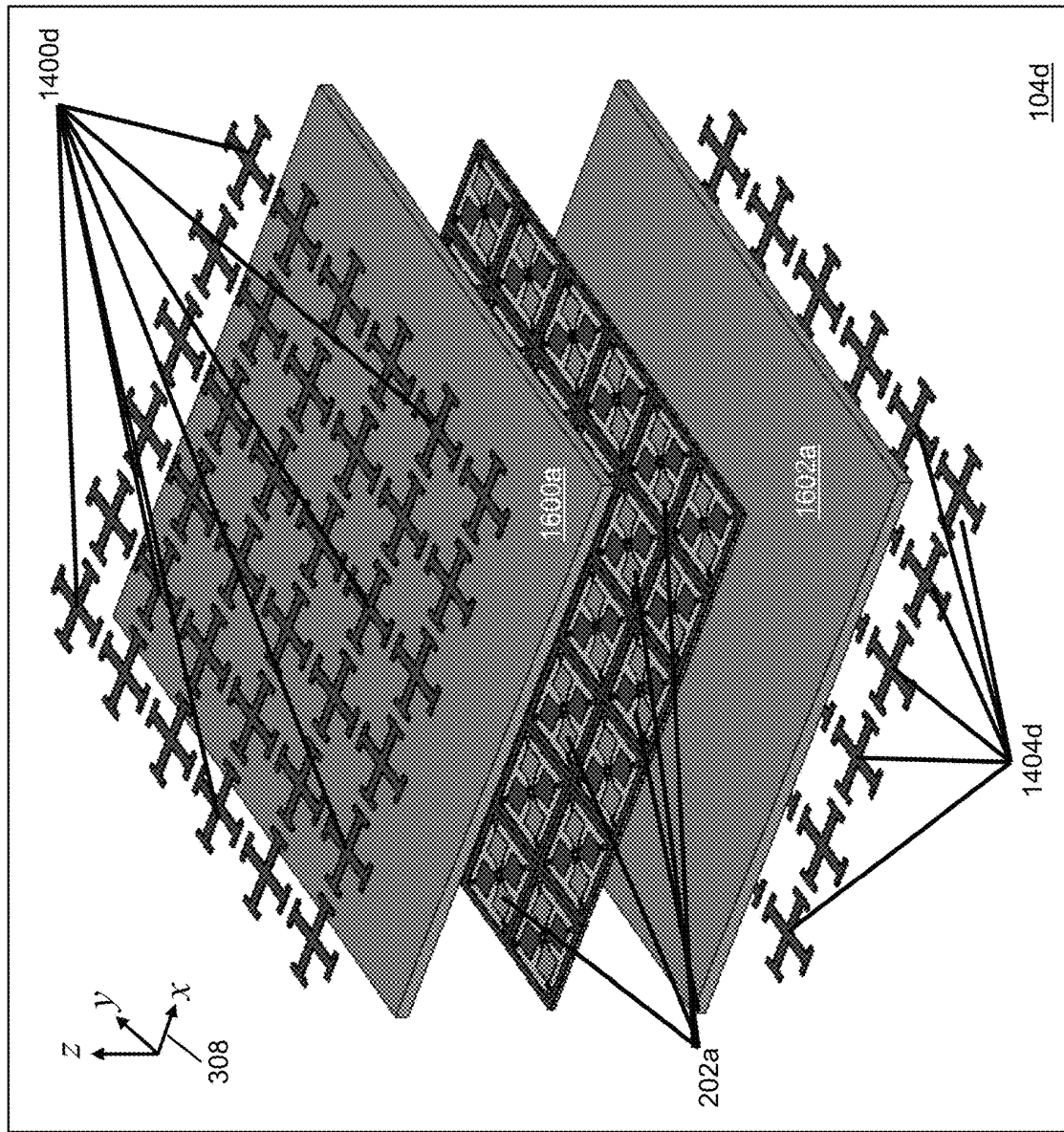


FIG. 16D

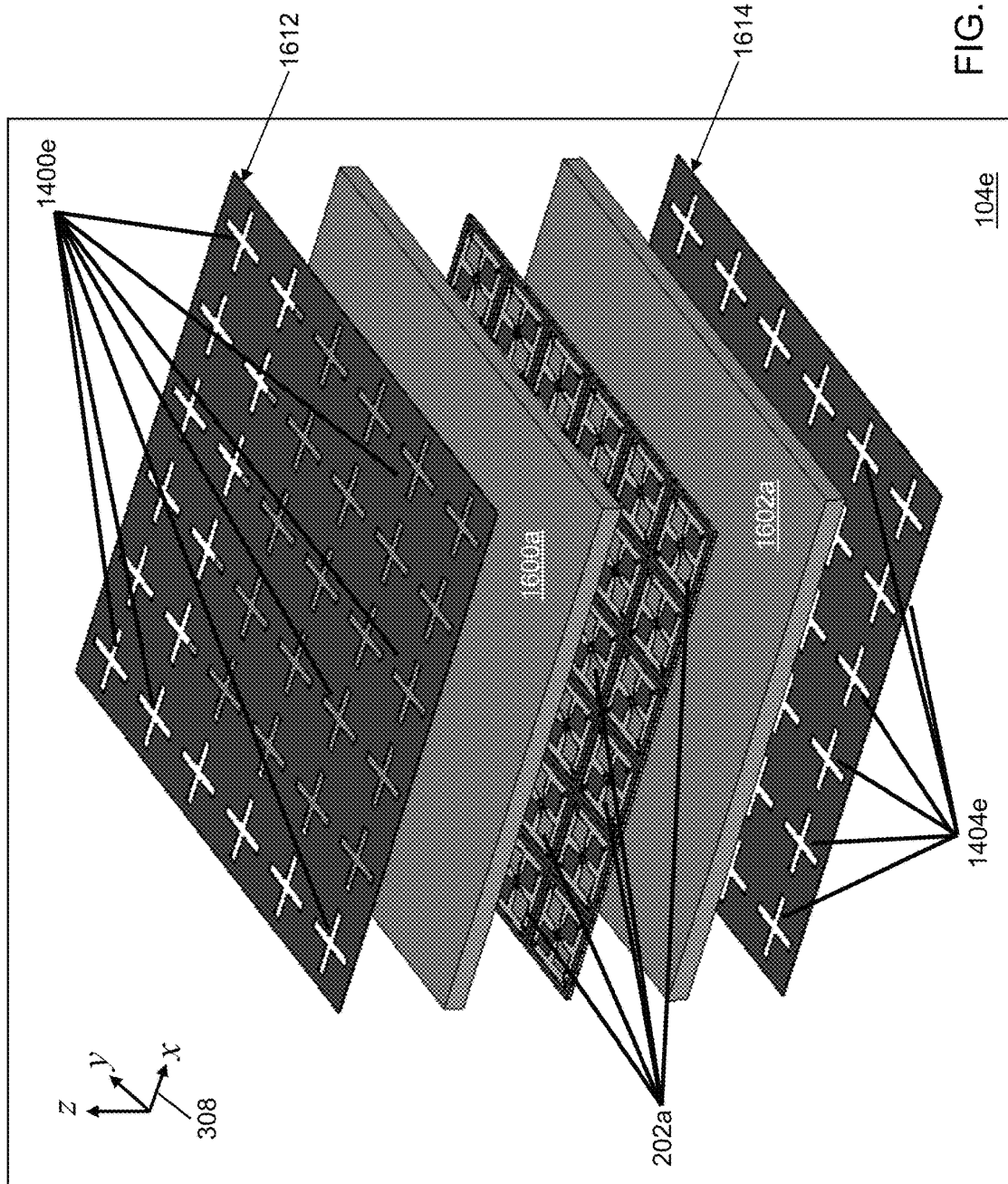


FIG. 16E

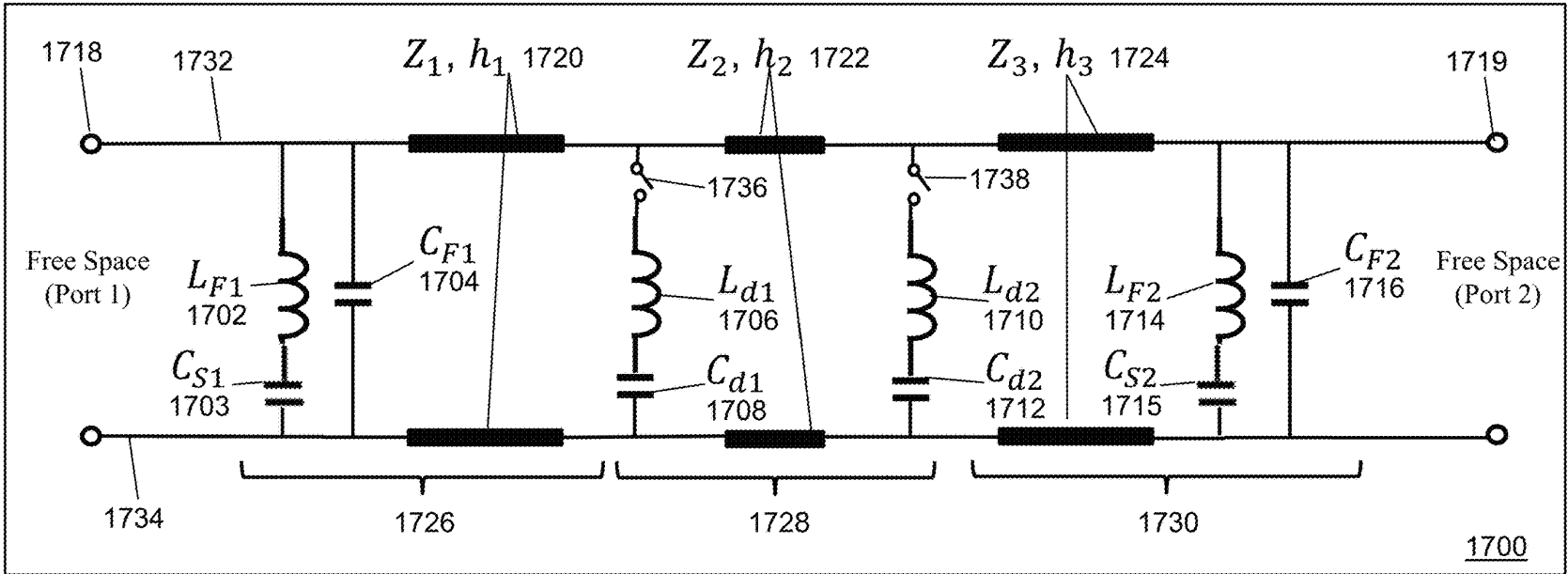


FIG. 17

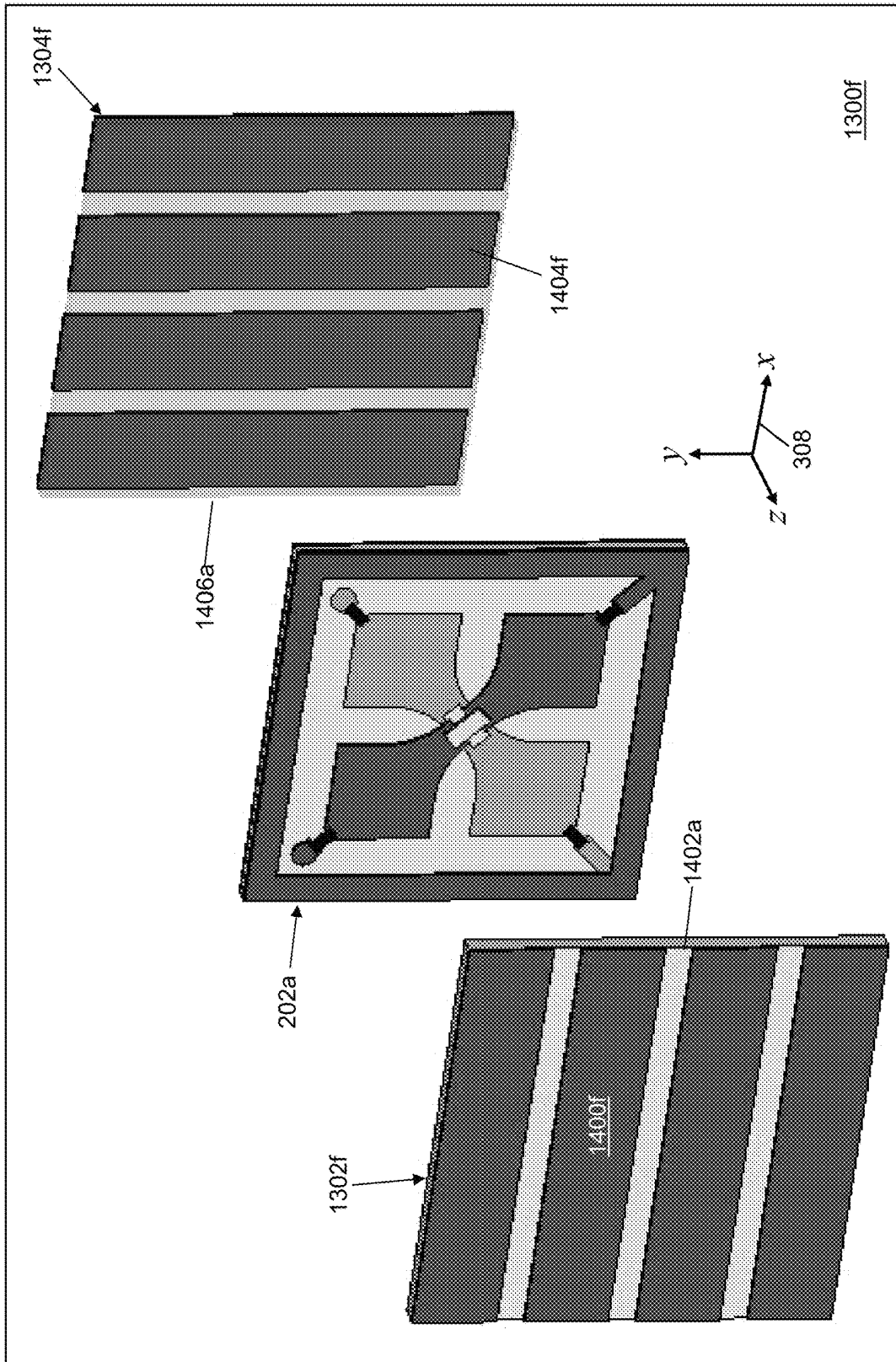


FIG. 18A

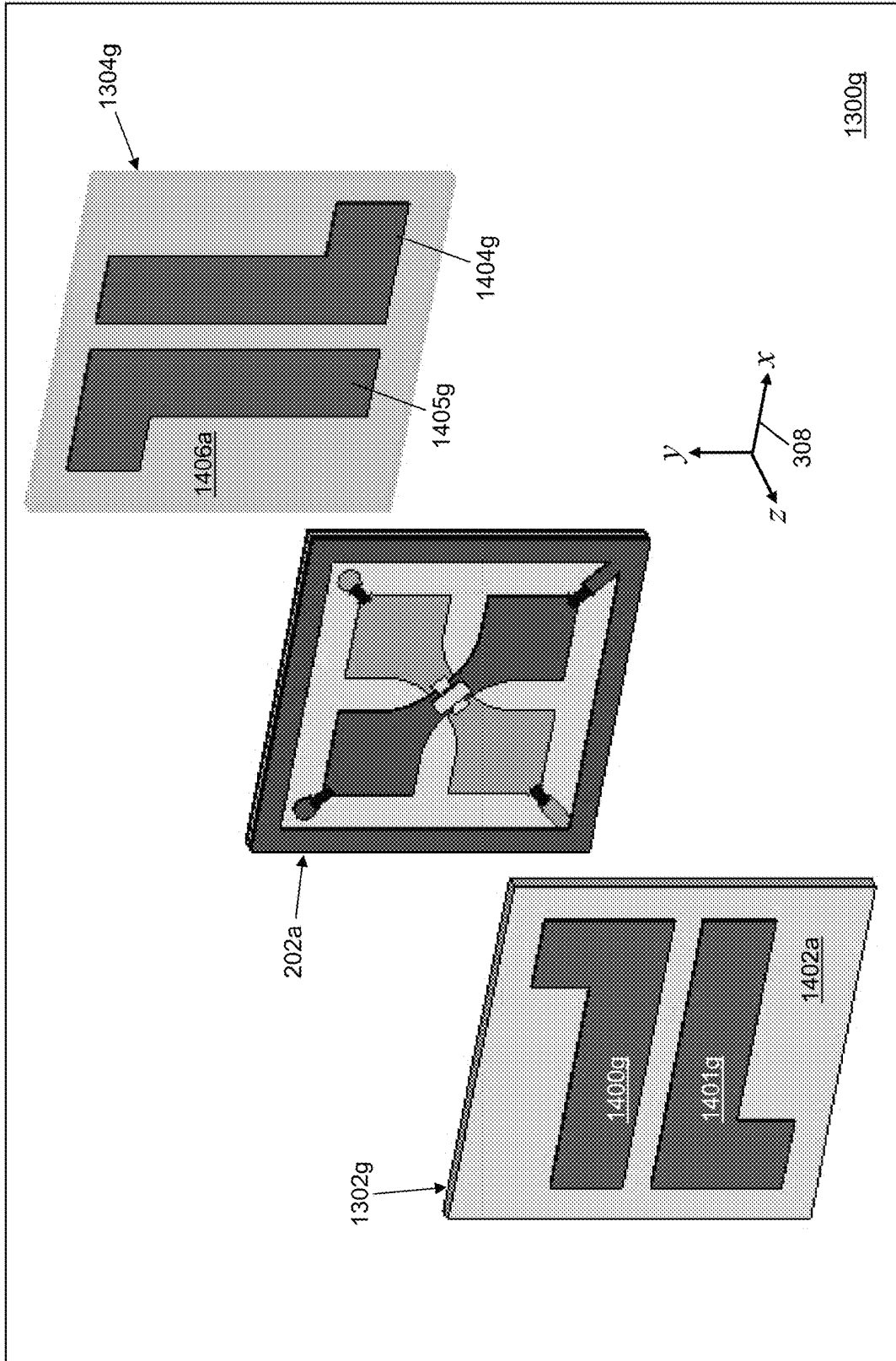


FIG. 18B

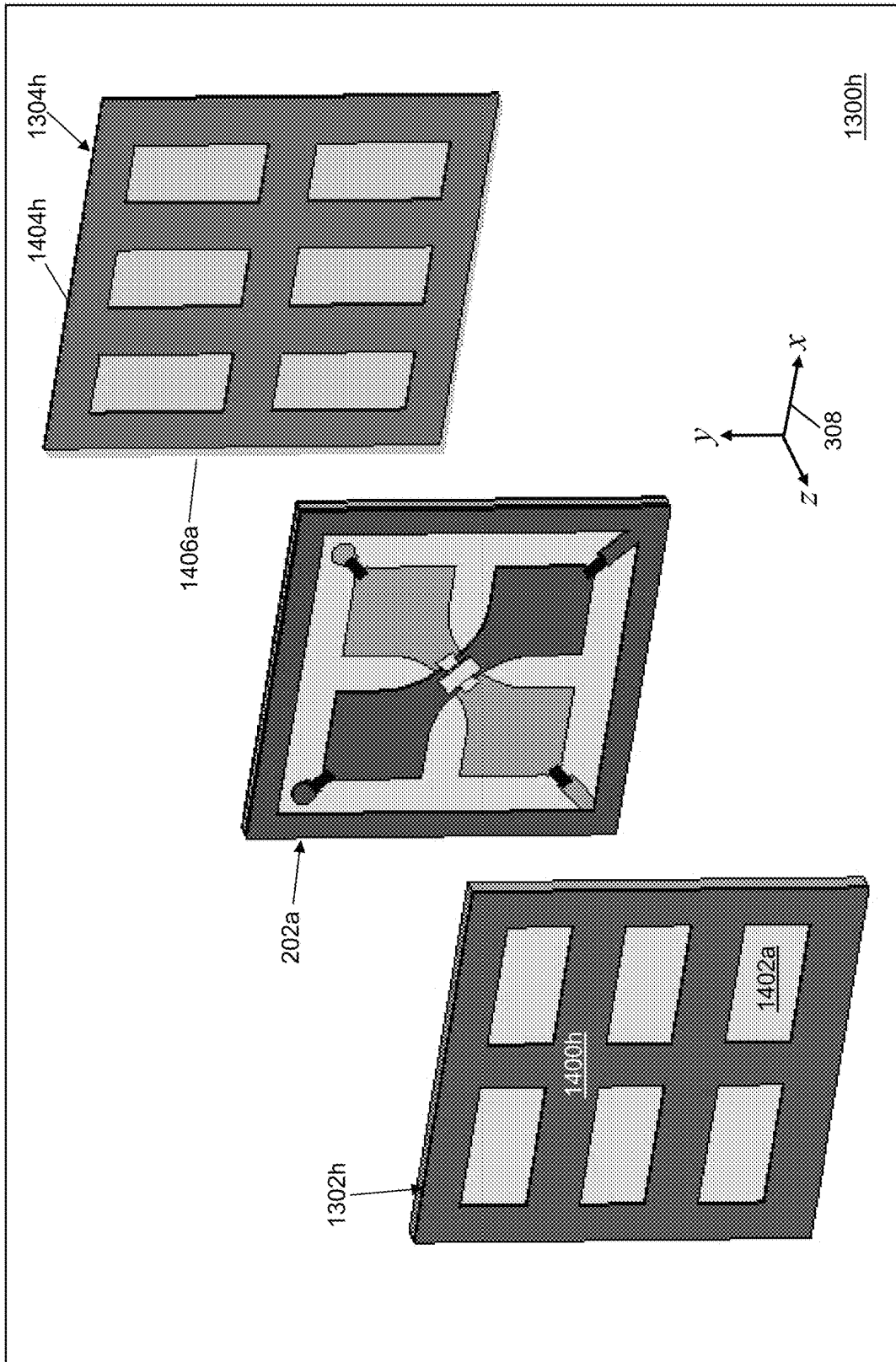


FIG. 18C

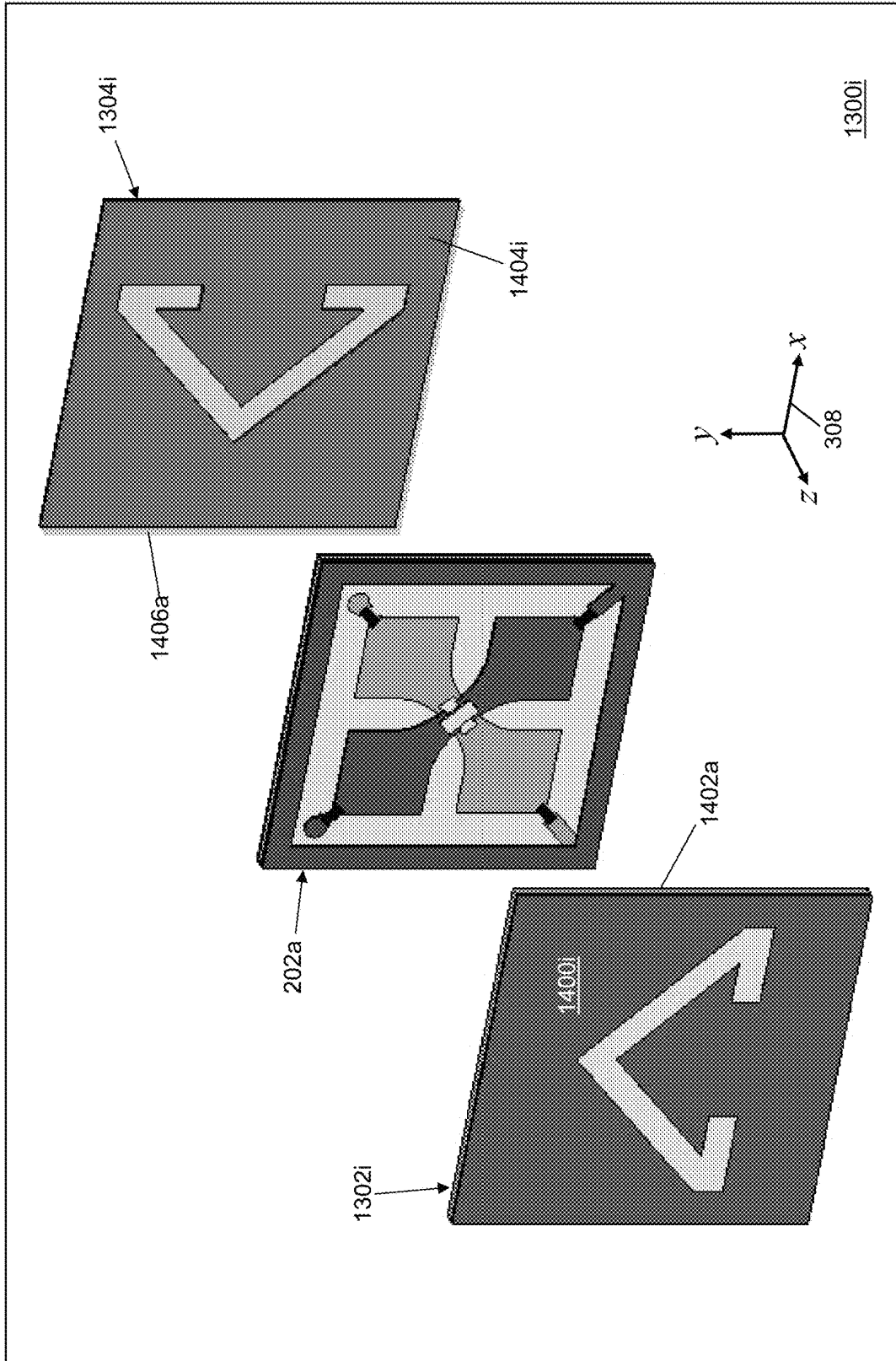


FIG. 18D

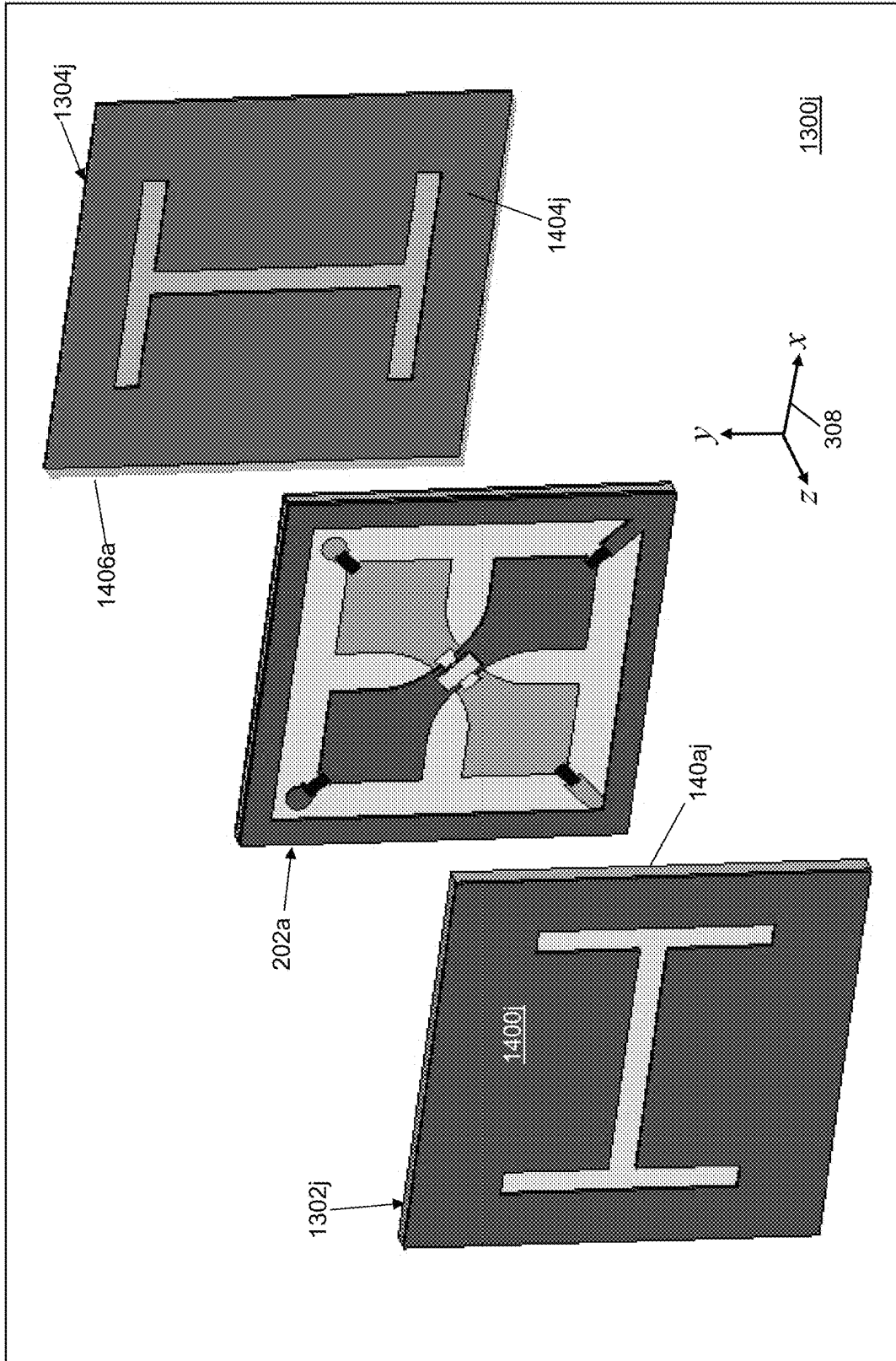


FIG. 18E

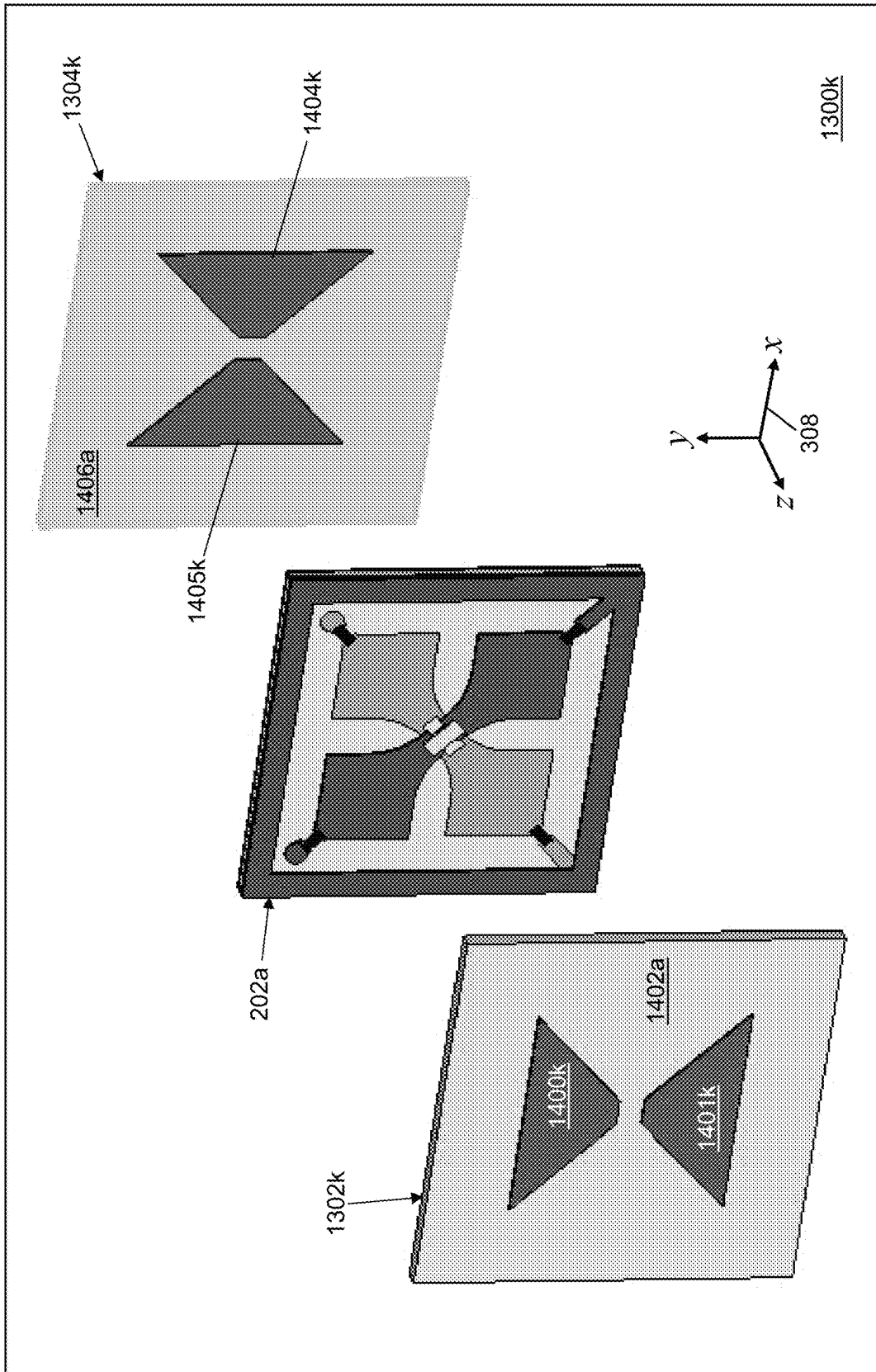


FIG. 18F

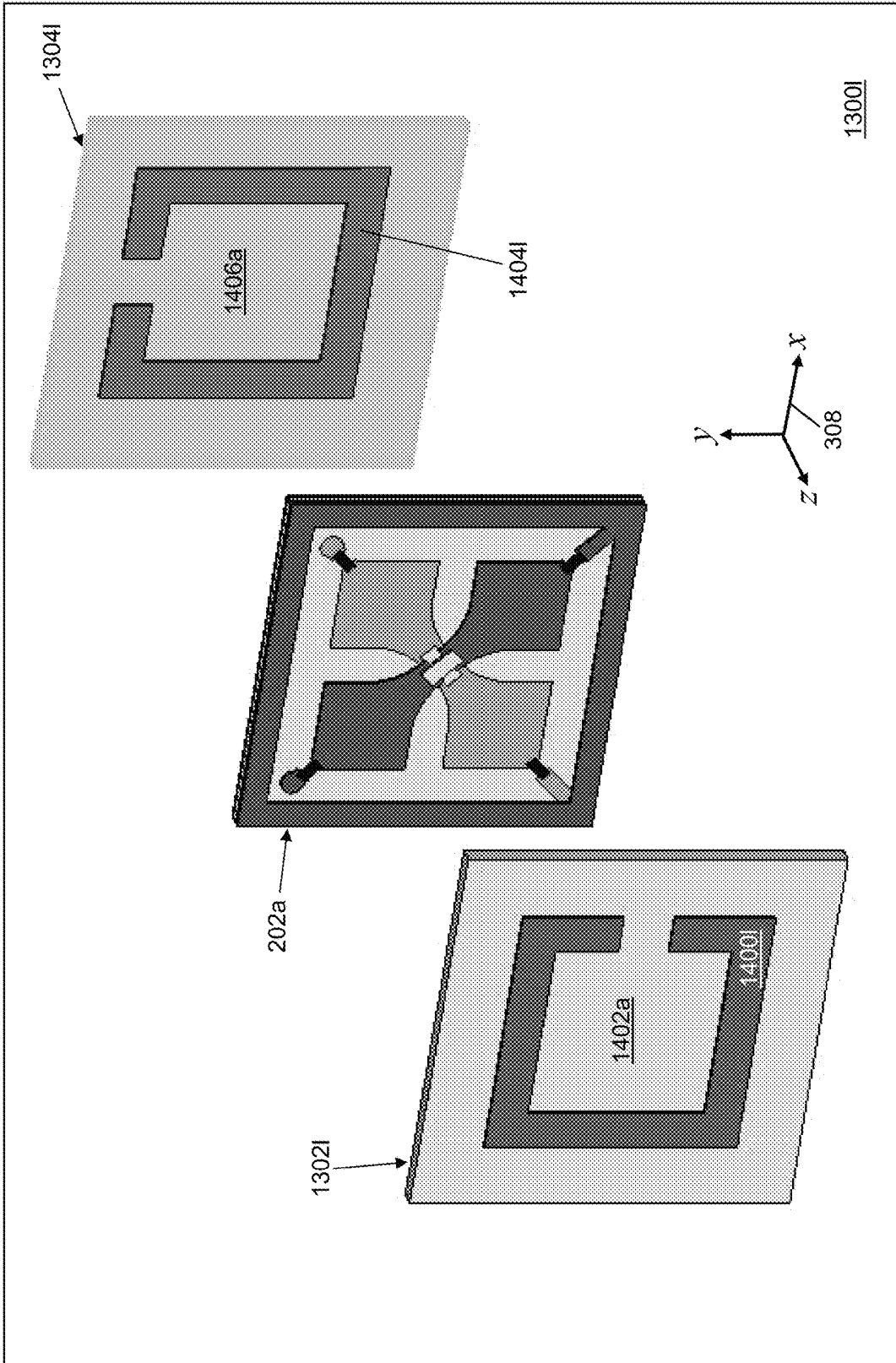


FIG. 18G

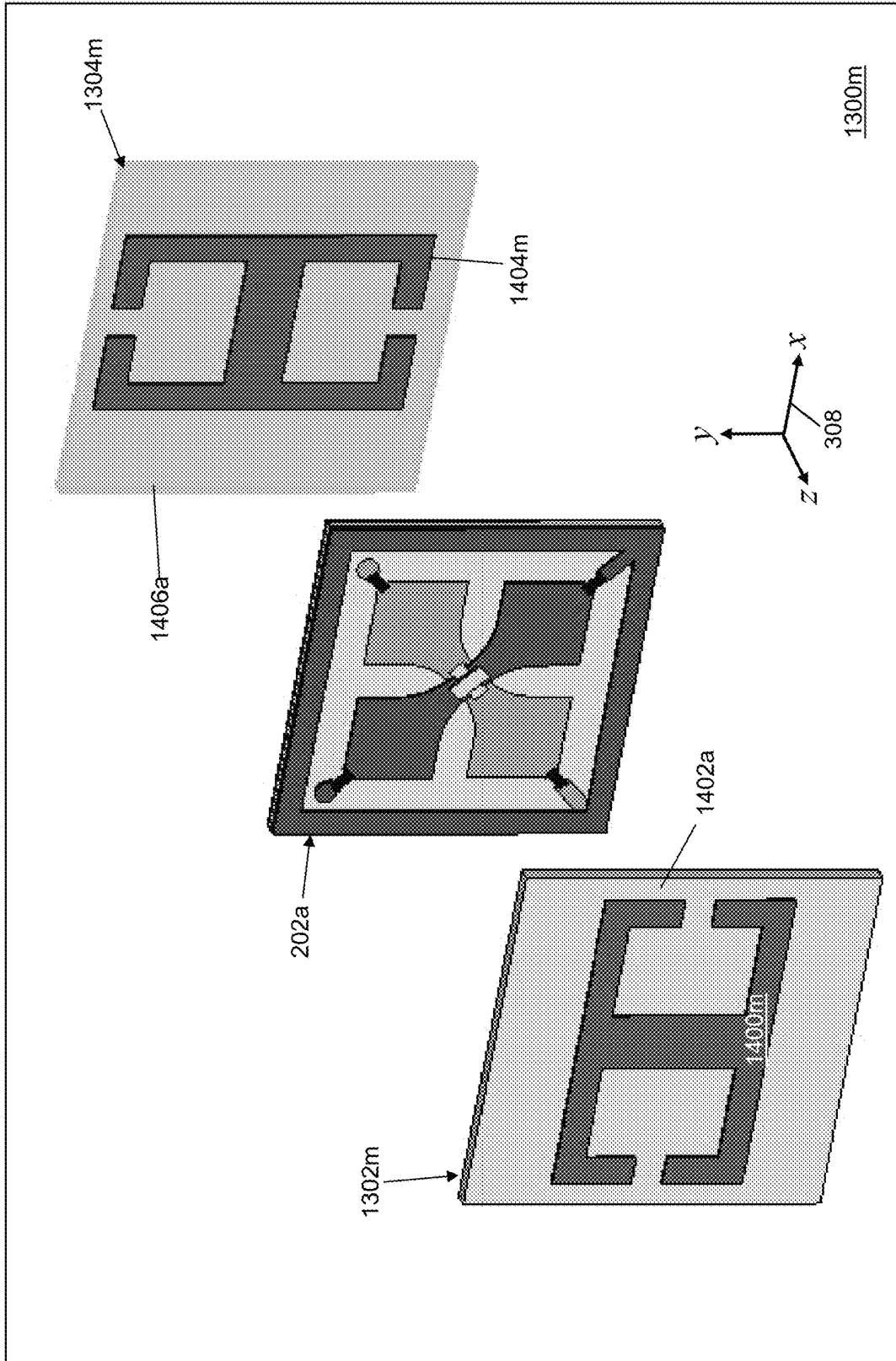


FIG. 18H

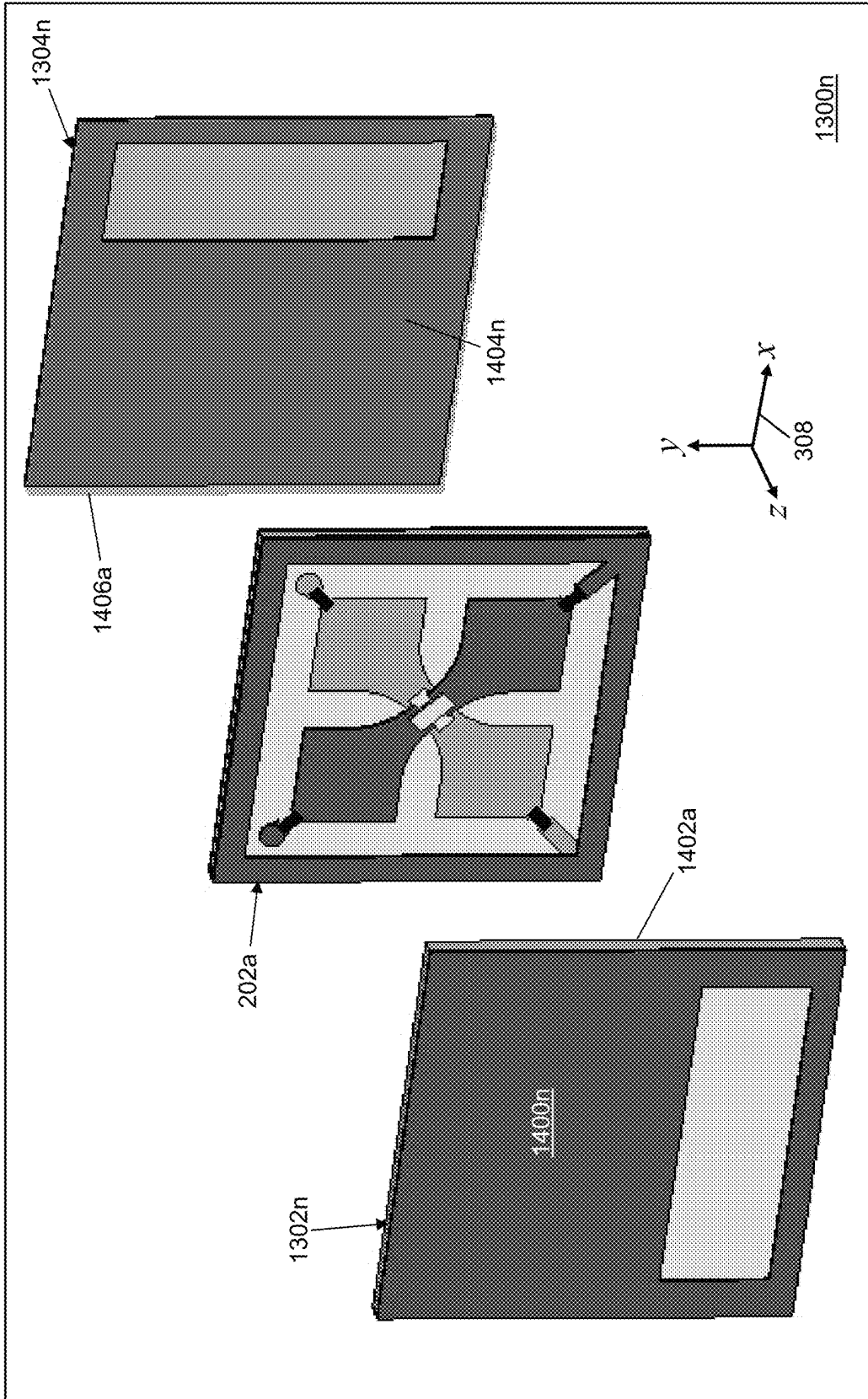


FIG. 18I

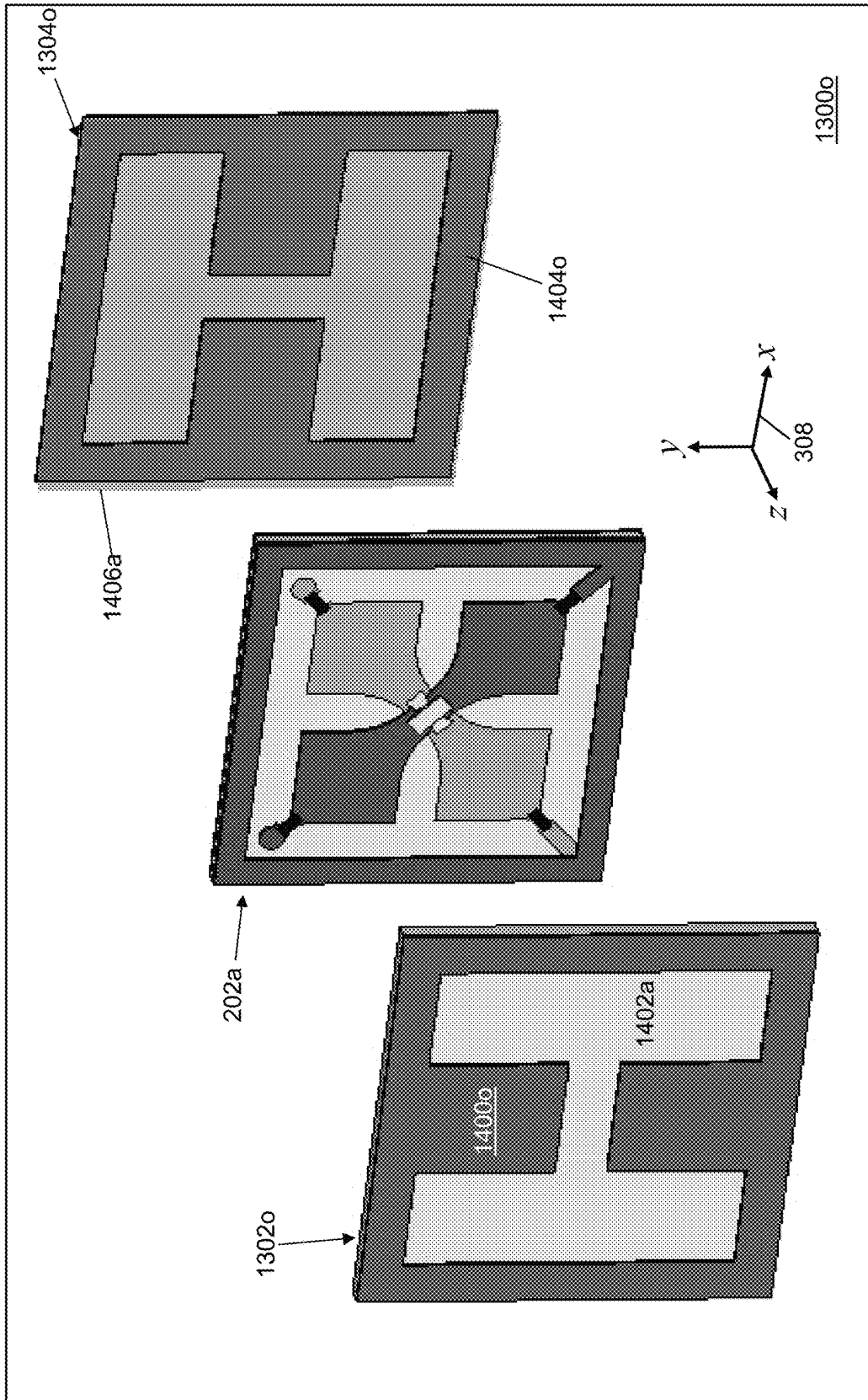


FIG. 18J

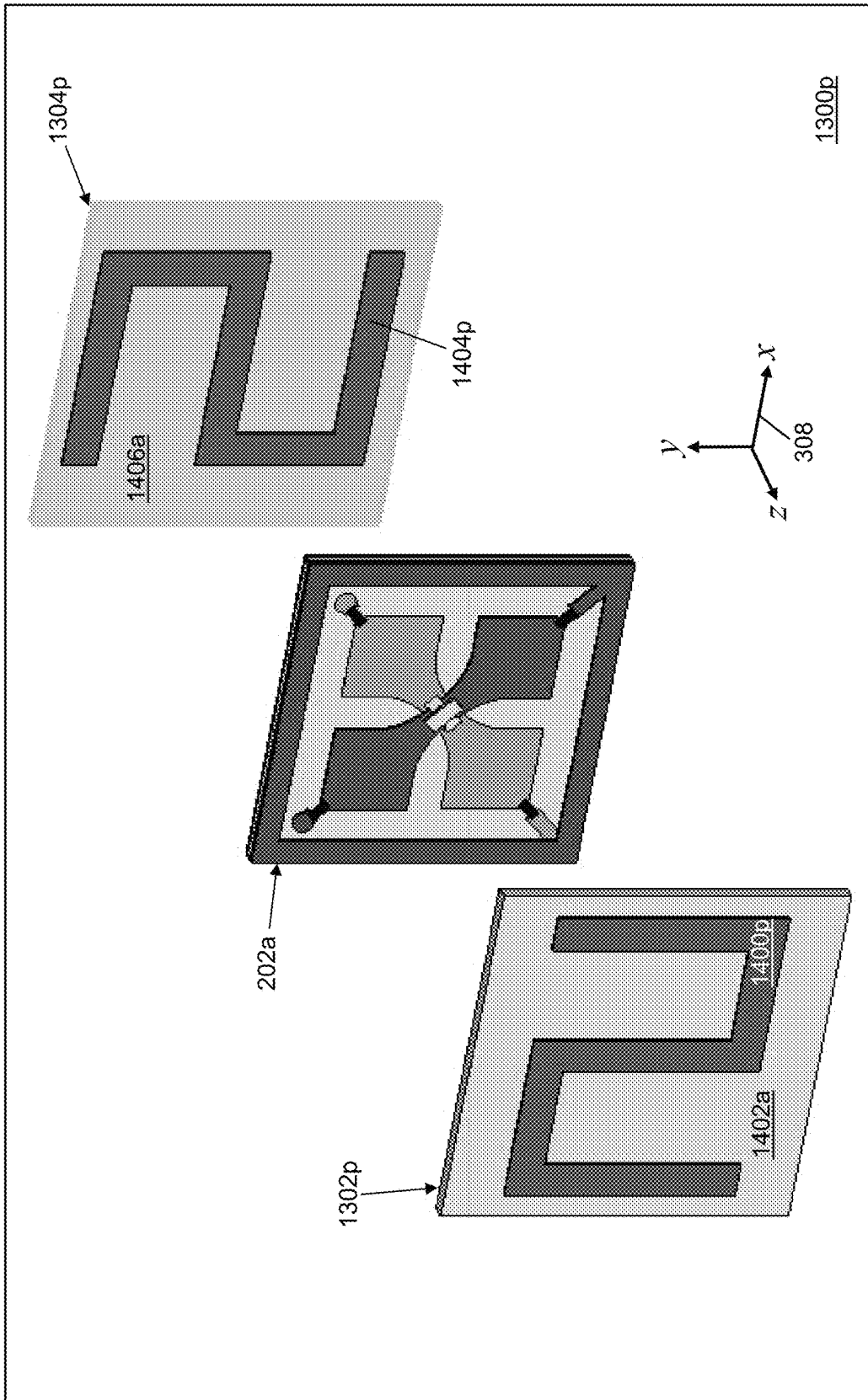


FIG. 18K

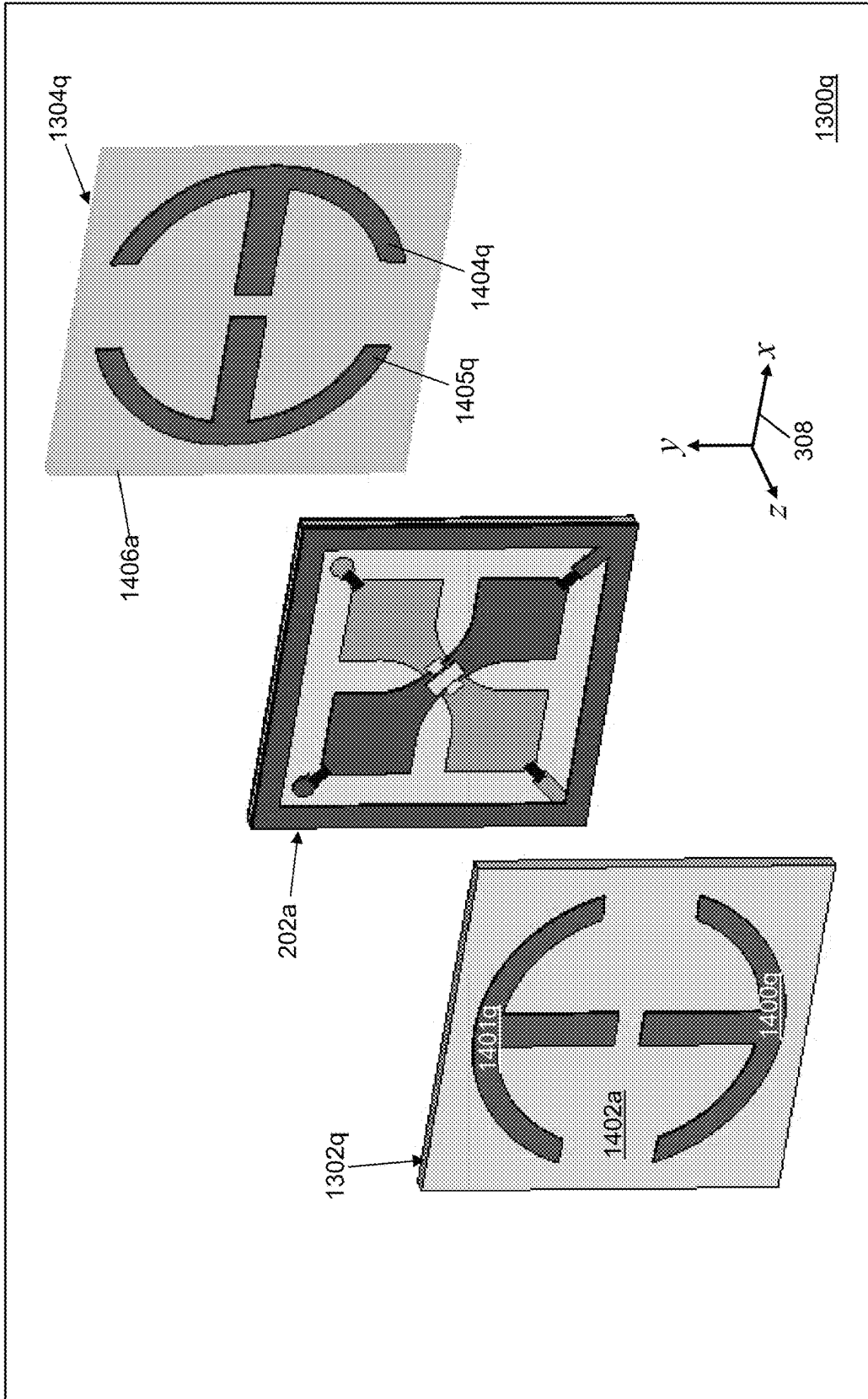


FIG. 18L

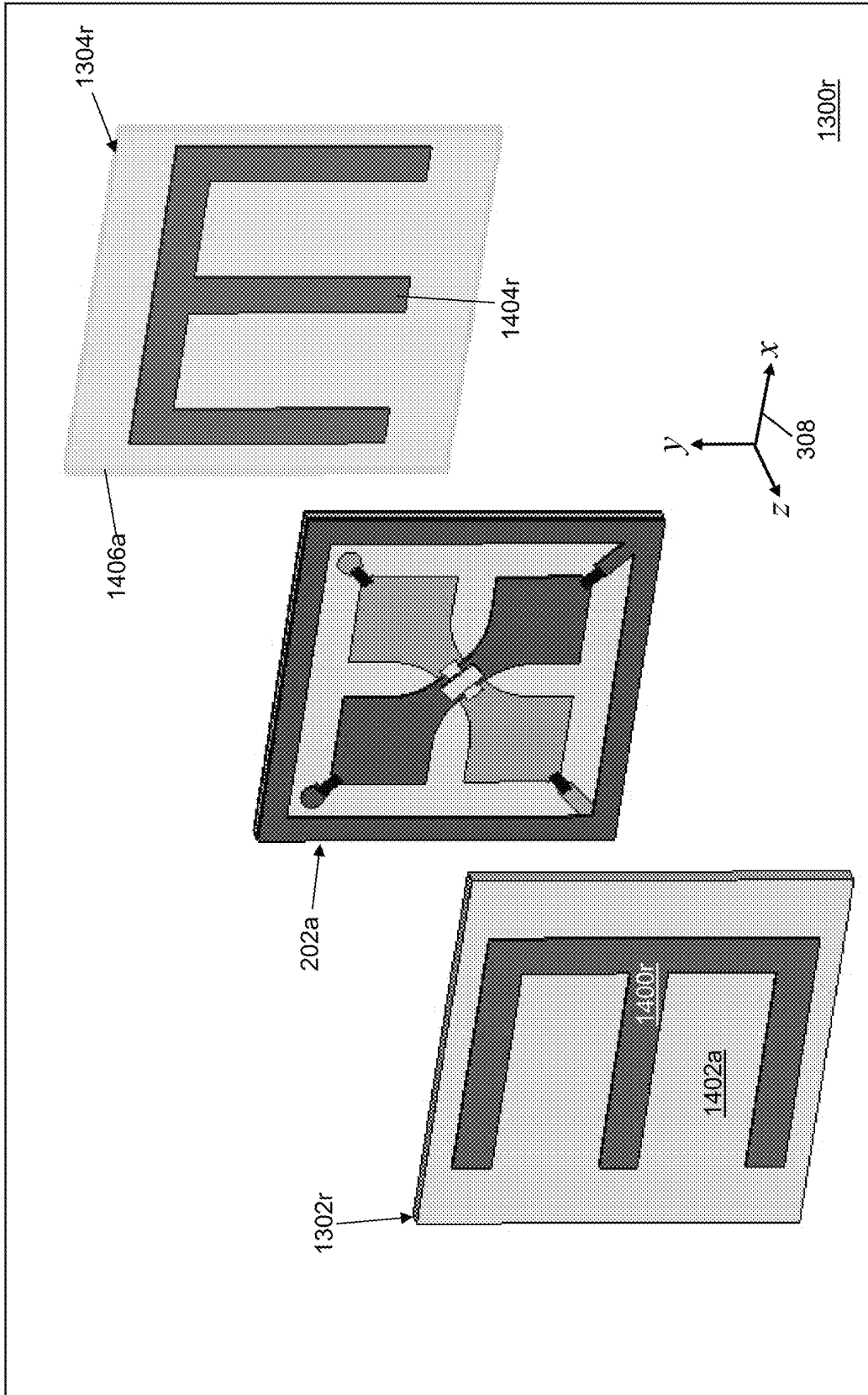


FIG. 18M

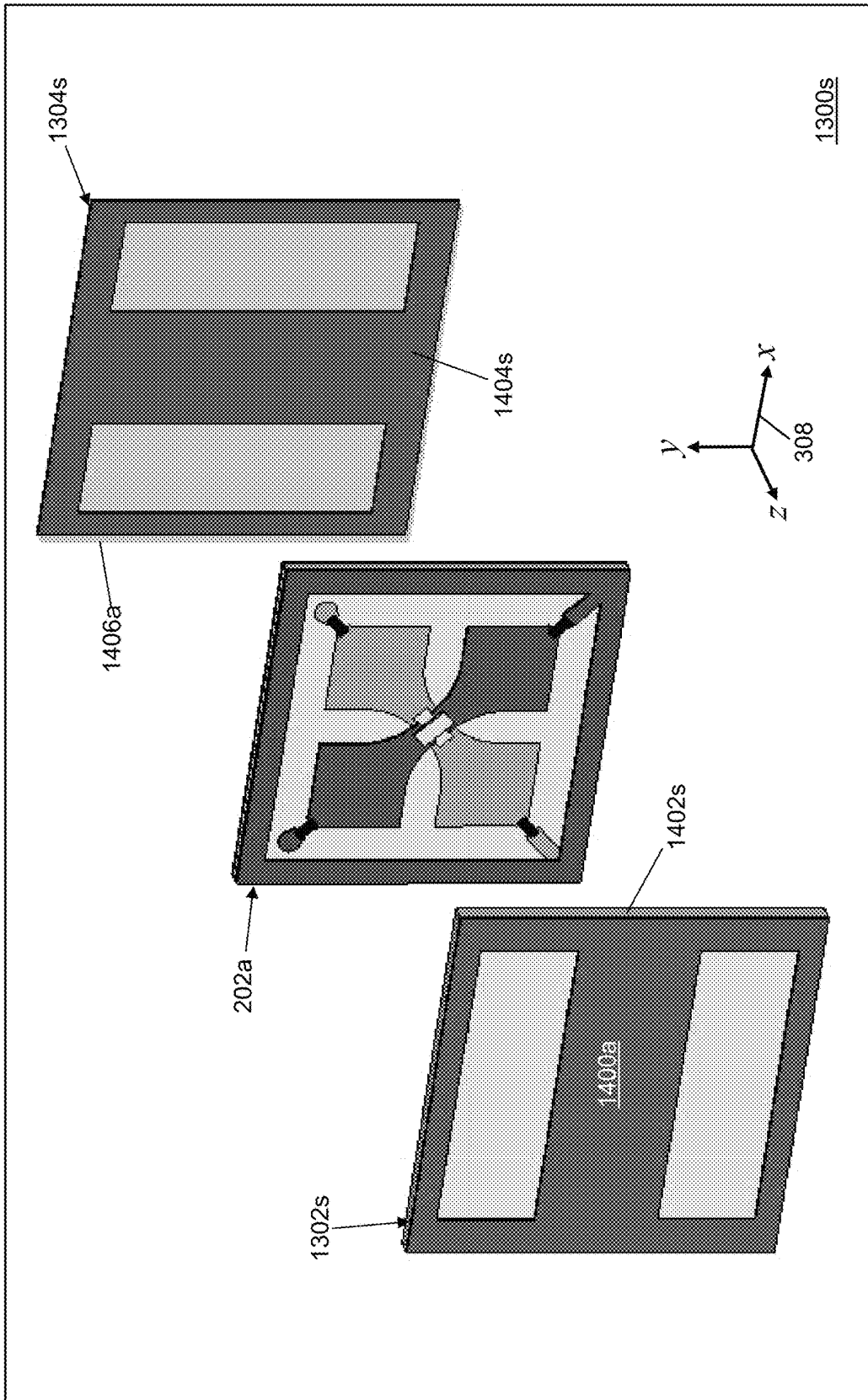


FIG. 18N

**ELECTRONICALLY RECONFIGURABLE
POLARIZATION-ROTATING PHASE
SHIFTER**

REFERENCE TO GOVERNMENT RIGHTS

This invention was made with government support under N00014-19-1-2502 and N00014-21-1-2387 awarded by the Navy/ONR. The government has certain rights in the invention.

BACKGROUND

A phased array antenna is an array of antennas in which a relative phase of signals feeding each antenna is varied such that an effective radiation pattern of the array is reinforced in a desired direction and suppressed in undesired directions to provide electronic steering of a beam. Beams are formed by shifting the phase of the signal emitted from each radiating element to provide either constructive or destructive interference to steer the beam. These antenna systems come in different sizes and scales due to several factors such as frequency and power requirements.

Each unit cell of the phased array antenna is configured to apply a specific phase shift to realize a desired phase profile over the array's aperture to form a high gain pencil beam at an intended direction. The direction of primary beam 116 can be steered by adaptively changing the phase of each array element. Ideally, it is desirable to have the phased array antenna's unit cells that can be reconfigured to yield any arbitrary phase shift values between 0° and 360° to provide perfect phase correction. However, the reconfiguration techniques to achieve any arbitrary phase shift values between 0° and 360° require changing the control voltage continuously and individually configuring the unit cells, which results in a relatively sophisticated architecture for voltage supply circuitry. Moreover, it is challenging to realize the full, reconfigurable 0° to 360° phase range over a broad frequency range (e.g., with fractional bandwidth of larger than 10%).

As a result, high-power phased array antenna technology that yields an affordable system is a major problem in the commercial and military wireless industry. Additionally, the solid-state technology that lies at the heart of current phased array antenna technology has inherent limitations when it comes to power and heat handling capability due to the generation of a large amount of heat. These limitations reduce the practicality of these reconfiguration techniques for various scenarios where phased array antennas having large numbers of unit cells and wideband operation is needed. Therefore, instead of fulfilling a continuous 0° to 360° phase range, discrete phase correction schemes that quantize this phase range into a number of discrete levels have been widely adopted in order to reduce the complexity of the control circuitry and increase operating bandwidths of beam-steerable phased array antennas. The simplest phase quantization scheme is 1-bit, which has been demonstrated as sufficient for beam scanning operation.

SUMMARY

In an illustrative embodiment, a polarization rotating antenna element is provided. The polarization rotating antenna element includes, but is not limited to, a first impedance structure, a second impedance structure, and a polarization rotating element. The first impedance structure comprising includes, but is not limited to, a first dielectric

slab and a first conducting pattern layer. The first dielectric slab is formed of a first dielectric material and has a first face and a second face. The first face is on an opposite side of the first dielectric slab relative to the second face. The first conducting pattern layer is formed of a first electrically conductive material mounted on the first face of the first dielectric slab. The second impedance structure includes, but is not limited to, a second dielectric slab and a second conducting pattern layer. The second dielectric slab is formed of a second dielectric material and has a third face and a fourth face. The third face is on an opposite side of the second dielectric slab relative to the fourth face. The second conducting pattern layer is formed of a second electrically conductive material mounted on the third face of the second dielectric slab. The polarization rotating element includes, but is not limited to, a frame, a third dielectric slab, a third conducting pattern layer, a first switch, a fourth conducting pattern layer, and a second switch. The frame is formed of a third electrically conductive material. The third dielectric slab includes a first dielectric surface and a second dielectric surface formed within the frame. The first dielectric surface is on an opposite side of the third dielectric slab relative to the second dielectric surface. The third dielectric slab is formed of a third dielectric material. The third conducting pattern layer is formed of a third electrically conductive material mounted to the first dielectric surface between the first dielectric surface and the second face of the first dielectric slab. The third conducting pattern layer includes a first conductor and a second conductor. The first switch is connected between the first conductor and the second conductor to electrically connect the first conductor to the second conductor or to electrically disconnect the first conductor from the second conductor. When the first conductor and the second conductor are electrically connected, the first conductor and the second conductor form a first dipole. The fourth conducting pattern layer is formed of a fourth electrically conductive material mounted to the second dielectric surface between the second dielectric surface and the fourth face of the second dielectric slab. The fourth conducting pattern layer includes a third conductor and a fourth conductor. The second switch is connected between the third conductor and the fourth conductor to electrically connect the third conductor to the fourth conductor or to electrically disconnect the third conductor from the fourth conductor. When the third conductor and the fourth conductor are electrically connected, the third conductor and the fourth conductor form a second dipole.

In another illustrative embodiment, a phased array antenna is provided. The phased array antenna includes, but is not limited to, a plurality of polarization rotating antenna elements.

Other principal features of the disclosed subject matter will become apparent to those skilled in the art upon review of the following drawings, the detailed description, and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Illustrative embodiments of the disclosed subject matter will hereafter be described referring to the accompanying drawings, wherein like numerals denote like elements.

FIG. 1 depicts a block diagram of a transceiver system in accordance with an illustrative embodiment.

FIG. 2 depicts alternative operational block diagrams of the transceiver system of FIG. 1 in accordance with an illustrative embodiment.

FIG. 3 depicts a perspective side view of the transceiver system of FIG. 1 in accordance with an illustrative embodiment.

FIG. 4 depicts a perspective back view of the transceiver system of FIG. 1 with a polarization rotating element layer separated from a back antenna element layer in accordance with an illustrative embodiment.

FIGS. 5A to 5E depict patterns of a distribution of switch modes for each polarization rotating element included in the polarization rotating element layer of FIG. 4 to generate a beam steered to 0°, 15°, 30°, 45°, 60°, respectively, in accordance with an illustrative embodiment.

FIG. 6 depicts a perspective view of a polarization rotating antenna element comprised of two ridge horn antennas in accordance with an illustrative embodiment.

FIG. 7A depicts a front cross-section view of the ridge horn antenna of FIG. 6 in accordance with an illustrative embodiment.

FIG. 7B depicts a side cross-section view of the ridge horn antenna of FIG. 6 in accordance with an illustrative embodiment.

FIG. 8A depicts a transparent perspective view of a polarization rotating element of the polarization rotating antenna element of FIG. 6 in accordance with an illustrative embodiment.

FIG. 8B depicts a back view of the polarization rotating element of FIG. 8A in accordance with an illustrative embodiment.

FIG. 8C depicts a front view of the polarization rotating element of FIG. 8A in accordance with an illustrative embodiment.

FIG. 9A depicts a simulated y-y reflection coefficient from the polarization rotating antenna element of FIG. 6 as a function of frequency for each switch mode in accordance with an illustrative embodiment.

FIG. 9B depicts a simulated x-y transmission coefficient from the polarization rotating antenna element of FIG. 6 as a function of frequency for each switch mode in accordance with an illustrative embodiment.

FIG. 9C depicts a simulated phase of each switch mode from the polarization rotating antenna element of FIG. 6 as a function of frequency in accordance with an illustrative embodiment.

FIG. 9D depicts a simulated phase difference between the two switch modes of the polarization rotating antenna element of FIG. 6 as a function of frequency in accordance with an illustrative embodiment.

FIG. 10 depicts a simulated realized gain for the distribution patterns of FIGS. 5A to 5E as a function of scan angle at 10.0 gigahertz (GHz) in accordance with an illustrative embodiment.

FIG. 11A depicts a perspective view of a second polarization rotating antenna element comprised of two quad-ridge horn antennas in accordance with an illustrative embodiment.

FIG. 11B depicts a perspective view of a third polarization rotating antenna element comprised of the polarization rotating antenna element of FIG. 6 with a dielectric lens in accordance with an illustrative embodiment.

FIG. 11C depicts a perspective view of the third polarization rotating antenna element of FIG. 11B with the dielectric lens exploded from the ridge horn antenna in accordance with an illustrative embodiment.

FIG. 11D depicts a side cross-section view of the dielectric lens of FIG. 11B in accordance with an illustrative embodiment.

FIG. 11E depicts a perspective view of a fourth polarization rotating antenna element comprised of the polarization rotating antenna element of FIG. 6 with a second dielectric lens in accordance with an illustrative embodiment.

FIG. 11F depicts a perspective view of a fifth polarization rotating antenna element comprised of the polarization rotating antenna element of FIG. 6 with a third dielectric lens in accordance with an illustrative embodiment.

FIG. 11G depicts a perspective view of a sixth polarization rotating antenna element comprised of the polarization rotating antenna element of FIG. 6 with a fourth dielectric lens in accordance with an illustrative embodiment.

FIG. 11H depicts a perspective view of a seventh polarization rotating antenna element comprised of the polarization rotating antenna element of FIG. 6 with a fifth dielectric lens in accordance with an illustrative embodiment.

FIG. 11I depicts a perspective view of a third polarization rotating antenna element comprised of two double-ridged antennas in accordance with an illustrative embodiment.

FIG. 12A depicts a back view of a second polarization rotating element in accordance with an illustrative embodiment.

FIG. 12B depicts a front view of the second polarization rotating element of FIG. 12A in accordance with an illustrative embodiment.

FIG. 12C depicts a back view of a third polarization rotating element in accordance with an illustrative embodiment.

FIG. 12D depicts a front view of the third polarization rotating element of FIG. 12C in accordance with an illustrative embodiment.

FIG. 12E depicts a back view of a fourth polarization rotating element in accordance with an illustrative embodiment.

FIG. 12F depicts a front view of the fourth polarization rotating element of FIG. 12E in accordance with an illustrative embodiment.

FIG. 12G depicts a back view of a fifth polarization rotating element in accordance with an illustrative embodiment.

FIG. 12H depicts a front view of the fifth polarization rotating element of FIG. 12G in accordance with an illustrative embodiment.

FIG. 12I depicts a back view of a sixth polarization rotating element in accordance with an illustrative embodiment.

FIG. 12J depicts a front view of the sixth polarization rotating element of FIG. 12I in accordance with an illustrative embodiment.

FIG. 12K depicts a back view of a seventh polarization rotating element in accordance with an illustrative embodiment.

FIG. 12L depicts a front view of the seventh polarization rotating element of FIG. 12K in accordance with an illustrative embodiment.

FIG. 13 depicts a block diagram of the transceiver system of FIG. 1 comprised of layer antennas in accordance with an illustrative embodiment.

FIG. 14A depicts a perspective view of a first polarization rotating layer antenna element comprised of two patch conducting layers in accordance with an illustrative embodiment.

FIG. 14B depicts a perspective view of a second polarization rotating layer antenna element comprised of two strip conducting layers in accordance with an illustrative embodiment.

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FIG. 14C depicts a perspective view of a third layered polarization rotating layer antenna element comprised of two cross conducting layers in accordance with an illustrative embodiment.

FIG. 14D depicts a perspective view of a fourth polarization rotating layer antenna element comprised of two Jerusalem cross conducting layers in accordance with an illustrative embodiment.

FIG. 14E depicts a perspective view of a fifth polarization rotating layer antenna element comprised of two cross slot conducting layers in accordance with an illustrative embodiment.

FIG. 15A depicts an exploded perspective view of the first polarization rotating layer antenna element of FIG. 14A in accordance with an illustrative embodiment.

FIG. 15B depicts an exploded perspective view of the second polarization rotating layer antenna element of FIG. 14B in accordance with an illustrative embodiment.

FIG. 15C depicts an exploded perspective view of the third polarization rotating layer antenna element of FIG. 14C in accordance with an illustrative embodiment.

FIG. 15D depicts an exploded perspective view of the fourth polarization rotating layer antenna element of FIG. 14D in accordance with an illustrative embodiment.

FIG. 15E depicts an exploded perspective view of the fifth polarization rotating layer antenna element of FIG. 14E in accordance with an illustrative embodiment.

FIG. 16A depicts an exploded perspective view of a first phased array antenna comprised of first polarization rotating layer antenna elements in accordance with an illustrative embodiment.

FIG. 16B depicts an exploded perspective view of a second phased array antenna comprised of second polarization rotating layer antenna elements in accordance with an illustrative embodiment.

FIG. 16C depicts an exploded perspective view of a third phased array antenna comprised of third polarization rotating layer antenna elements in accordance with an illustrative embodiment.

FIG. 16D depicts an exploded perspective view of a fourth phased array antenna comprised of fourth polarization rotating layer antenna elements in accordance with an illustrative embodiment.

FIG. 16E depicts an exploded perspective view of a fifth phased array antenna comprised of fifth polarization rotating layer antenna elements in accordance with an illustrative embodiment.

FIG. 17 depicts an equivalent circuit structure used to model a layer antenna element in accordance with an illustrative embodiment.

FIG. 18A depicts a perspective view of a sixth polarization rotating layer antenna element comprised of two wire-grid conducting layers in accordance with an illustrative embodiment.

FIG. 18B depicts a perspective view of a seventh polarization rotating layer antenna element comprised of two L-resonator conducting layers in accordance with an illustrative embodiment.

FIG. 18C depicts a perspective view of an eighth polarization rotating layer antenna element comprised of two slot array conducting layers in accordance with an illustrative embodiment.

FIG. 18D depicts a perspective view of a ninth polarization rotating layer antenna element comprised of two V-shaped slot conducting layers in accordance with an illustrative embodiment.

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FIG. 18E depicts a perspective view of a tenth polarization rotating layer antenna element comprised of two L-shaped slot conducting layers in accordance with an illustrative embodiment.

FIG. 18F depicts a perspective view of an eleventh polarization rotating layer antenna element comprised of two bow-tie conducting layers in accordance with an illustrative embodiment.

FIG. 18G depicts a perspective view of a twelfth polarization rotating layer antenna element comprised of two split-ring resonator conducting layers in accordance with an illustrative embodiment.

FIG. 18H depicts a perspective view of a thirteenth polarization rotating layer antenna element comprised of two double split-ring resonator conducting layers in accordance with an illustrative embodiment.

FIG. 18I depicts a perspective view of a fourteenth polarization rotating layer antenna element comprised of two rectangular slot conducting layers in accordance with an illustrative embodiment.

FIG. 18J depicts a perspective view of a fifteenth polarization rotating layer antenna element comprised of two H-shaped slot conducting layers in accordance with an illustrative embodiment.

FIG. 18K depicts a perspective view of a sixteenth polarization rotating layer antenna element comprised of two S-shaped resonator conducting layers in accordance with an illustrative embodiment.

FIG. 18L depicts a perspective view of a seventeenth polarization rotating layer antenna element comprised of two split-ring conducting layers in accordance with an illustrative embodiment.

FIG. 18M depicts a perspective view of an eighteenth polarization rotating layer antenna element comprised of two E-shaped resonator conducting layers in accordance with an illustrative embodiment.

FIG. 18N depicts a perspective view of a nineteenth polarization rotating layer antenna element comprised of two rectangular slot array conducting layers in accordance with an illustrative embodiment.

DETAILED DESCRIPTION

Referring to FIG. 1, a side view of a transceiver system **100** is shown in accordance with an illustrative embodiment. Transceiver system **100** may include a transceiver antenna **102**, a phased array antenna **104**, and a switch controller **108**. Transceiver system **100** may act as a transmitter and/or a receiver of analog or digital signals and need not necessarily support both transmission and reception of signals to/from phased array antenna **104**. Phased array antenna **104** includes a plurality of polarization rotating antenna elements.

Transceiver antenna **102** may be a dipole antenna, a monopole antenna, a helical antenna, a microstrip antenna, a patch antenna, a fractal antenna, a feed horn, a slot antenna, an end fire antenna, a parabolic antenna, double ridge horn antenna etc. Transceiver antenna **102** is positioned a focal distance **109**, f_a , from a back face of the plurality of polarization rotating antenna elements that is closest to transceiver antenna **102**.

In the illustrative embodiment, transceiver antenna **102** radiates an electromagnetic wave **113** towards the back face of phased array antenna **104**. Each polarization rotating antenna element **106** of the plurality of polarization rotating antenna elements rotates the incoming electromagnetic wave by either $+90^\circ$ or -90° dependent on a pair of switch

states of a polarization rotating element **202** (shown referring to FIG. **2**) of each polarization rotating antenna element **106**. Each polarization rotating antenna element **106** of the plurality of polarization rotating antenna elements may be connected to switch controller **108** that controls a switch state of each polarization rotating element **202** of each polarization rotating element to electronically steer a primary beam **116** radiated from phased array antenna **104**.

The plurality of polarization rotating antenna elements is arranged to form phased array antenna **104**. For example, a front of phased array antenna **104** may be arranged to form a one-dimensional (1D) or a two-dimensional (2D) array of the plurality of polarization rotating antenna elements. The plurality of polarization rotating antenna elements may form variously shaped apertures including circular, rectangular, square, elliptical, etc. The plurality of polarization rotating antenna elements can include any number of polarization rotating antenna elements.

Phased array antenna **104** can electronically change a pointing direction of primary beam **116** by changing a phase shift of the electric field output E^{out} from each polarization rotating antenna element **106** relative to an electric field input E^{inc} to each polarization rotating antenna element **106** under control of switch controller **108**. For example, a portion of the electric field input E^{inc} from transceiver antenna **102** having a radiating direction **110** is received by and radiated individually from each polarization rotating antenna element **106**. For example, a first electromagnetic field output **112** is shown radiated from an illustrative polarization rotating antenna element **106**. A boresight axis direction **114** is defined relative to a center of phased array antenna **104** and represents a zero-degree steering angle θ of primary beam **116**. Switch controller **108** thereby electronically steers primary beam **116** to different directions without moving any of the plurality of polarization rotating antenna elements or phased array antenna **104**.

The electromagnetic energy associated with the electrical energy field input E^{inc} from transceiver **102** is fed to each polarization rotating antenna element **106** of the plurality of polarization rotating antenna elements through free space in the illustrative embodiment though other types of feeds may be used in alternative embodiments. Based on the selected pointing direction of primary beam **116**, switch controller **108** defines a phase shift value to be generated by each polarization rotating antenna element **106** of the plurality of polarization rotating antenna elements. Each polarization rotating antenna element **106** provides 1-bit phase quantization as discussed further below so that each polarization rotating antenna element **106** acts as a 1-bit phase shifter.

With the phase relationship defined by switch controller **108** for each polarization rotating antenna element **106**, the electromagnetic waves from transceiver antenna **102** are rotated based on each switch state to add together to increase the radiation in the pointing direction of primary beam **116**, while cancelling to suppress radiation in undesired directions. The lines from each polarization rotating antenna element **106** represent a wave front **115** of the electromagnetic waves emitted by each polarization rotating antenna element **106**. The individual wave fronts are spherical, but they combine in front of phased array antenna **104** to create a plane wave such that primary beam **116** is radiated in the desired pointing direction.

In the illustration of FIG. **1**, a phase shift selected for each polarization rotating antenna element **106** delays the waves progressively going up the aperture of phased array antenna **104** so that each polarization rotating antenna element **106** emits its electromagnetic wave front later than the one below

it. The resulting plane wave is directed at the steering angle θ measured relative to boresight axis direction **114** of phased array antenna **104**. By changing the phase shifts of each polarization rotating antenna element **106**, switch controller **108** can quickly change the steering angle θ of primary beam **116**. A 2D phased array can steer primary beam **116** in two dimensions.

Transceiver system **100** may include a plurality of transceivers, and phased array antenna **104** may be organized into subarrays to support a plurality of main beams. For example, a distinct transceiver **102** may be associated with one or more polarization rotating antenna elements. Additionally, in alternative embodiments, transceiver **102** may only transmit or only receive.

Referring to FIG. **2**, a block diagram of operation of transceiver system **100** is shown in accordance with an illustrative embodiment. Polarization rotating antenna element **106** may have a first antenna **200**, polarization rotating element **202**, and a second antenna **204**. First antenna **200** may include a first impedance matching section **212a** and a first waveguide section **214a**. Second antenna **202** may include a second impedance matching section **212b** and a second waveguide section **214b**. Switch controller **108** is connected to control a switch state of polarization rotating element **202**. First impedance matching section **212a** matches an impedance between free space and first waveguide section **214a** to reduce a signal loss. Second impedance matching section **212b** matches an impedance between second waveguide section **214b** and free space.

When operating as a transmitter, transceiver antenna **102** may radiate electromagnetic wave **113** toward first impedance matching section **212a** of first antenna **200**. For illustration, electromagnetic wave **113** may be represented by a first electromagnetic (EM) orthogonal system **208**.

An EM orthogonal system defines an orthogonal system for an electromagnetic wave in free space and includes an electric field direction vector indicated by E, a magnetic field direction vector indicated by H, and a wave vector direction vector indicated by K. K indicates a direction of propagation of the electric field E and the magnetic field H that are orthogonal to each other. K is also orthogonal to the electric field E and the magnetic field H. By convention, the polarization of circularly polarized electromagnetic waves refers to a direction of the electric field E and the fields rotate in either a right-hand direction (the electric field E into the magnetic field H) or in a left-hand direction (the magnetic field H into the electric field E). For linearly polarized electromagnetic waves, the fields oscillate along their axes (up or down) as they propagate.

First EM orthogonal system **208** defines an orthogonal system for electromagnetic wave **113** radiated from transceiver antenna **102** in an illustrative embodiment where the incoming electric field E_{inc} is directed upwards meaning a vertically polarized radiated field. The radiated electric field E_{inc} may be oriented in alternative directions in alternative embodiments. Depending on a switch state of polarization rotating element **202**, polarization rotating antenna element **106** rotates the incoming electric field E_{inc} by $+90^\circ$ or -90° . Second EM orthogonal system **210a** defines an orthogonal system for a first outgoing electromagnetic wave $E_{out,1}$ from polarization rotating antenna element **106** that is rotated -90° . Third EM orthogonal system **210b** defines an orthogonal system for a second outgoing electromagnetic wave $E_{out,2}$ from polarization rotating antenna element **106** that is rotated $+90^\circ$. Based on first EM orthogonal system **208** and a switch state of polarization rotating element **202**, an orientation of first electromagnetic field output **112** radiated

from second impedance matching section **212b** of second antenna **204** of polarization rotating antenna element **106** is defined by either second EM orthogonal system **210a** or third EM orthogonal system **210b**. As a result, electromagnetic wave **113** is rotated by polarization rotating antenna element **106** by $+90^\circ$ or -90° .

When operating as a receiver, a first electromagnetic field input represented by first EM orthogonal system **208** is received by second impedance matching section **212b** of second antenna **204** and propagated through polarization rotating antenna element **106**. The propagated first electromagnetic field input is radiated from first impedance matching section **212a** of first antenna **202** toward transceiver antenna **102**. The electromagnetic field radiated toward transceiver antenna **102** may be represented by either second EM orthogonal system **210a** or third EM orthogonal system **210b** depending on a switch state of polarization rotating element **202**.

Referring to FIG. 3, a perspective side view of transceiver system **100** is shown in accordance with an illustrative embodiment. Referring to FIG. 4, a perspective back view of transceiver system **100** is shown in accordance with an illustrative embodiment. In the illustrative embodiment, phased array antenna **104** is a 2D array of 400 polarization rotating antenna elements arranged to form a 20×20 rectangle. First antenna **200**, polarization rotating element **202**, and second antenna **204** are mounted adjacent to each other in an axial direction parallel to a z-axis of an orthogonal coordinate reference frame **308** with polarization rotating element **202** between first antenna **200** that is closest to transceiver antenna **102** and second antenna **204**. The z-axis of orthogonal coordinate reference frame **308** is parallel to the direction of propagation K_{inc} of the incoming electric field E_{inc} and the incoming magnetic field H_{inc} . Based on this arrangement, phased array antenna **104** can be described as including a first antenna element grid **300**, a polarization rotating antenna layer **302**, and a second antenna element grid **304**. First antenna element grid **300** includes 400 first antennas **200**. Polarization rotating antenna layer **302** includes 400 polarization rotating elements **202**. Second antenna element grid **304** includes 400 second antennas **204**. Phased array antenna **104** has an aperture length **400** direction parallel to an x-axis of orthogonal coordinate reference frame **308**, an aperture width **402** direction parallel to a y-axis of first EM orthogonal system **208**, and an aperture depth **306** direction parallel to the z-axis. Orthogonal coordinate reference frame **308** includes an x-axis, a y-axis, and the z-axis to form a right-handed coordinate reference frame.

Distribution patterns for the switch positions of each polarization rotating element **202** of polarization rotating antenna layer **302** to generate a beam steered to scan angles at 0° , 15° , 30° , 45° , and 60° relative to boresight axis **114** are shown in FIGS. 5A to 5E, respectively, in accordance with an illustrative embodiment, where “Mode 1” indicates a first pair of switch positions for a respective polarization rotating element **202**, “and “Mode 2” indicates a second pair of switch positions for a respective polarization rotating element **202**, where each pixel represents a distinct polarization rotating element **202**.

Referring to FIG. 6, an exploded perspective view of a first polarization rotating antenna element **106a** is shown in accordance with an illustrative embodiment. First polarization rotating antenna element **106a** includes a first ridge horn antenna **200a**, a first polarization rotating element **202a**, and a second ridge horn antenna **204a**. Each of first ridge horn antenna **200a**, first polarization rotating element **202a**, and second ridge horn antenna **204a** has a square shaped cross-

section in the x-y plane defined by orthogonal coordinate reference frame **308** though other cross-sectional shapes may be used in alternative embodiments. Each of first ridge horn antenna **200a**, first polarization rotating element **202a**, and second ridge horn antenna **204a** further have common widths and lengths in the x-y plane. As understood by a person of skill in the art, dimensions of first ridge horn antenna **200a** and second ridge horn antenna **204a** may be defined based on a desired center frequency of the incoming electromagnetic wave. First ridge horn antenna **200a** and second ridge horn antenna **204a** are identical except that second ridge horn antenna **204a** is rotated 90° in the x-y plane relative to first ridge horn antenna **200a** and is rotated 180° in the x-z plane relative to first ridge horn antenna **200a**.

First polarization rotating element **202a** is shown as transparent and includes a first back dipole **604a**, a first switch **606**, a first front dipole **608a**, and a second switch **610**. Polarization rotating antenna element **202** is a conduit with a frame formed of electrically conductive material to confine and direct radio signals such that polarization rotating antenna element **202** acts as a resonator. First back dipole **604a** and first switch **606** are separated from first front dipole **608a** and second switch **610** by a dielectric material such that first back dipole **604a** and first switch **606** do not contact first front dipole **608a** and second switch **610**. The dielectric material may include one or more dielectric materials such as foamed polyethylene, solid polyethylene, polyethylene foam, polytetrafluoroethylene, air, air space polyethylene, vacuum, etc.

FIG. 7A depicts a front cross-section view of first ridge horn antenna **200a** in accordance with an illustrative embodiment. FIG. 7B depicts a side cross-section view of first ridge horn antenna **200a** in accordance with an illustrative embodiment. First ridge horn antenna **200a** includes first impedance matching section **212a** and first waveguide section **214a**. First waveguide section **214a** is a double-ridge waveguide comprised of sidewalls that form a frame and two ridges that face each other with a gap between end faces of the pair of ridges. First impedance matching section **212a** includes legs that taper toward the sidewalls and ridges of first waveguide section **214a**.

First ridge horn antenna **200a** has a total depth **700** parallel to the z-axis of orthogonal coordinate reference frame **308**, a tapered leg depth **701** parallel to the z-axis of orthogonal coordinate reference frame **308**, a center channel length **702** parallel to the y-axis of orthogonal coordinate reference frame **308**, a tapered leg length **703** parallel to the y-axis of orthogonal coordinate reference frame **308**, a conductor length **704** parallel to the y-axis of orthogonal coordinate reference frame **308**, a leg length **710** parallel to the y-axis of orthogonal coordinate reference frame **308**, a center channel width **705** parallel to the x-axis of orthogonal coordinate reference frame **308**, and a tapered leg width **706** parallel to the x-axis of orthogonal coordinate reference frame **308**. A conductor width parallel to the x-axis of orthogonal coordinate reference frame **308** is equal to conductor length **704** in the illustrative embodiment to form a square cross-section shape. As understood by a person of skill in the art, dimensions of first ridge horn antenna **200a** and second ridge horn antenna **204a** may be defined based on the desired center frequency of the incoming electromagnetic wave.

FIG. 8A depicts a transparent perspective view of first polarization rotating element **202a** in accordance with an illustrative embodiment. FIG. 8B depicts a back view of first polarization rotating element **202a** in accordance with an

illustrative embodiment. FIG. 8C depicts a front view of first polarization rotating element 202a in accordance with an illustrative embodiment. First polarization rotating element 202a further may include a dielectric layer 800 formed of a dielectric material surrounded by a conductive frame 802 formed of a conductive material. The electrically conductive material may be copper plated steel, silver plated steel, silver plated copper, silver plated copper clad steel, copper, copper clad aluminum, steel, etc. Conductive frame 802 has a conductive layer width 826 parallel to the x-axis of orthogonal coordinate reference frame 308, a conductive layer length 830 parallel to the y-axis of orthogonal coordinate reference frame 308, and a rotator depth (not shown) parallel to the z-axis of orthogonal coordinate reference frame 308. Dielectric layer 800 has a dielectric layer width 828 parallel to the x-axis of orthogonal coordinate reference frame 308 and a dielectric layer length 832 parallel to the y-axis of orthogonal coordinate reference frame 308.

First back dipole 604a includes a first conductor 820a and a second conductor 820b formed on a back surface of dielectric layer 800. First switch 606 is mounted to the back surface of dielectric layer 800 to electrically connect first conductor 820a and second conductor 820b. A first dielectric channel 822 is formed between first conductor 820a and second conductor 820b. First front dipole 608a includes a third conductor 820c and a fourth conductor 820d formed on a front surface of dielectric layer 800. Second switch 610 is mounted to the front surface of dielectric layer 800 to electrically connect third conductor 820c and fourth conductor 820d. A second dielectric channel 824 is formed between third conductor 820c and fourth conductor 820d.

First back dipole 604a defines a conducting pattern layer mounted to the back surface of dielectric layer 800, and first front dipole 608a defines an identical conducting pattern layer mounted to the front surface of dielectric layer 800. Each of first conductor 820a, second conductor 820b, third conductor 820c, and fourth conductor 820d is oriented $\pm 45^\circ$ relative to the incoming electric field E_{inc} and to first outgoing electromagnetic wave $E_{out,1}$ and to second outgoing electromagnetic wave $E_{out,2}$. Because first polarization rotating element 202a is a resonant structure, there is no loss of power at steady-state due to internal reflections of the incoming electric field E_{inc} regardless of the orientation of $\pm 45^\circ$ relative to the incoming electric field E_{inc} .

First conductor 820a, second conductor 820b, third conductor 820c, and fourth conductor 820d have a common shape and size though each is oriented toward a different corner of dielectric layer 800. In the illustrative embodiment of FIGS. 8A, 8B, and 8C, first conductor 820a, second conductor 820b, third conductor 820c, and fourth conductor 820d each have an arrow shape with a tip of the arrow pointed toward a different corner of dielectric layer 800 and a shaft of the arrow pointed toward either first switch 606 or second switch 610. First conductor 820a, second conductor 820b, third conductor 820c, and fourth conductor 820d may have other shapes and configurations in alternative embodiments as shown with reference to FIGS. 12A through 12L.

First switch 606 and second switch 610 may be mechanical switches, a microelectromechanical system (MEMS) switches, commercially available single-pole, single-throw switches, one or more PIN diodes, photoconductive switches, photoelectric switches, etc. Each of first switch 606 and second switch 610 form a switchable connection between two states: a conducting or closed state and a non-conducting or open state. First switch 606 and second switch 610 are connected to receive a signal from switch controller 108 to determine switching state. When first

switch 606 is controlled to the conducting or closed state, second switch 610 is controlled to the non-conducting or open state such that only one of first back dipole 604a and first front dipole 608a is in the conducting or closed state at a time.

When first switch 606 is in the conducting or closed state and second switch 610 is in the non-conducting or open state, first conductor 820a and second conductor 820b of first back dipole 604a are connected to form a dipole to rotate the incoming electric field E_{inc} -90° such that first polarization rotating element 202a forms first outgoing electromagnetic wave $E_{out,1}$ as illustrated by second EM orthogonal system 210a. "Mode 1" may be defined as first switch 606 in the conducting or closed state and second switch 610 in the non-conducting or open state.

When first switch 606 is in the non-conducting or open state and second switch 610 is in the conducting or closed state, third conductor 820c and fourth conductor 820d of first front dipole 608a are connected to form a dipole to rotate the incoming electric field E_{inc} $+90^\circ$ such that first polarization rotating element 202a forms second outgoing electromagnetic wave $E_{out,2}$ as illustrated by third EM orthogonal system 210b. "Mode 2" may be defined as first switch 606 in the non-conducting or open state and second switch 610 in the conducting or closed state. Thus, each mode defines a pair of switch states that each define a state of first switch 606 and of second switch 610.

In the illustrative embodiment, first switch 606 and second switch 610 are each PIN diodes. To provide radio frequency (RF) direct current (DC) isolation, a DC bias voltage is provided through the inductors. For example, a first inductor 804 is connected between an edge of first conductor 820a generally opposite first switch 606 and a first conductive channel 812, and a second inductor 806 is connected between an edge of second conductor 820b generally opposite first switch 606 and a first conductive via 814. First conductive channel 812 is connected to conductive frame 802. In an illustrative embodiment, conductive frame 802 may be maintained at a ground level voltage; whereas, a DC bias voltage may be provided through first conductive via 814 to thereby provide the DC bias voltage across first conductor 820a and second conductor 820b and thereby across first switch 606. First conductor 820a and second conductor 820b are electrically connected when first switch 606 is forward biased and electrically isolated when first switch 606 is reverse biased.

Similarly, a third inductor 808 is connected between an edge of third conductor 820c generally opposite second switch 610 and a second conductive channel 816, and a fourth inductor 810 is connected between an edge of fourth conductor 820d generally opposite second switch 610 and a second conductive via 818. Second conductive channel 816 is connected to conductive frame 802. The DC bias voltage may be provided through second conductive via 818 to thereby provide the DC bias voltage across third inductor 808 and fourth inductor 810 and thereby across second switch 610. Third conductor 820c and fourth conductor 820d are electrically connected when second switch 610 is forward biased and electrically isolated when second switch 610 is reverse biased.

For illustration, first polarization rotating antenna element 106a was designed to operate over a broad frequency band that covered the range of 6-12 gigahertz (GHz) and to support fast switching and high-power. First switch 606 and second switch 610 were implemented as high-power capable PIN diodes. Dielectric layer 800 was formed of a high-temperature-tolerant ceramic substrate with a relative per-

mittivity of 7.5, a loss tangent of 0.005, and a thermal conductivity of 170 Watts per meter Kelvin (W/mK). Conductive frame **802** was formed of copper. Conductive layer width **826** was 15 millimeters (mm), conductive layer length **830** was 15 mm, and the rotator depth was 0.63 mm. Dielectric layer width **828** was 12 mm and dielectric layer length **832** was 12 mm.

First ridge horn antenna **200a** and second ridge horn antenna **204a** were defined as small aperture, ridged, exponentially flared, horn antennas to simultaneously provide high-power handling capability and broad bandwidth. First ridge horn antenna **200a** and second ridge horn antenna **204a** were formed of copper. Total depth **700** was 41 mm, tapered leg depth **701** was 21.3 mm, center channel length **702** was 2.2 mm, tapered leg length **703** was 14 mm, leg length **710** was 12 mm, conductor length **704** was 15 mm, center channel width **705** was 5.5 mm, and tapered leg width **706** was 3.25 mm. The aperture size was a square with dimensions of 14 mm×14 mm. To improve the impedance matching of first polarization rotating antenna element **106a** to free space, a smooth exponential taper of the ridge was used for both first impedance matching section **212a** and second impedance matching section **212b**.

The designed first polarization rotating antenna element **106a** was simulated and optimized by three-dimensional full-wave electromagnetic software and scattering parameters of the structure were extracted. Referring to FIG. 9A, a simulated y-y reflection coefficient resulting from the designed implementation of first polarization rotating antenna element **106a** is shown as a function of frequency for each switch mode in accordance with an illustrative embodiment. A first reflection coefficient curve **900** shows the simulated y-y reflection coefficient when first polarization rotating element **202a** of first polarization rotating antenna element **106a** is in the Mode 1 state. A second reflection coefficient curve **902** shows the simulated y-y reflection coefficient when first polarization rotating element **202a** of first polarization rotating antenna element **106a** is in the Mode 2 state.

Referring to FIG. 9B, a simulated x-y transmission coefficient resulting from the designed implementation of first polarization rotating antenna element **106a** is shown as a function of frequency for each switch mode in accordance with an illustrative embodiment. A first transmission coefficient curve **910** shows the simulated x-y transmission coefficient when first polarization rotating element **202a** of first polarization rotating antenna element **106a** is in the Mode 1 state. A second transmission coefficient curve **912** shows the simulated x-y transmission coefficient when first polarization rotating element **202a** of first polarization rotating antenna element **106a** is in the Mode 2 state.

Referring to FIG. 9C, a simulated phase resulting from the designed implementation of first polarization rotating antenna element **106a** is shown as a function of frequency for each switch mode in accordance with an illustrative embodiment. A first phase curve **920** shows the simulated phase when first polarization rotating element **202a** of first polarization rotating antenna element **106a** is in the Mode 1 state. A second phase curve **922** shows the simulated phase when first polarization rotating element **202a** of first polarization rotating antenna element **106a** is in the Mode 2 state.

Referring to FIG. 9D, a simulated phase difference between the two switch modes of the designed implementation of first polarization rotating antenna element **106a** is shown as a function of frequency in accordance with an illustrative embodiment. A phase difference curve **930**

shows the simulated phase difference between the two states. The phase difference is approximately 180° across the entire frequency band of interest.

Full-wave simulations of phased array antenna **104** with the 400 polarization rotating antenna elements shown referring to FIGS. 3 and 4 using the distribution patterns configured for each scan angle 0° (FIG. 5A), 15° (FIG. 5B), 30° (FIG. 5C), 45° (FIG. 5D), 60° (FIG. 5E) relative to the boresight axis at 10 GHz were performed. Referring to FIG. 10, a simulated realized gain for the five different scan angles is shown in accordance with an illustrative embodiment. A first gain curve **1000** shows the simulated realized gain for a scan angle of 0° based on the distribution pattern shown in FIG. 5A. A second gain curve **1002** shows the simulated realized gain for a scan angle of 15° based on the distribution pattern shown in FIG. 5B. A third gain curve **1004** shows the simulated realized gain for a scan angle of 30° based on the distribution pattern shown in FIG. 5C. A fourth gain curve **1006** shows the simulated realized gain for a scan angle of 45° based on the distribution pattern shown in FIG. 5D. A fifth gain curve **1008** shows the simulated realized gain for a scan angle of 60° based on the distribution pattern shown in FIG. 5E.

The simulated co-polarized peak gain is 24.6 decibels with respect to an isotropic radiator (dBi), 24 dBi, 23.5 dBi, 22.9 dBi and 20.9 dBi for the scan angles of 0°, 15°, 30°, 45°, and 60°, respectively. As a result, the scan losses for steering the beam from broadside to scan angles of 30°, 45°, and 60° are about 1.1, 1.7, and 3.7 dB, respectively. Moreover, the simulated sidelobe level is -18.4 decibels (dB), -14.8 dB, -13.6 dB, -13.3 dB, and -13.8 dB for the scan angles of 0°, 15°, 30°, 45°, and 60°, respectively.

Referring to FIG. 11A, a perspective view is shown of a second polarization rotating antenna element **106b** in accordance with an illustrative embodiment. Second polarization rotating antenna element **106b** includes a first quad-ridge horn antenna **200b**, first polarization rotating element **202a**, and a second quad-ridge horn antenna **204b**. First quad-ridge horn antenna **200b** and second quad-ridge horn antenna **204b** are identical except that second quad-ridge horn antenna **204b** is rotated 90° in the x-y plane relative to first quad-ridge horn antenna **200b** and is rotated 180° in the x-z plane relative to first quad-ridge horn antenna **200b**.

Referring to FIG. 11B, an exploded perspective view of a third polarization rotating antenna element **106c** is shown in accordance with an illustrative embodiment. Third polarization rotating antenna element **106c** includes a first spherical dielectric lens **1110a**, first ridge horn antenna **200a**, first polarization rotating element **202a**, second ridge horn antenna **204a**, and a second spherical dielectric lens **1112a**. First spherical dielectric lens **1110a** fills a space within first ridge horn antenna **200a**, and second spherical dielectric lens **1112a** fills a space within second ridge horn antenna **204a**. In the illustrative embodiment, first spherical dielectric lens **1110a** and second spherical dielectric lens **1112a** may be identical. Each of first ridge horn antenna **200a**, first polarization rotating element **202a**, and second ridge horn antenna **204a** has a square shaped cross-section in the x-y plane defined by orthogonal coordinate reference frame **308** though other cross-sectional shapes may be used in alternative embodiments.

Referring to FIG. 11C, a perspective view of first ridge horn antenna **200a** is shown with first spherical dielectric lens **1110a** exploded from a body of first ridge horn antenna **200a** in accordance with an illustrative embodiment. Referring to FIG. 11D, a side cross-section view of first spherical dielectric lens **1110a** is shown in accordance with an illus-

trative embodiment. First spherical dielectric lens **1110a** has a sphere depth **1114** parallel to the z-axis of orthogonal coordinate reference frame **308**, a body depth **1115** parallel to the z-axis of orthogonal coordinate reference frame **308**, and a sphere length **1116** parallel to the x-axis of orthogonal coordinate reference frame **308**. First spherical dielectric lens **1110a** is formed of a dielectric material to replace air or another gas that may fill the space within the body of first ridge horn antenna **200a**.

First spherical dielectric lens **1110a** completely filled the taper of first ridge horn antenna **200a** to improve the aperture efficiency. In an illustrative embodiment, first spherical dielectric lens **1110a** may be formed using a low loss and thermally stable customized dielectric material with a permittivity of 2.03 and a loss tangent of 0.0004 at 6 GHz. Sphere depth **1114** may be 7.5 mm, body depth **1115** may be 22 mm, and sphere length **1116** may be 15 mm.

Referring to FIG. 11E, a perspective view is shown of a fourth polarization rotating antenna element **106d** in accordance with an illustrative embodiment. Fourth polarization rotating antenna element **106d** includes a first funnel-shaped dielectric lens **1110b**, first ridge horn antenna **200a**, first polarization rotating element **202a**, second ridge horn antenna **204a**, and a second funnel-shaped dielectric lens **1112b**. First funnel-shaped dielectric lens **1110b** fills a center channel space within first ridge horn antenna **200a**, and second funnel-shaped dielectric lens **1112b** fills a center channel space within second ridge horn antenna **204a**. First funnel-shaped dielectric lens **1110b** and second funnel-shaped dielectric lens **1112b** are identical though rotated 180° relative to each other and include a dielectric plate with a funnel shape that extends within a center channel of first ridge horn antenna **200a** or second ridge horn antenna **204a**, respectively. In the illustrative embodiment, each plate of first funnel-shaped dielectric lens **1110b** and second funnel-shaped dielectric lens **1112b** has a length and a width in the x-y plane defined by center channel length **702** at a center of each ridge in a face closest to first polarization rotating element **202a**. In the illustrative embodiment, each plate of first funnel-shaped dielectric lens **1110b** and second funnel-shaped dielectric lens **1112b** has a length parallel to the z-axis defined by body depth **1115**, a length parallel to the x-axis defined by sphere length **1116**, and a length parallel to the y-axis defined by center channel length **702**. In the illustrative embodiment, the funnel walls are tapered to fill the tapered legs of each respective ridge horn antenna **200a** or **204a**.

Referring to FIG. 11F, a perspective view is shown of a fifth polarization rotating antenna element **106e** in accordance with an illustrative embodiment. Twentieth polarization rotating antenna element **106e** includes a first bulb-shaped dielectric lens **1110c**, first ridge horn antenna **200a**, first polarization rotating element **202a**, second ridge horn antenna **204a**, and a second bulb-shaped dielectric lens **1112c**. First bulb-shaped dielectric lens **1110c** fills a back face space within first ridge horn antenna **200a**, and second bulb-shaped dielectric lens **1112c** fills a front face space within second ridge horn antenna **204a**. First bulb-shaped dielectric lens **1110c** and second bulb-shaped dielectric lens **1112c** are identical though rotated 180° relative to each other and include a dielectric plate with a center bulb protruding outward away from a respective ridge horn antenna **200a** or **204a**. In the illustrative embodiment, each plate of first bulb-shaped dielectric lens **1110c** and second bulb-shaped dielectric lens **1112c** has a length and a width in the x-y plane defined by tapered leg length **703**.

Referring to FIG. 11G, a perspective view is shown of a sixth polarization rotating antenna element **106f** in accordance with an illustrative embodiment. Sixth polarization rotating antenna element **106f** includes a first plate-shaped dielectric lens **1110d**, first ridge horn antenna **200a**, first polarization rotating element **202a**, second ridge horn antenna **204a**, and a second plate-shaped dielectric lens **1112d**. First plate-shaped dielectric lens **1110d** fills a back face space within first ridge horn antenna **200a**, and second plate-shaped dielectric lens **1112d** fills a front face space within second ridge horn antenna **204a**. First plate-shaped dielectric lens **1110d** and second plate-shaped dielectric lens **1112d** are identical though rotated 180° relative to each other and include a dielectric plate. In the illustrative embodiment, each of first plate-shaped dielectric lens **1110d** and second plate-shaped dielectric lens **1112d** has a length and a width in the x-y plane defined by tapered leg length **703**.

Referring to FIG. 11H, a perspective view is shown of a seventh polarization rotating antenna element **106g** in accordance with an illustrative embodiment. Seventh polarization rotating antenna element **106g** includes a first stacked plate-shaped dielectric lens **1110e**, first ridge horn antenna **200a**, first polarization rotating element **202a**, second ridge horn antenna **204a**, and a second stacked plate-shaped dielectric lens **1112e**. First stacked plate-shaped dielectric lens **1110e** fills a back face space within first ridge horn antenna **200a**, and second stacked plate-shaped dielectric lens **1112e** fills a front face space within second ridge horn antenna **204a**. First stacked plate-shaped dielectric lens **1110e** and second stacked plate-shaped dielectric lens **1112e** are identical though rotated 180° relative to each other and include a plurality of dielectric plates having different dielectric constants that are stacked successively parallel to the z-axis. In the illustrative embodiment, each plate has a length and a width in the x-y plane defined by tapered leg length **703**.

Referring to FIG. 11I, a perspective view is shown of a third polarization rotating antenna element **106c** in accordance with an illustrative embodiment. Third polarization rotating antenna element **106c** includes a first double-ridge antenna **200c**, first polarization rotating element **202a**, and a second double-ridge antenna **204c**. First double-ridge antenna **200c** and second double-ridge antenna **204c** are identical except that second double-ridge antenna **204c** is rotated 90° in the x-y plane relative to first double-ridge antenna **200c** and is rotated 180° in the x-z plane relative to first double-ridge antenna **200c**.

Referring to FIG. 12A, a back view is shown of a second polarization rotating element **202b** in accordance with an illustrative embodiment. Referring to FIG. 12B, a front view is shown of second polarization rotating element **202b** in accordance with an illustrative embodiment. Second polarization rotating element **202b** is shown as transparent and includes a second back dipole **604b**, first switch **606**, a second front dipole **608b**, and second switch **610**. Second back dipole **604b** and second front dipole **608b** are formed as arrows pointed to each corner of dielectric layer **800**. Each dipole of second polarization rotating element **202b** defines a conducting pattern layer mounted to either the back surface or the front surface of dielectric layer **800**. Again, each half of each dipole of second polarization rotating element **202b** is rotated $\pm 45^\circ$ relative to the incoming electric field E_{inc} .

Referring to FIG. 12C, a back view is shown of a third polarization rotating element **202c** in accordance with an illustrative embodiment. Referring to FIG. 12D, a front view is shown of third polarization rotating element **202c** in accordance with an illustrative embodiment. Third polariza-

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tion rotating element **202c** is shown as transparent and includes a third back dipole **604c**, first switch **606**, a third front dipole **608c**, and second switch **610**. Third back dipole **604c** and third front dipole **608c** are formed as three sections extending toward a distinct corner of dielectric layer **800**. The three sections include two rectangular bars separated from a central T-shaped center conductor pointed toward a center of each corner. First switch **606** or second switch **610** is connected between a top head of each central T-shaped center conductor. Each dipole of third polarization rotating element **202c** defines a conducting pattern layer mounted to either the back surface or the front surface of dielectric layer **800**. Again, each half of each dipole of third polarization rotating antenna element **604c** is rotated $\pm 45^\circ$ relative to the incoming electric field E_{inc} .

Referring to FIG. 12E, a back view is shown of a fourth polarization rotating element **202d** in accordance with an illustrative embodiment. Referring to FIG. 12F, a front view is shown of fourth polarization rotating element **202d** in accordance with an illustrative embodiment. Fourth polarization rotating element **202d** is shown as transparent and includes a fourth back dipole **604d**, first switch **606**, a fourth front dipole **608d**, and second switch **610**. Fourth back dipole **604d** and fourth front dipole **608d** are formed as three sections extending toward a distinct corner of dielectric layer **800**. The three sections include two rectangular bars separated from a central rectangular conductor pointed toward a center of each corner. First switch **606** or second switch **610** is connected between the central rectangular conductor. The two rectangular bars on either side of the central rectangular conductor are joined for each dipole half to form a single conductor on either side of the pair of central rectangular conductors. Each dipole of fourth polarization rotating element **202d** defines a conducting pattern layer mounted to either the back surface or the front surface of dielectric layer **800**. Again, each half of each dipole of fourth polarization rotating antenna element **604d** is rotated $\pm 45^\circ$ relative to the incoming electric field E_{inc} .

Referring to FIG. 12G, a back view is shown of a fifth polarization rotating element **202e** in accordance with an illustrative embodiment. Referring to FIG. 12H, a front view is shown of fifth polarization rotating element **202e** in accordance with an illustrative embodiment. Fifth polarization rotating element **202e** is shown as transparent and includes a fifth back dipole **604e**, first switch **606**, a fifth front dipole **608e**, and second switch **610**. Fifth back dipole **604e** and fifth front dipole **608e** are formed as split rings with a shaft of each split ring extending toward a distinct corner of dielectric layer **800**. First switch **606** or second switch **610** is connected between the shafts of each split ring. Each dipole of fifth polarization rotating element **202e** defines a conducting pattern layer mounted to either the back surface or the front surface of dielectric layer **800**. Again, each half of each dipole of fifth polarization rotating element **202e** is rotated $\pm 45^\circ$ relative to the incoming electric field E_{inc} .

Referring to FIG. 12I, a back view is shown of a sixth polarization rotating element **202f** in accordance with an illustrative embodiment. Referring to FIG. 12J, a front view is shown of sixth polarization rotating element **202f** in accordance with an illustrative embodiment. Sixth polarization rotating element **202f** is shown as transparent and includes a sixth back dipole **604f**, first switch **606**, a sixth front dipole **608f**, and second switch **610**. Sixth back dipole **604f** and sixth front dipole **608f** are formed as meander line dipoles with a first end of each square wave extending toward a distinct corner of dielectric layer **800**. First switch

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606 or second switch **610** is connected between a second end of each square wave opposite the first end. Each dipole of sixth polarization rotating element **202f** defines a conducting pattern layer mounted to either the back surface or the front surface of dielectric layer **800**. Again, each half of each dipole of sixth polarization rotating element **202f** is rotated $\pm 45^\circ$ relative to the incoming electric field E_{inc} .

Referring to FIG. 12K, a back view is shown of a seventh polarization rotating element **202g** in accordance with an illustrative embodiment. Referring to FIG. 12L, a front view is shown of seventh polarization rotating element **202g** in accordance with an illustrative embodiment. Seventh polarization rotating element **202g** is shown as transparent and includes a seventh back dipole **604g**, first switch **606**, a seventh front dipole **608g**, and second switch **610**. Seventh back dipole **604g** and seventh front dipole **608g** are formed as fans with a pointed tip of each fan extending toward a center of dielectric layer **800** and the fan centered toward a distinct corner of dielectric layer **800**. First switch **606** or second switch **610** is connected between the pointed tips. Each dipole of seventh polarization rotating element **202g** defines a conducting pattern layer mounted to either the back surface or the front surface of dielectric layer **800**. Again, each half of each dipole of seventh polarization rotating element **202g** is rotated $\pm 45^\circ$ relative to the incoming electric field E_{inc} .

As understood by a person of skill in the art, dimensions of each polarization rotating antenna element **106** may be defined based on a desired center frequency of the incoming electromagnetic wave. Any of second polarization rotating element **202b**, third polarization rotating element **202c**, fourth polarization rotating element **202d**, fifth polarization rotating element **202e**, sixth polarization rotating element **202f**, and seventh polarization rotating element **202g** may replace first polarization rotating element **202a** in the illustrative embodiments of polarization rotating antenna element **106** provided herein.

Referring to FIG. 13, a block diagram of transceiver system **100** comprised of layer antennas is shown in accordance with an illustrative embodiment. A polarization rotating layer antenna element **1300** may include a first impedance structure **1302**, polarization rotating element **202**, and a second impedance structure **1304**. Switch controller **108** is connected to control a switch state of polarization rotating element **202**. When operating as a transmitter, transceiver antenna **102** may radiate electromagnetic wave **113** toward a conducting pattern layer of first impedance structure **1302**. For illustration, electromagnetic wave **113** may be represented by first EM orthogonal system **208**. The layers of polarization rotating layer antenna element **1300** propagate the received electromagnetic wave **113** to second impedance structure **1304**. The conducting pattern layer of second impedance structure **1304** radiates first electromagnetic field output **112**. Based on first EM orthogonal system **208** and a switch state of polarization rotating element **202**, an orientation of first electromagnetic field output **112** radiated from the conducting pattern layer of second impedance structure **1304** is defined by either second EM orthogonal system **210a** or third EM orthogonal system **210b**. As a result, electromagnetic wave **113** is rotated by polarization rotating antenna element **106** by $+90^\circ$ or -90° .

When operating as a receiver, the first electromagnetic field input represented by first EM orthogonal system **208** is received by the conducting pattern layer of second impedance structure **1304** and propagated through polarization rotating layer antenna element **1300**. The propagated first electromagnetic field input is radiated from the conducting

pattern layer of first impedance structure **1302** toward transceiver antenna **102**. The electromagnetic field radiated toward transceiver antenna **102** may be represented by either second EM orthogonal system **210a** or third EM orthogonal system **210b** depending on a switch state of polarization rotating element **202**.

Referring to FIG. **14A**, a perspective view is shown of a first polarization rotating layer antenna element **1300a** in accordance with an illustrative embodiment. First polarization rotating layer antenna element **1300a** includes a first patch impedance structure **1302a**, first polarization rotating element **202a**, and a second patch impedance structure **1304a**. First patch impedance structure **1302a** and second patch impedance structure **1304a** are identical except that second patch impedance structure **1304a** is rotated 90° in the x-y plane and 180° in the x-z plane relative to first patch impedance structure **1302a**. First patch impedance structure **1302a** may include a first conductive patch **1400a** and a first dielectric slab **1402a**. First conductive patch **1400a** is a square patch of conductive material layered on, against, or adjacent to a center portion of first dielectric slab **1402a**, which is formed of a dielectric material. Second patch impedance structure **1304a** may include a second conductive patch **1404a** and a second dielectric slab **1406a**. Second conductive patch **1404a** is a square patch of conductive material layered on, against, or adjacent to a center portion of second dielectric slab **1406a**, which is formed of a dielectric material.

Referring to FIG. **14B**, a perspective view is shown of a second polarization rotating layer antenna element **1300b** in accordance with an illustrative embodiment. Second polarization rotating layer antenna element **1300b** includes a first strip impedance structure **1302b**, first polarization rotating element **202a**, and a second strip impedance structure **1304b**. First strip impedance structure **1302b** and second strip impedance structure **1304b** are identical except that second strip impedance structure **1304b** is rotated 90° in the x-y plane and 180° in the x-z plane relative to first strip impedance structure **1302b**. First strip impedance structure **1302b** may include a first conductive strip **1400b** and first dielectric slab **1402a**. First conductive strip **1400b** is a rectangular strip of conductive material layered on, against, or adjacent to the center portion of first dielectric slab **1402a**. Second strip impedance structure **1304b** may include a second conductive strip **1404b** and second dielectric slab **1406a**. Second conductive strip **1404b** is a rectangular strip of conductive material layered on, against, or adjacent to the center portion of second dielectric slab **1406a**.

Referring to FIG. **14C**, a perspective view is shown of a third polarization rotating layer antenna element **1300c** in accordance with an illustrative embodiment. Third polarization rotating layer antenna element **1300c** includes a first cross impedance structure **1302c**, first polarization rotating element **202a**, and a second cross impedance structure **1304c**. First cross impedance structure **1302c** and second cross impedance structure **1304c** are identical except that second cross impedance structure **1304c** is rotated 90° in the x-y plane and 180° in the x-z plane relative to first cross impedance structure **1302c**. First cross impedance structure **1302c** may include a first conductive cross **1400c** and first dielectric slab **1402a**. First conductive cross **1400c** is a cross-shaped layer of conductive material layered on, against, or adjacent to the center portion of first dielectric slab **1402a**. Second cross impedance structure **1304c** may include a second conductive cross **1404c** and second dielectric slab **1406a**. Second conductive cross **1404c** is a cross-

shaped layer of conductive material layered on, against, or adjacent to the center portion of second dielectric slab **1406a**.

Referring to FIG. **14D**, a perspective view is shown of a fourth polarization rotating layer antenna element **1300d** in accordance with an illustrative embodiment. Fourth polarization rotating layer antenna element **1300d** includes a first Jerusalem cross impedance structure **1302d**, first polarization rotating element **202a**, and a second Jerusalem cross impedance structure **1304d**. First Jerusalem cross impedance structure **1302d** and second Jerusalem cross impedance structure **1304d** are identical except that second Jerusalem cross impedance structure **1304d** is rotated 90° in the x-y plane and 180° in the x-z plane relative to first Jerusalem cross impedance structure **1302d**. First Jerusalem cross impedance structure **1302d** may include a first conductive Jerusalem cross **1400d** and first dielectric slab **1402a**. First conductive Jerusalem cross **1400d** is a Jerusalem cross-shaped layer of conductive material layered on, against, or adjacent to the center portion of first dielectric slab **1402a**. Second cross impedance structure **1304d** may include a second conductive Jerusalem cross **1404d** and second dielectric slab **1406a**. Second conductive Jerusalem cross **1404d** is a cross-shaped layer of conductive material layered on, against, or adjacent to the center portion of second dielectric slab **1406a**.

Referring to FIG. **14E**, a perspective view is shown of a fifth polarization rotating layer antenna element **1300e** in accordance with an illustrative embodiment. Fifth polarization rotating layer antenna element **1300e** includes a first cross slot impedance structure **1302e**, first polarization rotating element **202a**, and a second cross slot impedance structure **1304e**. First cross slot impedance structure **1302e** and second cross slot impedance structure **1304e** are identical except that second cross slot impedance structure **1304e** is rotated 90° in the x-y plane and 180° in the x-z plane relative to first cross slot impedance structure **1302e**. First cross slot impedance structure **1302e** may include a first conductive cross slot slab **1400e** and first dielectric slab **1402a**. First conductive cross slot slab **1400e** is a slab of conductive material with a first cross-shaped slot wall **1408** formed through a center portion of first conductive cross slot slab **1400e**. First conductive cross slot slab **1400e** is layered on, against, or adjacent to first dielectric slab **1402a**. Second conductive cross slot slab **1404e** is a slab of conductive material with a second cross-shaped slot wall **1410** formed through a center portion of second conductive cross slot slab **1404e**. Second conductive cross slot slab **1404e** is layered on, against, or adjacent to second dielectric slab **1406a**.

Referring to FIG. **15A**, an exploded perspective view of first polarization rotating layer antenna element **1300a** is shown in accordance with an illustrative embodiment. In the illustrative embodiment of FIG. **15A**, second conductive patch **1404a** has a patch length **1500** in the direction parallel to the x-axis of orthogonal coordinate reference frame **308**, a patch width **1501** in the direction parallel to the y-axis of first EM orthogonal system **208**, and a patch depth **1502** in the direction parallel to the z-axis. In the illustrative embodiment of FIG. **15A**, first dielectric slab **1402a** has a slab length **1503** in the direction parallel to the x-axis of orthogonal coordinate reference frame **308**, a slab width **1504** in the direction parallel to the y-axis of first EM orthogonal system **208**, and a slab depth **1505** in the direction parallel to the z-axis.

Referring to FIG. **15B**, an exploded perspective view of second polarization rotating layer antenna element **1300b** is shown in accordance with an illustrative embodiment. In the illustrative embodiment of FIG. **15B**, second conductive

strip **1404b** has a strip length **1510** in the direction parallel to the x-axis of orthogonal coordinate reference frame **308**, a strip width **1511** in the direction parallel to the y-axis of first EM orthogonal system **208**, and a strip depth **1512** in the direction parallel to the z-axis. In the illustrative embodiment of FIG. **15B**, first dielectric slab **1402a** has a slab length **1513** in the direction parallel to the x-axis of orthogonal coordinate reference frame **308**, a slab width **1514** in the direction parallel to the y-axis of first EM orthogonal system **208**, and a slab depth **1515** in the direction parallel to the z-axis.

Referring to FIG. **15C**, an exploded perspective view of third polarization rotating layer antenna element **1300c** is shown in accordance with an illustrative embodiment. In the illustrative embodiment of FIG. **15C**, second conductive cross **1404c** has a cross arm length **1520** in the direction parallel to the x-axis of orthogonal coordinate reference frame **308**, a cross arm width **1521** in the direction parallel to the y-axis of first EM orthogonal system **208**, and a cross depth **1522** in the direction parallel to the z-axis. In the illustrative embodiment of FIG. **15C**, first dielectric slab **1402a** has a slab length **1523** in the direction parallel to the x-axis of orthogonal coordinate reference frame **308**, a slab width **1524** in the direction parallel to the y-axis of first EM orthogonal system **208**, and a slab depth **1525** in the direction parallel to the z-axis.

Referring to FIG. **15D**, an exploded perspective view of fourth polarization rotating layer antenna element **1300d** is shown in accordance with an illustrative embodiment. In the illustrative embodiment of FIG. **15D**, second conductive Jerusalem cross **1404d** has a cross arm tip length **1530** in the direction parallel to the x-axis of orthogonal coordinate reference frame **308**, a cross arm length **1536** in the direction parallel to the x-axis of orthogonal coordinate reference frame **308**, a cross arm tip width **1531** in the direction parallel to the y-axis of first EM orthogonal system **208**, a cross arm width **1537** in the direction parallel to the y-axis of first EM orthogonal system **208**, and a cross depth **1532** in the direction parallel to the z-axis. In the illustrative embodiment of FIG. **15D**, two arms are perpendicular to each other with identical dimensions. In the illustrative embodiment of FIG. **15D**, first dielectric slab **1402a** has a slab length **1533** in the direction parallel to the x-axis of orthogonal coordinate reference frame **308**, a slab width **1534** in the direction parallel to the y-axis of first EM orthogonal system **208**, and a slab depth **1535** in the direction parallel to the z-axis.

Referring to FIG. **15E**, an exploded perspective view of fifth polarization rotating layer antenna element **1300e** is shown in accordance with an illustrative embodiment. In the illustrative embodiment of FIG. **15E**, second conductive cross slot slab **1404e** has a cross slot length **1540** in the direction parallel to the x-axis of orthogonal coordinate reference frame **308**, a cross slot width **1541** in the direction parallel to the y-axis of first EM orthogonal system **208**, and a cross depth **1542** in the direction parallel to the z-axis. In the illustrative embodiment of FIG. **15E**, first dielectric slab **1402a** has a slab length **1543** in the direction parallel to the x-axis of orthogonal coordinate reference frame **308**, a slab width **1544** in the direction parallel to the y-axis of first EM orthogonal system **208**, and a slab depth **1545** in the direction parallel to the z-axis. In the illustrative embodiment of FIG. **15E**, a length of second conductive cross slot slab **1404e** in the direction parallel to the x-axis of orthogonal coordinate reference frame **308** is equal to slab length **1543**, and a width of second conductive cross slot slab **1404e** in the

direction parallel to the y-axis of orthogonal coordinate reference frame **308** is equal to slab width **1544**.

In FIGS. **14A** through **14E**, second dielectric slab **1406a** is transparent. In FIGS. **15A** through **15E**, first dielectric slab **1402a** and second dielectric slab **1406a** may have different dimensions in the x-y plane and the y-z plane depending on the embodiment.

Referring to FIG. **16A**, an exploded perspective view of a first phased array antenna **104a** is shown in accordance with an illustrative embodiment. In the illustrative embodiment, first phased array antenna **104a** is a two-dimensional array of first polarization rotating layer antenna elements. The two-dimensional array of first polarization rotating layer antenna elements includes 36 first polarization rotating layer antenna elements arranged in a 6x6 pattern. Instead of forming individual antenna elements, a plurality of first conductive patches **1400a** may be layered on, against, or adjacent a third dielectric slab **1600a**, and a plurality of second conductive patches **1404a** may be layered on, against, or adjacent a fourth dielectric slab **1602a**. Third dielectric slab **1600a** and fourth dielectric slab **1602a** are formed of a dielectric material. 36 first polarization rotating elements **202a** are further arranged in a 6x6 pattern to align, in the direction parallel to the z-axis of orthogonal coordinate reference frame **308**, with the plurality of first conductive patches **1400a** and the plurality of second conductive patches **1404a**.

Referring to FIG. **16B**, an exploded perspective view of a second phased array antenna **104b** is shown in accordance with an illustrative embodiment. Second phased array antenna **104b** may include a two-dimensional array of second polarization rotating layer antenna elements. In the illustrative embodiment, the two-dimensional array of second polarization rotating layer antenna elements includes 36 second polarization rotating layer antenna elements arranged in a 6x6 pattern. Instead of forming individual antenna elements, a plurality of first conductive strips **1604** may be layered on, against, or adjacent third dielectric slab **1600a**, and a plurality of second conductive strips **1606** may be layered on, against, or adjacent fourth dielectric slab **1602a**. 36 first polarization rotating elements **202a** are further arranged in a 6x6 pattern to align, in the direction parallel to the z-axis of orthogonal coordinate reference frame **308**, with the plurality of first conductive strips **1604** and the plurality of second conductive strips **1606**.

Referring to FIG. **16C**, an exploded perspective view of a third phased array antenna **104c** is shown in accordance with an illustrative embodiment. Third phased array antenna **104c** may include a two-dimensional array of third polarization rotating layer antenna elements. In the illustrative embodiment, the two-dimensional array of third polarization rotating layer antenna elements includes 36 third polarization rotating layer antenna elements arranged in a 6x6 pattern. Instead of forming individual antenna elements, the plurality of first conductive strips **1604** and a plurality of third conductive strips **1608** may be layered on, against, or adjacent third dielectric slab **1600a**. The plurality of second conductive strips **1606** and a plurality of fourth conductive strips **1610** may be layered on, against, or adjacent fourth dielectric slab **1602a**. 36 first polarization rotating elements **202a** are further arranged in a 6x6 pattern to align, in the direction parallel to the z-axis of orthogonal coordinate reference frame **308**, with the plurality of first conductive strips **1604**, the plurality of second conductive strips **1606**, the plurality of third conductive strips **1608**, and the plurality of fourth conductive strips **1610**.

Referring to FIG. 16D, an exploded perspective view of a fourth phased array antenna **104d** is shown in accordance with an illustrative embodiment. Fourth phased array antenna **104d** may include a two-dimensional array of fourth polarization rotating layer antenna elements. In the illustrative embodiment, the two-dimensional array of fourth polarization rotating layer antenna elements includes 36 fourth polarization rotating layer antenna elements arranged in a 6×6 pattern. Instead of forming individual antenna elements, a plurality of first conductive Jerusalem crosses **1400d** may be layered on, against, or adjacent third dielectric slab **1600a**, and a plurality of second conductive Jerusalem crosses **1404d** may be layered on, against, or adjacent fourth dielectric slab **1602a**. 36 first polarization rotating elements **202a** are further arranged in a 6×6 pattern to align, in the direction parallel to the z-axis of orthogonal coordinate reference frame **308**, with the two-dimensional array of fourth polarization rotating layer antenna elements.

Referring to FIG. 16E, an exploded perspective view of a fifth phased array antenna **104e** is shown in accordance with an illustrative embodiment. Fifth phased array antenna **104e** may include a two-dimensional array of fifth polarization rotating layer antenna elements. In the illustrative embodiment, the two-dimensional array of fifth polarization rotating layer antenna elements includes 36 fifth polarization rotating layer antenna elements arranged in a 6×6 pattern. Instead of forming individual antenna elements, a first conductive slab **1612** may be layered on, against, or adjacent third dielectric slab **1600a**, and a second conductive slab **1614** may be layered on, against, or adjacent fourth dielectric slab **1602a**. First conductive slab **1612** may include a plurality of first cross-shaped slot walls **1408** formed through first conductive slab **1612**. Second conductive slab **1614** may include a plurality of second cross-shaped slot walls **1410** formed through second conductive slab **1614**. 36 first polarization rotating elements **202a** are further arranged in a 6×6 pattern to align, in the direction parallel to the z-axis of orthogonal coordinate reference frame **308**, with the plurality of first cross-shaped slot walls **1408** and the plurality of second cross-shaped slot walls **1410**.

FIGS. 14A-14E and 18A-18N depict low-profile, wide-band, and electronically reconfigurable lens array antenna elements based on polarization-rotating (PR) and frequency-selective surfaces. The illustrative polarization rotating layer antenna elements **1300** include three distinct layers: a PR phase shifter layer (polarization rotating element **202**) positioned between two layers that may be capacitive, inductive, or both capacitive and inductive. The outermost layers are in the form of two-dimensional (2-D) periodic arrangements of sub-wavelength elements (such as patches or strips) located on dielectric substrates. Meanwhile, the sandwiched PR phase shifter layer includes a pair of orthogonal dipoles separated from one another by a dielectric support substrate as described above. For high power applications, a recommended dielectric substrate may be a high-temperature-tolerant ceramic. The outer layers along with the dipole layers are oriented in a specific direction to enable rotation of the polarization of the transmitted wave by angles that achieve the intended phase shifts. A typical example choice would be for the polarization rotation to be $\pm 90^\circ$ with respect to the polarization of the incoming wave.

To better understand the operation of polarization rotating layer antenna element **1300**, an equivalent circuit **1700** is shown referring to FIG. 17 that may be used to model operation of polarization rotating layer antenna elements **1300** in accordance with an illustrative embodiment. Equivalent circuit **1700** is valid for normally-incident, y-po-

larized waves and treats polarization rotating layer antenna element **1300** as a two-port network. In a simplified equivalent-circuit model describing a transmission response of the PR unit cell, the two outermost layers may be modeled as shunt capacitors C_{F1} and C_{F2} , as shunt inductors L_{F1} and L_{F2} , as shunt capacitors C_{F1} and C_{F2} with parallel shunt inductors L_{F1} and L_{F2} , or as series circuit branches incorporating shunt inductors L_{F1} and L_{F2} in series with series capacitors C_{S1} and C_{S2} . The dipoles on the surfaces of polarization rotating element **202** are modeled with switches and series capacitor-and-inductor circuit branches L_{d1} and C_{d1} and L_{d2} and C_{d2} . The dielectric substrates are represented by short pieces of transmission lines, each with characteristic impedances of $Z_1=Z_0\sqrt{\epsilon_{r1}}$, $Z_2=Z_0\sqrt{\epsilon_{r1}}$, and $Z_3=Z_0\sqrt{\epsilon_{r3}}$ and lengths of h_1 , h_2 , and h_3 , respectively, where ϵ_{r1} , ϵ_{r2} , and ϵ_{r3} are the dielectric permittivity of the respective substrates and Z_0 is the impedance of free space. Matching the input impedances of the two outward-facing FSSs (labelled as “ports” in FIG. 17) to 377 Ohms (Ω), the impedance of free space, is crucial for efficient wave transmission and polarization conversion. Consequently, the equivalent circuit parameters, which are related to physical properties of each polarization rotating layer antenna elements **1300** (e.g., dimensions and materials), can be adjusted to achieve the desired input impedance.

The conducting pattern layer that is layered on, against, or adjacent first dielectric slab **1402a** or second dielectric slab **1406a** is sized, shaped, and arranged to form a conducting surface. Equivalent circuit parameters may be used to model performance of the conducting pattern layer as lumped circuit elements based on the size, shape and arrangement. The material used to form the conducting pattern layer is chosen to be a good conductor such as copper.

Some of the equivalent circuit parameters may not be included depending on whether the conducting pattern layer of first impedance structure **1302** and of second impedance structure **1304** are capacitive, inductive, or resonant. The choice of inductive versus capacitive may be based on the orientation of the incident wave’s electric field with respect to the alignment of conducting strips. When the E field is parallel to the strips, the magnetic field of the incident wave interacts with the magnetic field generated by the strip resulting in the strip(s) acting as an inductor. On the other hand, when the E field is perpendicular to the strips (while the magnetic field, H, is parallel to the strips), the electric field creates positive and negative charge accumulations on adjacent edges of the strips. In this configuration, the nearby edges of the adjacent strips act as two plates of a co-planar capacitor resulting in the strip(s) acting as a capacitor.

For example, first conductive patch **1400a** and second conductive patch **1404a** may be modeled as capacitive layers such that only the shunt capacitors C_{F1} and C_{F2} are included in equivalent circuit **1700**. For example, first conductive strip **1400b** and second conductive strip **1404b** may be modeled as capacitive layers such that only the shunt capacitors C_{F1} and C_{F2} are included in equivalent circuit **1700** or may be modeled as inductive layers such that only the shunt inductors L_{F1} and L_{F2} are included in equivalent circuit **1700** dependent on the orientation of the incident wave. For example, first conductive cross **1400c** and second conductive cross **1404c** may be modeled as inductive layers such that only the shunt inductors L_{F1} and L_{F2} are included in equivalent circuit **1700**. For example, first conductive Jerusalem cross **1400d** and second conductive Jerusalem cross **1404d** may be modeled as resonant layers that may include the shunt inductors L_{F1} and L_{F2} and the series

capacitors C_{S1} and C_{S2} in equivalent circuit 1700. Other resonant layers may include a different combination of the shunt inductors L_{F1} and L_{F2} , the shunt capacitors C_{F1} and C_{F2} , and/or the series capacitors C_{S1} and C_{S2} . When not included in equivalent circuit 1700, the shunt inductors L_{F1} and L_{F2} , the shunt capacitors C_{F1} and C_{F2} , and/or the series capacitors C_{S1} and C_{S2} may be considered to be parasitic or de minimis such that performance can be reasonably accurately modeled without their inclusion.

Equivalent circuit 1700 may include a first inductor 1702, a first capacitor 1703, a second capacitor 1704, a second inductor 1706, a third capacitor 1708, a third inductor 1710, a fourth capacitor 1712, a fourth inductor 1714, a fifth capacitor 1715, a sixth capacitor 1716, a first impedance 1720, a second impedance 1722, a third impedance 1724, a first bus line 1732, a second bus line 1734, a first switch 1736, and second switch 1738. A first port 1718 is indicated between first bus line 1732 and second bus line 1734. A second port 1719 is indicated between first bus line 1732 and second bus line 1734. First impedance 1720, second impedance 1722, and third impedance 1724 are connected in series in first bus line 1732. A first set of circuit elements 1726 includes first inductor 1702, first capacitor 1703, second capacitor 1704, and first impedance 1720 and represents first impedance structure 1302. A second set of circuit elements 1728 includes second inductor 1706, third capacitor 1708, third inductor 1710, fourth capacitor 1712, and second impedance 1722 and represents polarization rotating element 202. A third set of circuit elements 1730 includes fourth inductor 1714, fifth capacitor 1715, sixth capacitor 1716, and third impedance 1724 and represents second impedance structure 1304.

First inductor 1702 and first capacitor 1703 are connected in series between first bus line 1732 and second bus line 1734 opposite first port 1718. Fourth inductor 1714 and fifth capacitor 1703 are connected in series between first bus line 1732 and second bus line 1734. Second capacitor 1704 is connected between first bus line 1732 and second bus line 1734 in parallel with first inductor 1702 and first capacitor 1703. Sixth capacitor 1716 is connected between first bus line 1732 and second bus line 1734 in parallel with fourth inductor 1714 and fifth capacitor 1703 and opposite second port 1719.

First switch 1736, second inductor 1706, and third capacitor 1708 are connected in series between first impedance 1720 and second impedance 1722. Second switch 1738, third inductor 1710, and fourth capacitor 1712 are connected in series between second impedance 1722 and third impedance 1724.

For illustration, a paper by Mudar Al-Joumayly and Nader Behdad titled *A new technique for design of low-profile, second-order, bandpass frequency selective surfaces* published in IEEE transactions on antennas and propagation in volume 57.2 on pages 452-459 (2009) describes computation of the equivalent circuit parameters based on the structural characteristics of each polarization rotating layer antenna element 1300. As another example, a paper by Seyed Mohamad Amin Momeni Hasan Abadi and Nader Behdad titled *Inductively-coupled miniaturized-element frequency selective surfaces with narrowband, high-order bandpass responses* published in IEEE Transactions on Antennas and Propagation in volume 63.11 on pages 4766-4774 (2015) also describes computation of the equivalent circuit parameters based on the structural characteristics of each polarization rotating layer antenna element 1300. As yet another example, a paper by Xue Yang et al. titled *Design method for low-profile, harmonic-suppressed filter-antennas*

using miniaturized-element frequency selective surfaces published in IEEE Antennas and Wireless Propagation Letters in volume 18.3 on pages 427-431 (2019) also describes computation of the equivalent circuit parameters based on the structural characteristics of each polarization rotating layer antenna element 1300.

Referring to FIG. 18A, a perspective view of a sixth polarization rotating layer antenna element 1300f is shown comprised of two wire-grid conducting layers in accordance with an illustrative embodiment. Sixth polarization rotating layer antenna element 1300f includes a first wire-grid impedance structure 1302f, first polarization rotating element 202a, and a second wire-grid impedance structure 1304f. First wire-grid impedance structure 1302f and second wire-grid impedance structure 1304f are identical except that second wire-grid impedance structure 1304f is rotated 90° in the x-y plane and 180° in the x-z plane relative to first wire-grid impedance structure 1302f. First wire-grid impedance structure 1302f may include a first plurality of conductive strips 1400f and first dielectric slab 1402a. The first plurality of conductive strips 1400f extend parallel to each other and to the x-axis of orthogonal coordinate reference frame 308 and are formed of conductive material layered on, against, or adjacent to first dielectric slab 1402a. Second wire-grid impedance structure 1304a may include a second plurality of conductive strips 1404f and second dielectric slab 1406a. The second plurality of conductive strips 1404f extend parallel to each other and to the y-axis of orthogonal coordinate reference frame 308 and are formed of conductive material layered on, against, or adjacent to second dielectric slab 1406a. The first plurality of conductive strips 1400f and the second plurality of conductive strips 1404f may be modeled as capacitive layers such that only the shunt capacitors C_{F1} and C_{F2} are included in equivalent circuit 1700.

Referring to FIG. 18B, a perspective view of a seventh polarization rotating layer antenna element 1300g is shown comprised of two L-resonator conducting layers in accordance with an illustrative embodiment. Seventh polarization rotating layer antenna element 1300g includes a first L-resonator impedance structure 1302g, first polarization rotating element 202a, and a second L-resonator impedance structure 1304g. First L-resonator impedance structure 1302g and second L-resonator impedance structure 1304g are identical except that second L-resonator impedance structure 1304g is rotated 90° in the x-y plane and 180° in the x-z plane relative to first L-resonator impedance structure 1302g. First L-resonator impedance structure 1302g may include a first L-shaped conductive strip 1400g, a second L-shaped conductive strip 1401g, and first dielectric slab 1402a. First L-shaped conductive strip 1400g and second L-shaped conductive strip 1401g are formed of conductive material layered on, against, or adjacent to first dielectric slab 1402a. First L-shaped conductive strip 1400g and second L-shaped conductive strip 1401g are identical except that second L-shaped conductive strip 1401g is rotated 180° in the x-y plane relative to first L-shaped conductive strip 1400g. Second L-resonator impedance structure 1304g may include a third L-shaped conductive strip 1404g, a fourth L-shaped conductive strip 1405g, and second dielectric slab 1406a. Third L-shaped conductive strip 1404g and fourth L-shaped conductive strip 1405g are formed of conductive material layered on, against, or adjacent to second dielectric slab 1406a. Third L-shaped conductive strip 1404g and fourth L-shaped conductive strip 1405g are identical except that third L-shaped conductive strip 1404g is rotated 180° in the x-y plane relative to fourth L-shaped conductive strip 1405g.

First L-shaped conductive strip **1400g** and second L-shaped conductive strip **1401g** may be modeled as resonant layers that may include shunt inductors L_{F1} and L_{F2} and series capacitors C_{S1} and C_{S2} in equivalent circuit **1700**.

Referring to FIG. **18C**, a perspective view of an eighth polarization rotating layer antenna element **1300h** is shown comprised of two slot array conducting layers in accordance with an illustrative embodiment. Eighth polarization rotating layer antenna element **1300h** includes a first slot array impedance structure **1302h**, first polarization rotating element **202a**, and a second slot array impedance structure **1304h**. First slot array impedance structure **1302h** and second slot array impedance structure **1304h** are identical except that second slot array impedance structure **1304h** is rotated 90° in the x-y plane and 180° in the x-z plane relative to first slot array impedance structure **1302h**. First slot array impedance structure **1302h** may include a third conductive slab **1400h** formed of conductive material layered on, against, or adjacent to first dielectric slab **1402a**. A plurality of rectangular shaped slot walls may be formed through third conductive slab **1400h**. Second slot array impedance structure **1304h** may include a fourth conductive slab **1404h** formed of conductive material layered on, against, or adjacent to second dielectric slab **1406a**. A plurality of rectangular shaped slot wall may be formed through fourth conductive slab **1404h**. Third conductive slab **1400h** and fourth conductive slab **1404h** may be modeled as inductive layers such that only the shunt inductors L_{F1} and L_{F2} are included in equivalent circuit **1700**.

Referring to FIG. **18D**, a perspective view of a ninth polarization rotating layer antenna element **1300i** is shown comprised of two V-shaped slot conducting layers in accordance with an illustrative embodiment. Ninth polarization rotating layer antenna element **1300i** includes a first V-shaped slot impedance structure **1302i**, first polarization rotating element **202a**, and a second V-shaped slot impedance structure **1304i**. First V-shaped slot impedance structure **1302i** and second V-shaped slot impedance structure **1304i** are identical except that second V-shaped slot impedance structure **1304i** is rotated 90° in the x-y plane and 180° in the x-z plane relative to first V-shaped slot impedance structure **1302i**. First V-shaped slot impedance structure **1302i** may include a fifth conductive slab **1400i** formed of conductive material layered on, against, or adjacent to first dielectric slab **1402a**. A V-shaped slot wall may be formed through fifth conductive slab **1400i**. Second V-shaped slot impedance structure **1304i** may include a sixth conductive slab **1404i** formed of conductive material layered on, against, or adjacent to second dielectric slab **1406a**. A V-shaped slot wall may be formed through sixth conductive slab **1404i**. Fifth conductive slab **1400i** and sixth conductive slab **1404i** may be modeled as resonant layers that may include the shunt inductors L_{F1} and L_{F2} and the shunt capacitors C_{F1} and C_{F2} in equivalent circuit **1700**.

Referring to FIG. **18E**, a perspective view of a tenth polarization rotating layer antenna element **1300j** is shown comprised of two I-shaped slot conducting layers in accordance with an illustrative embodiment. Tenth polarization rotating layer antenna element **1300j** includes a first I-shaped slot impedance structure **1302j**, first polarization rotating element **202a**, and a second I-shaped slot impedance structure **1304j**. First I-shaped slot impedance structure **1302j** and second I-shaped slot impedance structure **1304j** are identical except that second I-shaped slot impedance structure **1304j** is rotated 90° in the x-y plane and 180° in the x-z plane relative to first I-shaped slot impedance structure **1302j**. First I-shaped slot impedance structure **1302j** may

include a seventh conductive slab **1400j** formed of conductive material layered on, against, or adjacent to first dielectric slab **1402a**. An I-shaped slot wall may be formed through seventh conductive slab **1400j**. Second I-shaped slot impedance structure **1304j** may include an eighth conductive slab **1404j** formed of conductive material layered on, against, or adjacent to second dielectric slab **1406a**. An I-shaped slot wall may be formed through eighth conductive slab **1404j**. Sixth conductive slab **1400j** and seventh conductive slab **1404j** may be modeled as resonant layers that may include the shunt inductors L_{F1} and L_{F2} and the shunt capacitors C_{F1} and C_{F2} in equivalent circuit **1700**.

Referring to FIG. **18F**, a perspective view of an eleventh polarization rotating layer antenna element **1300k** is shown comprised of two bow-tie conducting layers in accordance with an illustrative embodiment. Eleventh polarization rotating layer antenna element **1300k** includes a first bow-tie impedance structure **1302k**, first polarization rotating element **202a**, and a second bow-tie impedance structure **1304k**. First bow-tie impedance structure **1302k** and second bow-tie impedance structure **1304k** are identical except that second bow-tie impedance structure **1304k** is rotated 90° in the x-y plane and 180° in the x-z plane relative to first bow-tie impedance structure **1302k**. First bow-tie impedance structure **1302k** may include a first triangular-shaped conductive strip **1400k**, a second triangular-shaped conductive strip **1401k**, and first dielectric slab **1402a**. First triangular-shaped conductive strip **1400k** and second triangular-shaped conductive strip **1401k** are formed of conductive material layered on, against, or adjacent to first dielectric slab **1402a**. First triangular-shaped conductive strip **1400k** and second triangular-shaped conductive strip **1401k** are identical except that second triangular-shaped conductive strip **1401k** is rotated 180° in the x-y plane relative to first triangular-shaped conductive strip **1400k**. First triangular-shaped conductive strip **1400k** and second triangular-shaped conductive strip **1401k** each form a top squared off triangle. Second bow-tie impedance structure **1304k** may include a third triangular-shaped conductive strip **1404k**, a fourth triangular-shaped conductive strip **1405k**, and second dielectric slab **1406a**. Third triangular-shaped conductive strip **1404k** and fourth triangular-shaped conductive strip **1405k** are formed of conductive material layered on, against, or adjacent to second dielectric slab **1406a**. Third triangular-shaped conductive strip **1404k** and fourth triangular-shaped conductive strip **1405k** are identical except that third triangular-shaped conductive strip **1404k** is rotated 180° in the x-y plane relative to fourth triangular-shaped conductive strip **1405k**. Third triangular-shaped conductive strip **1404k** and fourth triangular-shaped conductive strip **1405k** each form a top squared off triangle. First triangular-shaped conductive strip **1400k** and second triangular-shaped conductive strip **1401k** may be modeled as resonant layers that may include the shunt inductors L_{F1} and L_{F2} and the series capacitors C_{S1} and C_{S2} in equivalent circuit **1700**.

Referring to FIG. **18G**, a perspective view of a twelfth polarization rotating layer antenna element **1300l** is shown comprised of two split-ring resonator conducting layers in accordance with an illustrative embodiment. Twelfth polarization rotating layer antenna element **1300l** includes a first split-ring resonator impedance structure **1302l**, first polarization rotating element **202a**, and a second split-ring resonator impedance structure **1304l**. First split-ring resonator impedance structure **1302l** and second split-ring resonator impedance structure **1304l** are identical except that second split-ring resonator impedance structure **1304l** is rotated 90° in the x-y plane and 180° in the x-z plane relative to first

split-ring resonator impedance structure **1302i**. First split-ring resonator impedance structure **1302i** may include a first square C-shaped conductive strip **1400i** and first dielectric slab **1402a**. First square C-shaped conductive strip **1400i** is formed of conductive material layered on, against, or adjacent to first dielectric slab **1402a**. Second split-ring resonator impedance structure **1304i** may include a second square C-shaped conductive strip **1404i** and second dielectric slab **1406a**. Second square C-shaped conductive strip **1404i** is formed of conductive material layered on, against, or adjacent to second dielectric slab **1406a**. First square C-shaped conductive strip **1400i** and second square C-shaped conductive strip **1404i** may be modeled as resonant layers that may include the shunt inductors L_{F1} and L_{F2} and the series capacitors C_{S1} and C_{S2} in equivalent circuit **1700**.

Referring to FIG. **18H**, a perspective view of a thirteenth polarization rotating layer antenna element **1300m** is shown comprised of two double split-ring resonator conducting layers in accordance with an illustrative embodiment. Thirteenth polarization rotating layer antenna element **1300m** includes a first double split-ring resonator impedance structure **1302m**, first polarization rotating element **202a**, and a second double split-ring resonator impedance structure **1304m**. First double split-ring resonator impedance structure **1302m** and second double split-ring resonator impedance structure **1304m** are identical except that second double split-ring resonator impedance structure **1304m** is rotated 90° in the x-y plane and 180° in the x-z plane relative to first double split-ring resonator impedance structure **1302m**. First double split-ring resonator impedance structure **1302m** may include a first double square C-shaped conductive strip **1400m** and first dielectric slab **1402a**. First double square C-shaped conductive strip **1400m** is formed of conductive material layered on, against, or adjacent to first dielectric slab **1402a**. Second double split-ring resonator impedance structure **1304m** may include a second double square C-shaped conductive strip **1404m** and second dielectric slab **1406a**. Second double square C-shaped conductive strip **1404m** is formed of conductive material layered on, against, or adjacent to second dielectric slab **1406a**. First double square C-shaped conductive strip **1400m** and third double square C-shaped conductive strip **1404m** are formed as two back-to-back square shaped Cs. First double square C-shaped conductive strip **1400m** and second double square C-shaped conductive strip **1404m** may be modeled as resonant layers that may include the shunt inductors L_{F1} and L_{F2} and the shunt capacitors C_{F1} and C_{F2} in equivalent circuit **1700**.

Referring to FIG. **18I**, a perspective view of a fourteenth polarization rotating layer antenna element **1300n** is shown comprised of two rectangular slot conducting layers in accordance with an illustrative embodiment. Fourteenth polarization rotating layer antenna element **1300n** includes a first rectangular slot impedance structure **1302n**, first polarization rotating element **202a**, and a second rectangular slot impedance structure **1304n**. First rectangular slot impedance structure **1302n** and second rectangular slot impedance structure **1304n** are identical except that second rectangular slot impedance structure **1304n** is rotated 90° in the x-y plane and 180° in the x-z plane relative to first rectangular slot impedance structure **1302n**. First rectangular slot impedance structure **1302n** may include a ninth conductive slab **1400n** formed of conductive material layered on, against, or adjacent to first dielectric slab **1402a**. A rectangular slot wall may be formed through ninth conductive slab **1400n**. Second rectangular slot impedance structure **1304n** may include a tenth conductive slab **1404n** formed of

conductive material layered on, against, or adjacent to second dielectric slab **1406a**. A rectangular slot wall may be formed through tenth conductive slab **1404n**. First rectangular slot impedance structure **1302n** and second rectangular slot impedance structure **1304n** may be modeled as inductive layers such that only the shunt inductors L_{F1} and L_{F2} are included in the equivalent circuit without the shunt capacitors C_{F1} and C_{F2} or the series capacitors C_{S1} and C_{S2} . Ninth conductive slab **1400n** and tenth conductive slab **1404n** may be modeled as inductive layers such that only the shunt inductors L_{F1} and L_{F2} are included in equivalent circuit **1700**.

Referring to FIG. **18J**, a perspective view of a fifteenth polarization rotating layer antenna element **1300o** is shown comprised of two H-shaped slot conducting layers in accordance with an illustrative embodiment. Fifteenth polarization rotating layer antenna element **1300o** includes a first H-shaped slot impedance structure **1302o**, first polarization rotating element **202a**, and a second H-shaped slot impedance structure **1304o**. First H-shaped slot impedance structure **1302o** and second H-shaped slot impedance structure **1304o** are identical except that second H-shaped slot impedance structure **1304o** is rotated 90° in the x-y plane and 180° in the x-z plane relative to first H-shaped slot impedance structure **1302o**. First H-shaped slot impedance structure **1302o** may include an eleventh conductive slab **1400o** formed of conductive material layered on, against, or adjacent to first dielectric slab **1402a**. An H-shaped slot wall may be formed through eleventh conductive slab **1400o**. Second H-shaped slot impedance structure **1304o** may include a twelfth conductive slab **1404o** formed of conductive material layered on, against, or adjacent to second dielectric slab **1406a**. An H-shaped slot wall may be formed through twelfth conductive slab **1404o**. Eleventh conductive slab **1400o** and twelfth conductive slab **1404o** may be modeled as resonant layers that may include the shunt inductors L_{F1} and L_{F2} and the shunt capacitors C_{F1} and C_{F2} in equivalent circuit **1700**.

Referring to FIG. **18K**, a perspective view of a sixteenth polarization rotating layer antenna element **1300p** is shown comprised of two S-shaped resonator conducting layers in accordance with an illustrative embodiment. Sixteenth polarization rotating layer antenna element **1300p** includes a first S-shaped resonator impedance structure **1302p**, first polarization rotating element **202a**, and a second S-shaped resonator impedance structure **1304p**. First S-shaped resonator impedance structure **1302p** and second S-shaped resonator impedance structure **1304p** are identical except that second S-shaped resonator impedance structure **1304p** is rotated 90° in the x-y plane and 180° in the x-z plane relative to first S-shaped resonator impedance structure **1302p**. First S-shaped resonator impedance structure **1302p** may include a first S-shaped conductive strip **1400p** and first dielectric slab **1402a**. First square S-shaped conductive strip **1400p** is formed of conductive material layered on, against, or adjacent to first dielectric slab **1402a** in the shape of a square S. Second S-shaped resonator impedance structure **1304p** may include a second S-shaped conductive strip **1404p** and second dielectric slab **1406a**. Second S-shaped conductive strip **1404p** is formed of conductive material layered on, against, or adjacent to second dielectric slab **1406a** in the shape of a square S. First S-shaped conductive strip **1400p** and second S-shaped conductive strip **1404p** may be modeled as resonant layers that may include the shunt inductors L_{F1} and L_{F2} and the series capacitors C_{S1} and C_{S2} in equivalent circuit **1700**.

Referring to FIG. 18L, a perspective view of a seventeenth polarization rotating layer antenna element **1300q** is shown comprised of two split-ring conducting layers in accordance with an illustrative embodiment. Seventeenth polarization rotating layer antenna element **1300q** includes a first split-ring impedance structure **1302q**, first polarization rotating element **202a**, and a second split-ring impedance structure **1304q**. First split-ring impedance structure **1302q** and second split-ring impedance structure **1304q** are identical except that second split-ring impedance structure **1304q** is rotated 90° in the x-y plane and 180° in the x-z plane relative to first split-ring impedance structure **1302q**. First split-ring antenna **1302q** may include a first split-ring conductive strip **1400q**, a second split-ring conductive strip **1401q**, and first dielectric slab **1402a**. First split-ring conductive strip **1400q** and second split-ring conductive strip **1401q** are formed of conductive material layered on, against, or adjacent to first dielectric slab **1402a**. First split-ring conductive strip **1400q** and second split-ring conductive strip **1401q** are identical except that second split-ring conductive strip **1401q** is rotated 180° in the x-y plane relative to first split-ring conductive strip **1400q**. First split-ring conductive strip **1400q** and second split-ring conductive strip **1401q** together form a broken ring with a broken center conductor. Second split-ring impedance structure **1304q** may include a third split-ring conductive strip **1404q**, a fourth split-ring conductive strip **1405q**, and second dielectric slab **1406a**. Third split-ring conductive strip **1404q** and fourth split-ring conductive strip **1405q** are formed of conductive material layered on, against, or adjacent to second dielectric slab **1406a**. Third split-ring conductive strip **1404q** and fourth split-ring conductive strip **1405q** are identical except that fourth split-ring conductive strip **1405q** is rotated 180° in the x-y plane relative to third split-ring conductive strip **1404q**. Third split-ring conductive strip **1404q** and fourth split-ring conductive strip **1405q** together form a broken ring with a broken center conductor. First split-ring conductive strip **1400q** and second split-ring conductive strip **1401q** may be modeled as resonant layers that may include the shunt inductors L_{F1} and L_{F2} and the shunt capacitors C_{F1} and C_{F2} in equivalent circuit **1700**.

Referring to FIG. 18M, a perspective view of an eighteenth polarization rotating layer antenna element **1300r** is shown comprised of two E-shaped resonator conducting layers in accordance with an illustrative embodiment. Eighteenth polarization rotating layer antenna element **1300r** includes a first E-shaped resonator impedance structure **1302r**, first polarization rotating element **202a**, and a second E-shaped resonator impedance structure **1304r**. First E-shaped resonator impedance structure **1302r** and second E-shaped resonator impedance structure **1304r** are identical except that second E-shaped resonator impedance structure **1304r** is rotated 90° in the x-y plane and 180° in the x-z plane relative to first E-shaped resonator impedance structure **1302r**. First E-shaped resonator impedance structure **1302r** may include a first E-shaped conductive strip **1400r** and first dielectric slab **1402a**. First square E-shaped conductive strip **1400r** is formed of conductive material layered on, against, or adjacent to first dielectric slab **1402a** in the shape of an E. Second E-shaped resonator impedance structure **1304r** may include a second E-shaped conductive strip **1404r** and second dielectric slab **1406a**. Second E-shaped conductive strip **1404r** is formed of conductive material layered on, against, or adjacent to second dielectric slab **1406a** in the shape of an E. First E-shaped conductive strip **1400r** and second E-shaped conductive strip **1404r** may be

modeled as resonant layers that may include the shunt inductors L_{F1} and L_{F2} and the series capacitors C_{S1} and C_{S2} in equivalent circuit **1700**.

Referring to FIG. 18N, a perspective view of a nineteenth polarization rotating layer antenna element **1300s** is shown comprised of two rectangular slot array conducting layers in accordance with an illustrative embodiment. Nineteenth polarization rotating layer antenna element **1300s** includes a first rectangular slot array impedance structure **1302s**, first polarization rotating element **202a**, and a second rectangular slot array impedance structure **1304s**. First rectangular slot array impedance structure **1302s** and second rectangular slot array impedance structure **1304s** are identical except that second rectangular slot array impedance structure **1304s** is rotated 90° in the x-y plane and 180° in the x-z plane relative to first rectangular slot array impedance structure **1302s**. First rectangular slot array impedance structure **1302s** may include a thirteenth conductive slab **1400s** formed of conductive material layered on, against, or adjacent to first dielectric slab **1402a**. Two identical rectangular slot walls may be formed through thirteenth conductive slab **1400s**. Second rectangular slot array impedance structure **1304s** may include a fourteenth conductive slab **1404s** formed of conductive material layered on, against, or adjacent to second dielectric slab **1406a**. Two identical rectangular slot walls may be formed through fourteenth conductive slab **1404s**. Thirteenth conductive slab **1400s** and fourteenth conductive slab **1404s** may be modeled as inductive layers such that only the shunt inductors L_{F1} and L_{F2} are included in the equivalent circuit without the shunt capacitors C_{F1} and C_{F2} or the series capacitors C_{S1} and C_{S2} .

In FIGS. 18A through 18N, second dielectric slab **1406a** is transparent. In FIGS. 18A through 18N, first dielectric slab **1402a** and second dielectric slab **1406a** may have different dimensions in the x-y plane and the y-z plane depending on the embodiment.

Though the illustrative embodiments of polarization rotating antenna element **106** and of polarization rotating layer antenna element **1300** are shown with the first antenna and the second antenna identical except that the second antenna is rotated 90° in the x-y plane and 180° in the x-z plane relative to the first antenna, the first antenna and the second antenna need not be identical. For example, an antenna system may be housed within a radome to protect it from the environment. Radomes are typically composed of dielectric materials and are often placed in close proximity to the antenna itself. The radome may load the structure asymmetrically because the radome is only positioned on one side of the antenna. The presence of the radome changes the effective wave impedance on one side of the antenna and not on the other. To compensate for this effect, asymmetric antennas can be designed to account for the different wave impedance on the sides of the antenna.

Further, first dielectric slab **1402a** and second dielectric slab **1406a** need not be identical.

As understood by a person of skill in the art, dimensions of each polarization rotating antenna element **106** may be defined based on a desired center frequency of the incoming electromagnetic wave. Further, the design may vary based on a location in the array. For example, a key challenge in designing a phase array system involves addressing performance issues related to unit cell size and spacing, particularly concerning grating lobes. The demand for wide bandwidth and wide-scan angle capabilities may lead to a preference for smaller spacing between the elements (typically limited to 0.5) for a wide-angle scanned beam) to avoid formation of high grating lobes. However, the use of densely

packed arrays with small element spacing, especially within large apertures, introduces significant costs and complexity of implementation due to the need for a substantial number of electronically reconfigurable phase shifters and associated components. A possible solution involves the use of unit cell sizes with different sizes and shapes within the same array.

To balance the trade-off between performance and cost within the large aperture, a potentially effective approach involves modifying the element spacing based on their proximity to the array center. Recognizing that in an antenna array with a large aperture, elements closer to the center have a more significant impact on the array's overall performance due to amplitude tapering over the aperture. Therefore, smaller element spacings may be used in regions closer to a center of the aperture. Since these elements have the largest excitation coefficients (due to amplitude tapering from the feed), their performance is the most important to the overall performance of the phased-array. Simultaneously, adopting a triangular, rectangular, or hexagonal lattice for the border elements enables us to use fewer elements on the periphery of the aperture where the excitation coefficients of the elements are lower and the performance of those elements are less significant to the overall performance of the array. This choice allows for increasing the effective spacing between peripheral elements, resulting in a reduction of the number of required elements in the array without considerably compromising functionality. This strategic adjustment offers a balance between the desired performance and the cost/complexity of the phased-array.

In contrast to a square-shaped unit cell that provides symmetric beam steering across azimuth and elevation, a rectangular lattice introduces an asymmetry. This asymmetry becomes advantageous when a wider beam scan angle is desired in one direction compared to the other. This allows larger element spacing along the directions where a limited scan angle is needed thereby reducing the total elements of the array that need to be electronically controlled.

A hexagonal shaped unit cell is useful for designing phased-array antennas with triangular lattice shapes compared to square or rectangular lattice shapes for the array element. Depending on the desired beam scan angle in the principal planes of radiation, arrays with triangular grids can be designed to provide the desired scan coverage with a fewer number of radiating elements.

Any of second polarization rotating element **202b**, third polarization rotating element **202c**, fourth polarization rotating element **202d**, fifth polarization rotating element **202e**, sixth polarization rotating element **202f**, and seventh polarization rotating element **202g** may replace first polarization rotating element **202a** in the illustrative embodiments of polarization rotating antenna element **106** provided herein.

As understood by a person of skill in the art, dimensions of each polarization rotating layer antenna element **1300** may be defined based on a desired center frequency of the incoming electromagnetic wave. For example, equivalent circuit **1700** may be used to determine the dimensions of each polarization rotating layer antenna element **1300** based on the materials selected for use. Any of second polarization rotating element **202b**, third polarization rotating element **202c**, fourth polarization rotating element **202d**, fifth polarization rotating element **202e**, sixth polarization rotating element **202f**, and seventh polarization rotating element **202g** may replace first polarization rotating element **202a** in the illustrative embodiments of polarization rotating layer antenna element **1300** provided herein.

As understood by a person of skill in the art, different shaped conducting layers may be formed on first dielectric slab **1402a** and second dielectric slab **1406a** in addition to those illustrated in FIGS. **14A-14D** and **18A, 18B, 18F-18H, and 18K-18M**. As understood by a person of skill in the art, different shaped slot walls may be formed on a conducting slab in addition to those illustrated in FIGS. **14E and 18C-18E, 18I, 18J, and 18N**.

As used herein, the term "mount" includes join, unite, connect, couple, associate, insert, hang, hold, affix, attach, fasten, bind, paste, secure, bolt, screw, rivet, solder, weld, glue, form over, form in, layer, mold, rest on, rest against, etch, abut, and other like terms. The phrases "mounted on", "mounted to", and equivalent phrases indicate any interior or exterior portion of the element referenced. These phrases also encompass direct mounting (in which the referenced elements are in direct contact) and indirect mounting (in which the referenced elements are not in direct contact, but are connected through an intermediate element).

The word "illustrative" is used herein to mean serving as an example, instance, or illustration. Any aspect or design described herein as "illustrative" is not necessarily to be construed as preferred or advantageous over other aspects or designs. Further, for the purposes of this disclosure and unless otherwise specified, "a" or "an" means "one or more". Still further, using "and" or "or" in the detailed description is intended to include "and/or" unless specifically indicated otherwise.

Any directional references used herein, such as left-side, right-side, top, bottom, back, front, up, down, above, below, etc., are for illustration only based on the orientation in the drawings selected to describe the illustrative embodiments.

The foregoing description of illustrative embodiments of the disclosed subject matter has been presented for purposes of illustration and of description. It is not intended to be exhaustive or to limit the disclosed subject matter to the precise form disclosed, and modifications and variations are possible in light of the above teachings or may be acquired from practice of the disclosed subject matter. The embodiments were chosen and described in order to explain the principles of the disclosed subject matter and as practical applications of the disclosed subject matter to enable one skilled in the art to utilize the disclosed subject matter in various embodiments and with various modifications as suited to the particular use contemplated.

What is claimed is:

1. An antenna element comprising:

a first impedance structure comprising:

a first dielectric slab formed of a first dielectric material, wherein the first dielectric slab has a first face and a second face, wherein the first face is on an opposite side of the first dielectric slab relative to the second face; and

a first conducting pattern layer formed of a first electrically conductive material, wherein the first conducting pattern layer is mounted on the first face of the first dielectric slab;

a second impedance structure comprising:

a second dielectric slab formed of a second dielectric material, wherein the second dielectric slab has a third face and a fourth face, wherein the third face is on an opposite side of the second dielectric slab relative to the fourth face; and

a second conducting pattern layer formed of a second electrically conductive material, wherein the second conducting pattern layer is mounted on the third face of the second dielectric slab; and

- a polarization rotating element comprising:
- a frame formed of a third electrically conductive material;
 - a third dielectric slab including a first dielectric surface and a second dielectric surface formed within the frame, wherein the first dielectric surface is on an opposite side of the third dielectric slab relative to the second dielectric surface, wherein the third dielectric slab is formed of a third dielectric material;
 - a third conducting pattern layer formed of a third electrically conductive material mounted to the first dielectric surface between the first dielectric surface and the second face of the first dielectric slab, wherein the third conducting pattern layer includes a first conductor and a second conductor;
 - a first switch connected between the first conductor and the second conductor to electrically connect the first conductor to the second conductor or to electrically disconnect the first conductor from the second conductor, wherein, when the first conductor and the second conductor are electrically connected, the first conductor and the second conductor form a first dipole;
 - a fourth conducting pattern layer formed of a fourth electrically conductive material mounted to the second dielectric surface between the second dielectric surface and the fourth face of the second dielectric slab, wherein the fourth conducting pattern layer includes a third conductor and a fourth conductor; and
 - a second switch connected between the third conductor and the fourth conductor to electrically connect the third conductor to the fourth conductor or to electrically disconnect the third conductor from the fourth conductor, wherein, when the third conductor and the fourth conductor are electrically connected, the third conductor and the fourth conductor form a second dipole.
2. The antenna element of claim 1, wherein an incoming electric field propagates through the first impedance structure, the polarization rotating element, and the second impedance structure in the axial direction.
3. The antenna element of claim 1, wherein at least one of the first electrically conductive material, the second electrically conductive material, the third electrically conductive material, and the fourth electrically conductive material is formed of a different electrically conductive material relative to any other of the first electrically conductive material, the second electrically conductive material, the third electrically conductive material, and the fourth electrically conductive material.
4. The antenna element of claim 1, wherein the fourth conducting pattern layer is identical to the third conducting pattern layer.
5. The antenna element of claim 1, wherein the first conducting pattern layer is identical to the second conducting pattern layer.
6. The antenna element of claim 1, wherein the first dielectric slab layer is identical to the second dielectric slab.
7. The antenna element of claim 6, wherein the first conducting pattern layer is identical to the second conducting pattern layer.
8. The antenna element of claim 1, wherein, when the first switch electrically connects the first conductor to the second conductor, the second switch electrically disconnects the third conductor from the fourth conductor to define a first mode of the polarization rotating element.

9. The antenna element of claim 8, wherein the first mode is configured to rotate a polarization of an outgoing electric field by 90 degrees relative to an incoming electric field.
10. The antenna element of claim 9, wherein, when the second switch electrically connects the third conductor to the fourth conductor, the first switch electrically disconnects the first conductor from the second conductor to define a second mode of the polarization rotating element.
11. The antenna element of claim 10, wherein the second mode is configured to rotate the polarization of the outgoing electric field by -90 degrees relative to the incoming electric field.
12. The antenna element of claim 1, wherein the first switch and the second switch are single pole, single throw switches.
13. The antenna element of claim 1, wherein the first switch comprises:
- a diode connected between the first conductor and the second conductor;
 - a first bias line connected to a first end of the first conductor opposite where the diode is connected to the first conductor; and
 - a second bias line connected to a first end of the second conductor opposite where the diode is connected to the second conductor.
14. The antenna element of claim 13, wherein a voltage applied to the first bias line or to the second bias line controls whether the first switch electrically connects the first conductor to the second conductor or electrically disconnects the first conductor from the second conductor.
15. The antenna element of claim 1, wherein the first conducting pattern layer comprises a conductive slab with a slot wall formed through the conductive slab.
16. The antenna element of claim 15, wherein the slot wall forms at least one shape selected from the group consisting of a polygonal shape, a cross shape, a V-shape, an H-shape.
17. The antenna element of claim 1, wherein the first conducting pattern layer comprises a conductive slab, wherein the conductive slab is sized and shaped identical to the first dielectric slab.
18. The antenna element of claim 1, wherein the first conducting pattern layer comprises at least one continuous conductive strip forming a shape selected from the group consisting of a polygonal shape, a strip shape, a cross shape, a Jerusalem cross shape, an L-shape, a top squared off triangle shape, a square C-shape, a square S-shape, an E-shape, and a split-ring shape.
19. The antenna element of claim 1, wherein the first conducting pattern layer comprises a plurality of conductive strips.
20. A phased array antenna comprising:
- a plurality of antenna elements, wherein each antenna element of the plurality of antenna elements comprises a first impedance structure comprising:
 - a first dielectric slab formed of a first dielectric material, wherein the first dielectric slab has a first face and a second face, wherein the first face is on an opposite side of the first dielectric slab relative to the second face; and
 - a first conducting pattern layer formed of a first electrically conductive material, wherein the first conducting pattern layer is mounted on the first face of the first dielectric slab;
 - a second impedance structure comprising:
 - a second dielectric slab formed of a second dielectric material, wherein the second dielectric slab has a third face and a fourth face, wherein the third face

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is on an opposite side of the second dielectric slab relative to the fourth face; and

a second conducting pattern layer formed of a second electrically conductive material, wherein the second conducting pattern layer is mounted on the third face of the second dielectric slab; and

a polarization rotating element comprising:

- a frame formed of a third electrically conductive material;
- a third dielectric slab including a first dielectric surface and a second dielectric surface formed within the frame, wherein the first dielectric surface is on an opposite side of the third dielectric slab relative to the second dielectric surface, wherein the third dielectric slab is formed of a third dielectric material;
- a third conducting pattern layer formed of a third electrically conductive material mounted to the first dielectric surface between the first dielectric surface and the second face of the first dielectric slab, wherein the third conducting pattern layer includes a first conductor and a second conductor;
- a first switch connected between the first conductor and the second conductor to electrically connect

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the first conductor to the second conductor or to electrically disconnect the first conductor from the second conductor, wherein, when the first conductor and the second conductor are electrically connected, the first conductor and the second conductor form a first dipole;

a fourth conducting pattern layer formed of a fourth electrically conductive material mounted to the second dielectric surface between the second dielectric surface and the fourth face of the second dielectric slab, wherein the fourth conducting pattern layer includes a third conductor and a fourth conductor; and

a second switch connected between the third conductor and the fourth conductor to electrically connect the third conductor to the fourth conductor or to electrically disconnect the third conductor from the fourth conductor, wherein, when the third conductor and the fourth conductor are electrically connected, the third conductor and the fourth conductor form a second dipole.

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