Office de la Propriété Intellectuelle du Canada
Un organisme d'Industrie Canada

Canadian Intellectual Property Office
An agency of Industry Canada

CA 2378736 C 2010/03/23

(11)(21) 2 378 736

(12) BREVET CANADIEN
CANADIAN PATENT

(13) C

(86) Date de dépôt PCT/PCT Filing Date: 2000/07/13
(87) Date publication PCT/PCT Publication Date: 2001/01/18
(45) Date de délivrance/Issue Date: 2010/03/23
(85) Entrée phase nationale/National Entry: 2002/01/09
(86) N° demande PCT/PCT Application No.: US 2000/018998
(87) N° publication PCT/PCT Publication No.: 2001/004680
(30) Priorité/Priority: 1999/07/13 (US09/352,835)

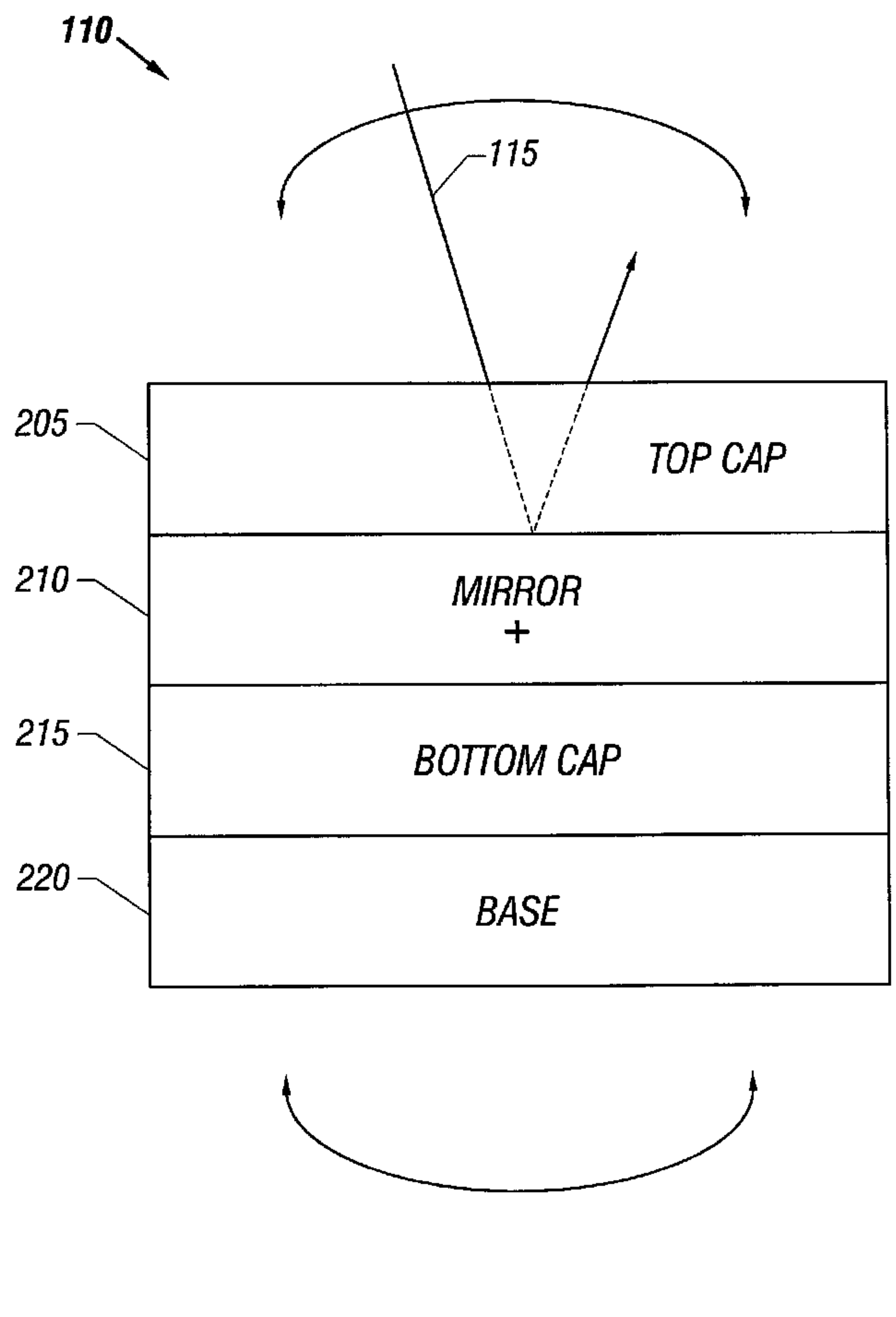
(51) Cl.Int./Int.Cl. *G02B 7/182* (2006.01), *G02B 26/08* (2006.01)

(72) Inventeurs/Inventors:
YU, DULI, US;
YU, LIANZHONG, US;
GOLDBERG, HOWARD D., US;
SCHMIDT, MARTIN A., US;
RIED, ROBERT P., US

(73) Propriétaire/Owner:
ION GEOPHYSICAL CORPORATION, US

(74) Agent: CASSAN MACLEAN

(54) Titre : DISPOSITIF A MIROIR MICRO-USINE
(54) Title: MICRO-MACHINED MIRROR DEVICE



(57) Abrégé/Abstract:
A micro machined mirror assembly is provided that includes a micro machined top cap (205), mirror (210), and bottom cap (215) mounted onto a ceramic substrate. The micro machined mirror is resiliently supported by a pair of T-shaped hinges and includes travel stops that limit motion of the mirror in the x-, y-, and z-directions. The top and bottom micro machined caps also include travel stops that limit motion of the mirror in the z-direction.

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
18 January 2001 (18.01.2001)

PCT

(10) International Publication Number
WO 01/04680 A1

(51) International Patent Classification[7]: G02B 7/182

(21) International Application Number: PCT/US00/18998

(22) International Filing Date: 13 July 2000 (13.07.2000)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
09/352,835 13 July 1999 (13.07.1999) US

(71) Applicant: INPUT OUTPUT, INC. [US/US]; 12300 Charles E. Selecman Drive, Stafford, TX 77477 (US).

(72) Inventors: YU, Duli; 15700 Lexington Boulevard, No. 301, Sugar Land, TX 77478 (US). YU, Lianzhong; Apartment No. A-2, 13906 NE 9th PL, Bellevue, WA 98005 (US). GOLDBERG, Howard, D.; 3007 Colony Crossing Drive, Sugar Land, TX 77479 (US). SCHMIDT, Martin, A.; 78 Ashley Place, Reading, MA 01867 (US). RIED, Robert, P.; 5010 Grove West Boulevard, No. 1602, Stafford, TX 77477-2622 (US).

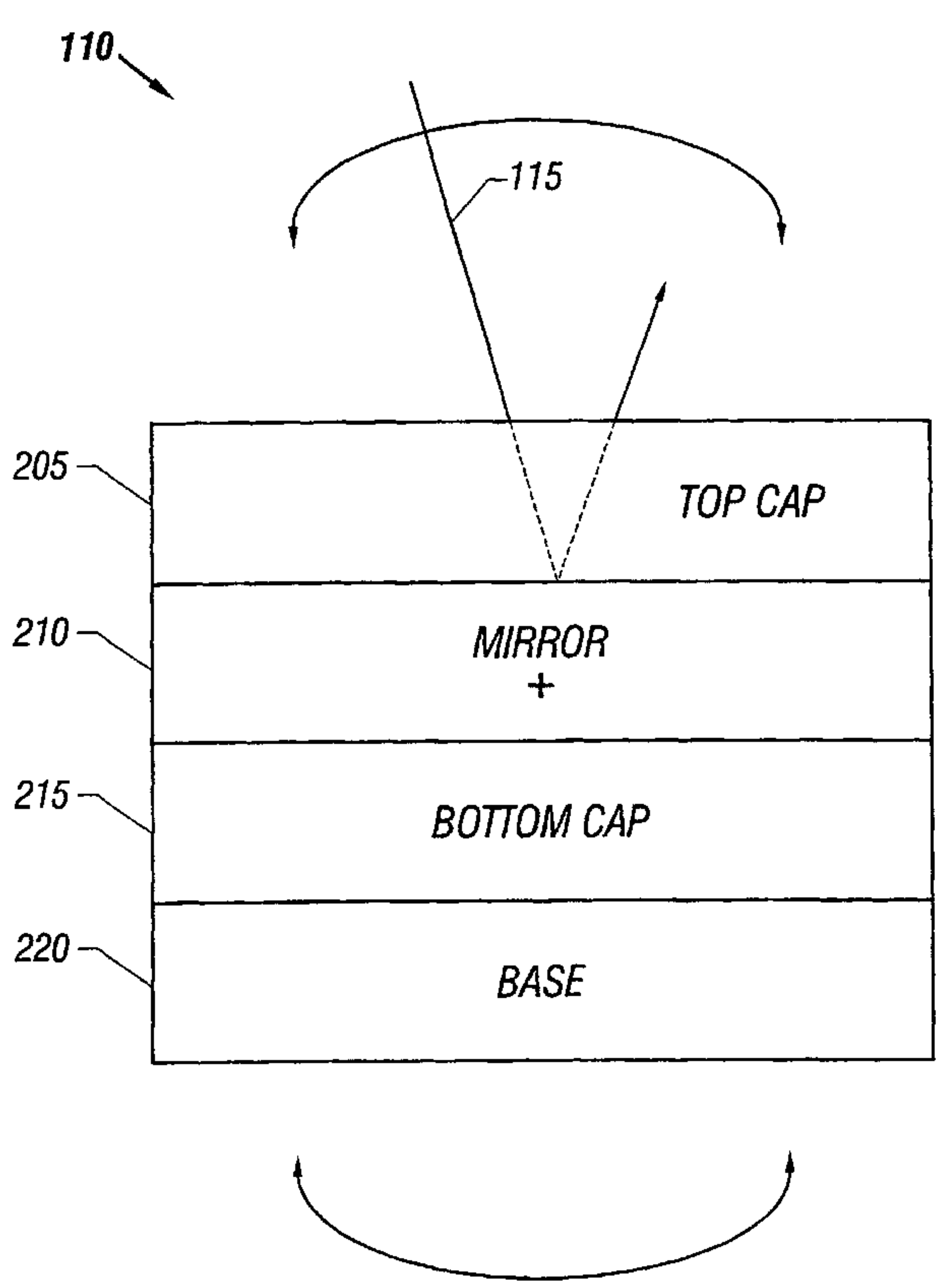
(74) Agent: MADAN, Paul, S.; Madan, Mossman & Sriram, P.C., Suite 700, 2603 Augusta, Houston, TX 77057 (US).

(81) Designated States *(national)*: AE, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CR, CU, CZ, DE, DK, DM, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, UZ, VN, YU, ZA, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European

[Continued on next page]

(54) Title: MICRO-MACHINED MIRROR DEVICE



(57) Abstract: A micro machined mirror assembly is provided that includes a micro machined top cap (205), mirror (210), and bottom cap (215) mounted onto a ceramic substrate. The micro machined mirror is resiliently supported by a pair of T-shaped hinges and includes travel stops that limit motion of the mirror in the x-, y-, and z-directions. The top and bottom micro machined caps also include travel stops that limit motion of the mirror in the z-direction.

WO 01/04680 A1

APPLICATION FOR PATENT

Title: MICRO-MACHINED MIRROR DEVICE

Background of the Invention

This invention relates generally to micro-machined three-dimensional structures, and in particular to micro-machined mirrors for use in optical readers, such as bar code readers or scanners.

Conventional bar code scanners are used to scan a surface with a laser beam. Conventional bar code scanners further typically utilize mirrors that are oscillated to permit the laser beam to scan. Conventional mirrors for bar code scanners are relatively large and imprecise.

In order to manufacture smaller and more precise bar code mirrors, micro-machining processes have been used in which a silicon substrate is micro-machined to produce a mirror. However, conventional micro-machined mirrors and their manufacturing processes suffer from a number of limitations. Prior art micro-machined mirrors do not provide appropriate compliance in all directions of the movement of the mirror. Such mirrors typically are not sufficiently shock resistant or able to operate over wide ranges of temperature over extended use.

The present invention provides micro-machined mirror devices which overcome one or more limitations of the existing micro-machined devices.

Summary of the Invention

According to one aspect of the present invention, a mirror assembly is provided that includes a mirror, a top cap, and a bottom cap. The mirror includes a mirror support structure, a pair of T-shaped hinges coupled to the mirror support structure and a mirrored plate coupled to the T-shaped hinges. The mirrored plate includes one or more travel stops for limiting movement of the mirrored plate. The top cap is coupled to one side of the mirror. The top cap includes a top cap support structure that includes an opening for permitting light to reflect off of the mirrored plate and one or more travel stops coupled to the top cap support structure for limiting movement of the mirrored plate. The bottom cap is coupled to another side of the mirror. The bottom cap includes a bottom cap support structure including an opening and one or more travel stops coupled to the bottom cap support structure for limiting movement of the mirrored plate.

According to another aspect of the present invention, a mirror assembly is provided that includes a support structure, pair of T-shaped hinges coupled to the support structure and a mirrored plate coupled to the T-shaped hinges. The mirrored plate includes one or more travel stops for limiting movement of the mirrored plate.

According to another aspect of the present invention, an apparatus is provided that includes a housing, a mass, and one or more springs for coupling the mass to the housing. Each spring includes a rotational spring constant and a translational spring constant. The rotational spring constant is decoupled from the translational spring constant.

According to another aspect of the present invention, a method of resiliently supporting a mass in a housing is provided that includes coupling the mass to the housing using one or more hinges having translational spring constants and rotational spring constants and decoupling the translational spring constants from the rotational spring constants.

According to another aspect of the present invention, a method of resiliently supporting a mass in a housing is provided that includes limiting translational movement of the mass in the X, Y and Z directions and limiting rotational or torsional movement of the mass.

According to another aspect of the present invention, an apparatus is provided that includes a housing and a mass resiliently coupled to the housing. The mass includes one or more travel stops for limiting rotational and translational or planar movement of the mass.

According to another aspect of the present invention, a method of reflecting rays of light is provided that includes a reflective surface and providing an optical pathway for accessing the reflective surface or planar one or more cutouts for minimizing clipping of the incident and reflected light rays.

Brief Description of the Drawings

FIG. 1 is a cross section view of a laser scanning device according to the present invention.

FIG. 2 is a schematic side view of a preferred embodiment of the mirror assembly of **FIG. 1**.

FIG. 3 is a top view of the top cap of the mirror assembly of **FIG. 2**.

FIG. 4 is a cross-sectional view of the top cap of **FIG.3**.

FIG. 5 is a cross-sectional view of the top cap of **FIG. 3**.

FIG. 6 is a top view of the mirror of the mirror assembly of **FIG. 2**.

FIG. 6A is a top view of an alternative embodiment of the hinge of the mirror assembly of **FIG. 2**.

FIG. 6B is a top view of an alternative embodiment of the hinge of the mirror assembly of **FIG. 2**.

FIG. 6C is a top view of an alternative embodiment of the hinge of the mirror assembly of **FIG. 2**.

FIG. 6D is a top view of an alternative embodiment of the mirror of the mirror assembly of **FIG. 2**.

FIG. 7 is a cross-sectional view of the mirror of **FIG. 6**.

FIG. 8 is a cross-sectional view of the mirror of **FIG. 6**.

FIG. 9 is a bottom view of the mirror of **FIG. 6**.

FIG. 10 is a top view of the bottom cap of the mirror assembly of **FIG. 2**.

FIG. 11 is a cross-sectional view of the bottom cap of **FIG. 10**.

FIG. 12 is a cross-sectional view of the bottom cap of **FIG. 10**.

FIG. 13 is a top view of the base member of the mirror assembly of **FIG. 2**.

FIG. 14 is a cross-sectional view of the base member of **FIG. 13**.

FIG. 15 is a cross-sectional view of the base member of **FIG. 13**.

FIG. 16 is a top view of the top cap and mirror of the mirror assembly of **FIG. 2**.

FIG. 17 is a top view of the bottom cap and base member of the mirror assembly of **FIG. 2**.

FIG. 18 is a cross-sectional view of the mirror assembly of **FIG. 16** illustrating the oscillation of the mirror collection plate.

FIG. 19 is a view of the mirror assembly of **FIG. 18** illustrating the use of tapered surfaces to minimize clipping of the laser light.

Detailed Description of the Preferred Embodiments

A mirror assembly for use in a bar code reader is provided. The mirror assembly preferably includes a micro-machined three-dimensional mirror supported generally by a pair of "T" shaped hinges in a support structure. The mirror assembly further preferably includes one or more travel stops for limiting the movement of the mirror. The mirror assembly further preferably includes one or more tapered edge surfaces and cut-outs for minimizing clipping of incident and reflected laser beams.

FIG. 1 is a cross section view of a laser scanning device such as a bar code scanner **100** having a light beam **115** that emanates from the device to strike a target **120.** The light beam is reflected or scattered by the target **120**. The bar code scanner **100** includes a laser beam source **105** and a mirror assembly **110.** During the operation of the bar code scanner **100**, the optically reflective portion **111** of the mirror assembly **110** is preferably oscillated to permit the laser beam **115** to scan a surface, such as a bar code symbol **120,** by reflecting the laser beam **115** off of the optically reflective portion **111** of the mirror assembly **110**. The reflected light **125** enters the bar code scanner **100** through a window **165** and is detected by a light detector **160**. The laser beam source **105** may comprise any number of conventional commercially available devices to generate the laser beam **115**.

The bar code scanner **100** may include additional features for user interface, control and data processing. These features may comprise a processor **130** and memory device **135** as part of a central processing unit **140**, a controller **145** for generating voltage used to oscillate the mirror **110**, a data entry device such as a keypad **150** and a data display device such as a liquid crystal display **155**. The mirror assembly **110** made according to the present invention is described below in reference to **FIGS. 2-19**.

Referring to **FIG. 2**, in a preferred embodiment, the mirror assembly **110** includes a top cap **205**, a mirror **210**, a bottom cap **215**, and a base member **220**. The top cap **205** includes an opening that permits the laser beam **115** to reflect off of the mirror **210**. In this manner, the mirror **210** is surrounded and protected by the top cap **205** and the bottom cap **215**. The sub-assembly that includes the top cap **205**, mirror **210** and bottom cap **215** is formed and then mounted onto the base member **220**.

The top cap **205** and bottom cap **215** may be fabricated from any number of conventional commercially available materials such as, for example, silicon glass, ceramic or plastic. In a preferred embodiment, the top cap **205** is fabricated by micro-machining a silicon wafer.

FIGS. 3-5 show various views of a preferred embodiment of the top cap **205** which has a frame **301** that includes a top, bottom, left and right support members **305**, **315**, **325** and **335**. Top and bottom travel stop members **310** and **320** are coupled respectively to the top and bottom support members **305** and **315**. The left and right support members **325** and **335** include corresponding left and right rim cutouts **330** and **340** for minimizing clipping of the incident light.

The top cap frame **301** provides an overall support structure for the top cap **205**. The thickness of the frame **301** may range, for example, from about 400 to 600 microns with a preferred thickness ranging from about 390 to 400 microns in order to provide a compact structure having a low mass.

The top travel stop **310** preferably limits the motion of the reflective portion of the mirror **210** in the direction normal to the plane of the reflective portion of the mirror **210** (the Z-direction). The top travel stop **310** preferably extends in substantially orthogonal direction from the top support member **305**. In a preferred embodiment, the top travel stop **310** is positioned within the plane of the top support member **305**. The thickness of the top travel stop **310** may range, for example, from about 340 to 580 microns. In a preferred embodiment, the thickness of the top travel stop **310** ranges from about 350 to 380 microns in order to provide optimum shock protection, freedom of motion, and a compact structure having a low mass.

Referring to **FIG. 4**, in a particularly preferred embodiment, the bottom surface **310b** of the top travel stop **310** is recessed below the level of the bottom surface **305b** of the top support member **305**. In this manner, the bottom surface **310b** of the top travel stop **310** is preferably positioned above the level of the reflective surface of the mirror **210**. The length of the top travel stop member **310** may range, for example, from about 800 to 2800 microns. In a preferred embodiment, the length of the top travel stop member **310** ranges from about 2000 to 2500 microns. In a particularly preferred embodiment, the length of the top travel stop member **310** is selected to overlap with the mirror collection plate **610** of the mirror by about 300 microns.

The bottom travel stop **320** extends in a substantially orthogonal direction from the bottom support member **315** and is substantially identical to the top travel stop **310**. An opening **345** permits light to reflect off of the reflective surface of the mirror **210**. The opening **345** preferably includes a left rim cut out **330** and a right rim cut out **340**. The left and right rim cut outs, **330** and **340**, are preferably positioned on opposite sides in surrounding relation to the reflective surface of the mirror **210**. In this manner, the left and right rim cut-outs, **330** and **340**, provide optical access to the reflective surface of the mirror **210**.

In a preferred embodiment, the top cap frame **301**, travel stops **310** and **320**, rim cut outs **330** and **340**, and the opening **345** all include tapered edges, **350A** and **350B**, to facilitate optical access to the reflective surface of the mirror **210 (FIG. 5)**. The taper angle of the tapered edges, **350A** and **350B**, preferably ranges from about 50 to 60 degrees in order to optimally facilitate the reflection of laser light transmitted at an angle towards the edge portions of the reflective surface of the mirror **210**.

FIG. 6 shows a top view of a mirror or mirror assembly **210** made according to one embodiment of the present invention. The mirror **210** includes a frame or mirror support structure **600** having support members

602, 604, 606 and 608. The mirror **210** further comprises a mirror collection plate **610** with a reflective surface **628**, a top T-shaped hinge **612**, a bottom T-shaped hinge **614**, a top left travel stop finger **616**, a top right travel stop finger **618**, a bottom left travel stop finger **620**, a bottom right travel stop finger **622**, an opening **624**, a conductive layer **626**, and a reflective surface **628**.

The mirror frame **600** provides the overall support structure for the mirror **210**. The thickness of the frame **600** may range, for example, from about 400 to 600 microns with a preferred thickness ranging from about 400 to 450 microns in order to provide a compact structure having a low mass. In a preferred embodiment, the support members **602**, **604**, **606**, and **608** provide effective beam lengths ranging from about 500-2500 microns and cross sections of about 8,000 microns^2 to 160,000 microns^2 in order to optimally absorb shock loads of about 2000g/0.5 mS half sine wave input.

The mirror collection plate **610** is coupled to the top T-shaped hinge **612** and the bottom T-shaped hinge **614**. In this manner, the mirror collection plate **610** rotates about the axis **630** i.e. has torsional movement about such axis. In a preferred embodiment, the axis **630** is positioned substantially along the centerline of the mirror collection plate 610 and is coincident with the center of the T-shaped hinges, **612** and **614,** thereby providing a common axis of rotation for the springs. The reflective surface **628** is coupled to the top **632** of the mirror collection plate **610**. In this manner, rotation of the mirror collection plate **610** about the axis **630** causes laser light from a stationary laser to reflect off of the reflective surface **628** in a plurality of directions.

The thickness of the mirror collection plate **610** may range, for example, from about 100 to 600 microns with a preferred thickness ranging from about 100 to 250 microns to provide a low mass and maximize the effective natural frequency of the mirror **210**.

The reflective surface **628** may be comprised of any number of conventional commercially available optically reflective surfaces such as, for example, gold, silver or aluminum. In a preferred embodiment, the reflective surface **628** comprises gold in order to optimize the amount of optical energy that is reflected. In a preferred embodiment, the surface roughness of the reflective surface **628** is less than about 0.1 wavelengths of the reflected light in order to optimize the amount of optical energy that is reflected.

The **FIGS. 7 and 8** show cross-sectional views of the mirror of **FIG. 6** and **FIG. 9** shows a bottom view of the mirror of **FIG. 6**. As illustrated in **FIGS. 7-9**, in a preferred embodiment, the bottom **634** of the mirror collection plate **610** includes a top travel stop **710**, a bottom travel stop **715**, and a cavity **720**. The top travel stop **710** extends from the bottom **634** of the mirror collection plate **610**. The top travel stop **710** preferably limits movement of the mirror collection plate **610** in the z-direction. The top travel stop **710** preferably extends from the bottom **634** of the mirror collection plate **610** in a substantially orthogonal direction. The top travel stop **710** may extend from the bottom **634** of the mirror collection plate **610** for a distance ranging, for example, from about 200 to 400 microns with a preferred distance ranging from about 200 to 250 microns to optimally limit movement of the mirror collection plate **610**. In a preferred embodiment, the top travel stop **710** is centered about the axis **630** and is positioned adjacent to and on one side of the cavity **720**. The bottom travel stop **715** is preferably identical to the top travel stop **710** described above.

The cavity **720** extends into the bottom of the mirror collection plate **610**, which reduces the mass of the mirror collection plate **610**. In this manner, the droop of the mirror **210** is reduced. In a preferred embodiment, the depth and volume of the cavity **720** ranges from about 200 to 500 microns and $8X10^6$ to $1X10^9$ microns.[3] In a preferred embodiment, the cavity **720** is centrally positioned along the axis **630** and within the back side **634** of the mirror collection plate **610**.

For typical bar code scanner applications, the rotational accuracy of the laser beam may be required to be within 1.3° when the mirror collection plate **610** is subjected to an across-the-hinge self-induced gravity torque. Where torque $T = mg*h/2$, with mg = mirror collection plate weight and h = mirror collection plate thickness. The mirror accuracy is a function of the pointing accuracy and mirror droop. The torsional spring constant K_r of the T-shaped hinges, **612** and **614**, is determined by the resonant frequency F of the mirror collection plate **610** and the size and mass of the mirror collection plate **610**. The mirror tilt angle θ due to a gravity torque is determined by the relation, $\theta=T/K_r$. Consequently, the thickness and mass of the mirror collection plate **610**, are preferably selected to provide a mirror tilt angle less than 1.3°. In a preferred embodiment, the thickness and mass of the mirror collection plate **610** are reduced by reducing the thickness of the mirror collection plate **610** and by providing one or more cavities in the mirror collection plate **610**.

The top T-shaped hinge **612** is coupled to the left support member **606**, the right support member **608**, and the top portion of the mirror collection plate **610**. The top T-shaped hinge **612** preferably includes a vertical support member **644** (beam or leg) and a second or horizontal support member **646** (T-member). The horizontal support member **646** preferably is supported at opposite ends by the left support member **606** and the right support member **608**. In a preferred embodiment, the horizontal support member **646** is substantially orthogonal to both the left support member **606** and the right support member **608**. The vertical support member **644** is coupled to the horizontal support member **646**. In a preferred embodiment, the vertical support member **644** is substantially orthogonal to the horizontal support member **646**. The vertical support member **644** is coupled to the mid-point of the horizontal support member **646**. The vertical support member **644** is positioned along the axis **630**. The length, width and thickness of the vertical support member **644** may range, for example, from about 100 to 2500 microns, 2 to 100 microns and 2 to 100 microns, respectively. In a preferred embodiment, the length, width and thickness of the vertical support member **644** range from about 800 to 1000 microns, 8 to 15 microns and 8 to 15 microns, respectively. The torsional spring constant of the vertical support member **644** may range, for example, from about $2x10^{-9}$ to $10x10^{-7}$ lbf-ft/radian. In a preferred embodiment, the torsional spring constant of the vertical support member **644** ranges from about $2x10^{-8}$ to $10x10^{-8}$ lbf-ft/radian. The length, width and thickness of the horizontal support member **646** may range, for example, from about 500 to 4500 microns, 6 to 100 microns and 6 to 100 microns, respectively. In a preferred embodiment, the length, width and thickness of the horizontal support member **646** range from about 2200 to 2500 microns, 15 to 25 microns and 15 to 25 microns, respectively.

The bottom T-shaped hinge **614** is coupled to the left support member **606**, the right support member **608**, and the bottom portion of the mirror collection plate **610**. The bottom T-shaped hinge **614** has the same structure as the top T-shaped hinge **612**.

Other embodiments of a T-shaped hinge according to the present invention, as illustrated in **FIGS. 6A-6C**, provide enhanced sensitivity for sensing acceleration loading conditions. In **FIG. 6A**, a T-shaped hinge **612A** includes a vertical support member **644A** having a serpentine shape and a horizontal support member **646A** having a substantially linear shape. In **FIG. 6B**, an alternative embodiment of a T-shaped hinge **612B** includes a vertical support member **644B** coupled to a horizontal support member **646B** at location that is off-center. In **FIG. 6C**, one or both of the T-shaped hinges **612** and **614** are modified to include a T-shaped hinge **612C** having a vertical support member **644C** that intersects a horizontal support member **646C** at an acute angle and is also coupled to the horizontal support member **646C** at location that is off-center.

The top left travel stop **616** extends from and is coupled to the top left portion of the mirror collection plate **610**. The top left travel stop **616** preferably limits the motion of the mirror collection plate **610** in the x-direction. The top left travel stop **616** preferably is positioned in the plane of the mirror collection plate **610**. In a preferred embodiment, the top left travel stop **616** extends from the mirror collection plate **610** in a substantially orthogonal direction. The thickness of the top left travel stop **616** may range, for example, from about 200 to 600 microns. In a preferred embodiment, the thickness of the top left travel stop **616** ranges from about 250 to 350 microns in order to optimally provide shock protection, and a resilient compact structure having a low mass. The length of the top left travel stop **616** may range, for example, from about 500 to 2000 microns. In a preferred embodiment, the length of the top left travel stop **616** ranges from about 900 to 1100 microns. In a particularly preferred embodiment, the top surface of the top left travel stop **616** is planar with the top surface of the mirror collection plate **610**. In a particularly preferred embodiment, the bottom surface of the top left travel stop **616** is planar with the bottom surface of the mirror collection plate **610**.

The top right and bottom left and right travel stops **618**, **620** and **622** are substantially identical to the top left travel stop **616**. These travel stops are positioned in corresponding locations about the mirror collection plate **610**.

The travel stops, **616**, **618**, **620** and **622**, preferably provide overswing and x-axis shock protection for the mirror collection plate **610** during manufacturing and operation. In a preferred embodiment, the travel stops **616**, **618**, **620**, and **622** are formed as integral parts of the mirror collection plate **610**. In a preferred embodiment, the travel stops **616**, **618**, **620**, and **622** provide effective beam lengths greater than about 500 microns and cross sections of about 40,000 microns^2 to 240,000 microns^2 in order to optimally absorb shock loads of about 2000g/0.5 mS half sine wave input.

The opening **624** preferably permits the mirror collection plate **610** to rotate about the axis **630**. The walls **636** of the opening **624** preferably limit movement of the mirror collection plate **610** in the x-direction and the y-directions. The opening **624** preferably includes a top section **638**, a middle section **640**, and a bottom section **642**. The top section **638** of the opening **624** preferably contains the top T-shaped hinge **612** and the top left and right travel stops, **616** and **618**. The middle section **640** of the opening **624** preferably contains the mirror collection plate **610**. The bottom section **642** of the opening **624** preferably contains the bottom T-shaped hinge **614** and the bottom left and right travel stops, **620** and **622**.

The walls of the middle section **640** of the opening **624** may be spaced apart from the opposing edges of the mirror collection plate **610** by a distance ranging, for example, from about 30 to 150 microns. In a preferred embodiment, the walls of the middle section **640** of the opening **624** are spaced apart from the opposing edges of the mirror collection plate **610** by a distance ranging from about 60 to 100 microns in order to optimally minimize movement of the mirror collection plate **610** in the x and y directions. In a preferred embodiment, the gap in the x-direction is different from the gap in the y-direction in order to optimally protect the mirror collection plate **610** from shocks. In a preferred embodiment, the gap between the mirror collection plate **610** and the middle section **640** of the opening **624** provides a spacing in the y-direction ranging from about 15 to 45 microns and a spacing in the x-direction ranging from about 50 to 180 microns in order to optimally limit shock loads on the mirror collection plate **610**.

The conductive layer **626** is preferably coupled to the outer periphery of the top surface of the mirror **210**. The conductive surface **626** preferably provides a conductive electrical path. The conductive layer **626** may be fabricated from any number of conventional commercially available materials such as, for example, gold, aluminum, or silver. In a preferred embodiment, the conductive layer **626** is fabricated from gold. In a preferred embodiment, the conductive layer **626** is bonded to the underlying substrate by an intermediate layer of titanium.

The mirror **210** may be fabricated from any number of conventional commercially available materials such as, for example, silicon, plated metal or plastic. In a preferred embodiment, the mirror **210** is fabricated by micro-machining a silicon wafer using any one, or combination, of the known micro-machining processes.

In a preferred embodiment, the released and free-standing mirror collection plate **610** is connected to the surrounding support frame, **600** by the T-shaped hinges, **612** and **614**. In a preferred embodiment, the travel stop fingers, **616**, **618**, **620** and **622**, provide overswing protection for the mirror collection plate **610**. In a preferred embodiment, a 200-micron deep anisotropic deep reactive ion etching (DRIE) process is used to form very precise, narrow gaps for X-axis shock protection and Y-axis shock protection, where the mirror collection plate **610** is preferably completely confined within the frame, **602**, **604**, **606** and **608**, for X-axis and Y-axis translational or planar motion i.e. in the planes of the mirrored surface. Persons having ordinary skill in the art and the benefit of the present disclosure will recognize that the term DRIE refers to deep reactive ion etching of a substrate. In a preferred implementation, the DRIE process is provided substantially as disclosed in United States Patent Nos. 5,498,312 and 5,501,893, which are incorporated herein by reference. The T-shaped hinges, **612** and **614**, preferably provide the collection plate **610** with optimal translational motion in X-axis and Y-axis directions, in which the mirror collection plate **610** is shock-stopped by the frame, **602**, **604**, **606** and **608**, while also simultaneously maintaining low stress levels within the T-shaped hinges, **612** and **614**, to avoid fracture. In a preferred embodiment, the T-shape hinges, **612** and **614**, are relatively compliant in the X-axis and Y-axis directions, while they are sufficiently rigid for rotational motion about the axis **630** for establishing the resonant frequency of the mirror collection plate **610**.

Thus, in a preferred embodiment of the present invention, the mirror collection plate **610** is supported and suspended by a pair of hinges **612 and 614**. These hinges permit torsional movement or rotation of the mirror collection plate **610** about the common hinge axis **630** and movement of the mirror collection in each of the x, y and z direction. The gap or space **648** between the mirror plate **610** and the frame **601** in the y-direction permits movement of the mirror collection plate **610** in the y-direction while the spacing **611** between the stops **616, 618, 620 and 621** and the frame **601** permit movement in the x-direction. The gap **647** provides a hinge compliance in the y-direction. The movements in the x and y directions are sometimes referred to the planar or translational movements and the hinges as springs. The beams **644 and 628** also permit the mirror collection plate **610** to move in the z-direction. The T-hinges provide the necessary compliance to the mirror collection plate motion in the y-direction, which improves the shock tolerance of the hinge to y-axis shock loads generated by the mirror collection plate **610**. Prior art typically utilizes a straight-beam hinge, i.e. a beam connected to the frame without a T-member, such as the member **646**. Such straight-beam hinges tend to buckle and fracture due to y-axis shock loads. Also, the beams or legs **644 and 648** of the T-hinges **612 and 614** move up in the z-direction due to shock loads. The members **646 and 650** can torsionally rotate, which reduces the stress induced in the **644 and 648** members of the hinges, which stress has been found to be less than the stress induced in the straight-beam hinges. The amount of stress reduction is a function of the "aspect ratio" of the hinges **612 and 614,** which is a ratio of the width/thickness.

As illustrated in **FIGS. 7-9**, the mirror **210** preferably includes portions, **602**, **604**, **606** and **608**, that are full-wafer thickness (e.g., 400 microns), and portions, **610**, that are half-wafer thickness (e.g., 200 microns). The cavity **720** in the center of the mirror collection plate **610** is preferably etched 150-microns down from the bottom surface **634** of the mirror collection plate 610, and the T-shape hinges, **612** and **614**, are preferably about 8-15 microns thick. The half-thickness mirror collection plate **610** reduces the amount of deep reactive ion etching (DRIE) and also improves the position accuracy of the mirror collection plate **610**. The cavity **720**, preferably etched in the center of the mirror collection plate **610**, is preferably primarily used to improve the position accuracy of the mirror collection plate **610** and reduce the mass of the mirror collection plate **610** without substantially altering the resonant frequency.

The backside of the mirror collection plate **610** preferably includes the Z travel-stops, **710** and **715**, that preferably are full-wafer thickness (e.g., 400-microns). Since the mirror collection plate **610**, is preferably 200-microns thick, the thicker travel-stops, **710** and **715**, optimally maintain the 50-micron gap with the travel-stop fingers, **1010** and **1020**, of the bottom cap **215** and, therefore, help provide shock protection in the Z-direction. A mirror collection plate **610** having minimum x-y plane dimensions of about 3-mm x 3-mm is preferred.

In an alternative embodiment, as illustrated in **FIG. 6D**, the left and right support members, **606** and **608**, of the mirror **210** further include cut-outs, **660A** and **660B**, positioned on opposite sides of the mirror collection plate **610**. In this manner, the amount of viscous damping due to the resistance to the passage of air between the mirror collection plate **610** and the left and right support members, **606** and **608**, is reduced. In this manner, the frequency response characteristics of the mirror **210** are enhanced.

As illustrated in **FIGS. 10-12**, the bottom cap **215** includes a bottom cap frame **1000** to provide support for the bottom cap. The frame **1000** includes support members and top and bottom travel stop members as described above for the top cap and shown in **FIG. 3**. The bottom cap further comprises an upper left beam **1035**, an upper right beam **1040**, a lower left beam **1045**, a lower right beam **1050**, a top conductive surface **1055**, a bottom conductive surface **1060**, and an opening **1065**.

The thickness of the bottom cap frame **1000** may range, for example, from about 400 to 600 microns with preferred thickness ranging from about 400 to 450 microns to provide a compact structure having a low mass.

The top travel stop member **1010** preferably limits the motion of the reflective portion of the mirror **210** in the z-direction. The top travel stop member **1010** preferably extends in a substantially orthogonal direction from the top support member **1005**. In a preferred embodiment, the top travel stop member **1010** is positioned within the plane of the top support member **1005**. The thickness of the top travel stop member **1010** may range, for example, from about 350 to 550 microns. In a preferred embodiment, the thickness of the top travel stop **1010** ranges from about 350 to 380 microns in order to provide a compact structure having a low mass. In a particularly preferred embodiment, the top surface **1010A** of the top travel stop member **1010** is recessed below the level of the top surface **1005A** of the top support member **1005**. In this manner, the top surface **1010A** of the top travel stop **1010** is preferably positioned below the level of the mirror collection plate **610** of the mirror **210**. The length of the top travel stop member **1010** may range, for example, from about 1200 to 2800 microns. In a preferred embodiment, the length of the top travel stop member **1010** ranges from about 2000 to 2500 microns. In a particularly preferred embodiment, the length of the top travel stop member **1010** is selected to overlap with the mirror collection plate **610** of the mirror by about 300 microns.

The bottom travel stop member **1020** preferably extends in a substantially orthogonal direction from the bottom support member **1015**. The bottom travel stop member **1020** is otherwise substantially identical to the above-described top travel stop member **1010**.

The upper left beam **1035** preferably provides support and limits the motion of the mirror collection plate **610** of the mirror **210** in the z-direction during the manufacturing process. In this manner, defective mirrors **210** are protected from shock, catastrophic failure and from falling into the process equipment during the manufacturing process. The upper left beam **1035** preferably extends is a substantially orthogonal direction from the left support member **1025**. In a preferred embodiment, the upper left beam **1035** is positioned within the plane of the left support member **1025**. The thickness of the upper left beam **1035** may range, for example, from about 150 to 250 microns. In a preferred embodiment, the thickness of the upper left beam **1035** ranges from about 200 to 220 microns in order to optimally provide a compact structure having a low mass. In a particularly preferred embodiment, the top surface of the upper left beam **1035** is recessed below the level of the top surface **1025A** of the left support member **1025**. In this manner, the top surface of the upper left beam **1035** is preferably positioned below the level of the top left travel stop member **616** of the mirror **210**. The length of the upper left beam **1035** may range, for example, from about 1500 to 2200 microns. In a preferred embodiment, the length of the upper left beam **1035** is about 1800 microns.

The upper right and lower left and right beams **1040**, **1045** and **1050** are substantially identical to the upper left beam **1035**. These beams are positioned within the plane of corresponding support members.

The top conductive surface **1055** is preferably coupled to the outer periphery of the top surface of the bottom cap **215**. The top conductive surface **1055** preferably provides a conductive electrical path. The top conductive surface **1055** further preferably provides a bonding ring for subsequent compression bonding of the bottom cap **215** to the mirror **210**. The top conductive surface **1055** may be fabricated from any number of conventional commercially available materials such as, for example, gold, aluminum, or silver. In a preferred embodiment, the top conductive surface **1055** is fabricated from gold. In a preferred embodiment, the top conductive surface **1055** is bonded to the bottom cap **215** using an intermediate layer of titanium. The bottom conductive surface **1060** is preferably coupled to the outer periphery of the bottom surface of the bottom cap **215** and is otherwise substantially identical to the top conductive surface **1055**.

In a preferred embodiment, the conductive surfaces **1055** and **1060** conformally coat all of the exposed surfaces of the bottom cap **215**.

The opening **1065** preferably permits the drive pad electrodes, **1310** and **1315**, of the base member **220** to electrostatically drive and capacitatively sense the position of the mirror collection plate **610** of the mirror **210**. The opening **1065** preferably comprises a substantially rectangular opening of greater size than the mirror collection plate **610** of the mirror **210**.

As illustrated in **FIGS. 13-15**, in a preferred embodiment, the base member **220** includes a bottom plate **1305**, a left drive pad electrode **1310**, a right drive pad electrode **1315**, a frame **1300**, a conductive layer **1340**, and conductive paths **1345**, **1350** and **1355**.

The bottom plate **1305**, and frame **1300** together provide structural support for the base member **220**. The base member **220** preferably supports the bottom cap **215**, mirror **210** and the top cap **205**.

The bottom plate **1305** preferably comprises a solid member fabricated from any number of conventional commercially available materials such as, for example, ceramic, silicon or glass. In a preferred embodiment, the thickness of the bottom plate **1305** ranges from about 200 to 400 microns.

The left drive pad electrode **1310** is coupled to the bottom plate **1305**. The left drive pad electrode **1310** preferably permits the mirror collection plate **610** of the mirror **210** to be driven using electrostatic force and/or the position of the mirror collection plate **610** of the mirror **210** to be capacitively sensed. In this manner, the mirror collection plate **610** of the mirror **210** oscillates about the axis **630**. In a preferred embodiment, the left drive pad electrode **1310** includes a conductive layer **1310A** that is coupled to the conductive path **1350**. In this manner, an electrical connection can be provided to the conductive layer **1310A**. The conductive layer **1310A** may be fabricated from any number of conventional commercially available materials such as, for example, metal, polysilicon or conductive epoxy. In a preferred embodiment, the conductive layer **1310A** is fabricated from metal.

The left drive pad electrode **1310** may have a top surface area ranging, for example, from about $3X10^6$ to $10X10^6$ microns.^{2} In a preferred embodiment, the top surface area of the left drive pad electrode **1310** is about $4.5X10^6$ microns^2 in order to optimally drive the mirror collection plate **610** of the mirror **210**. The left drive pad electrode **1310** preferably extends from the bottom plate **1305** in a substantially orthogonal direction. The left drive pad electrode **1310** may extend from the bottom plate **1305** for a distance ranging, for example, from about 50 to 200 microns. In a preferred embodiment, the left drive pad electrode **1310** extends from the bottom plate **1305** for a distance ranging from about 50 to 100 microns. In a particularly preferred embodiment, gap between the top of the left drive pad electrode **1310** and the bottom of the mirror collection plate **610** of the mirror **210** ranges from about 300 to 400 microns.

The right drive pad electrode **1315** is substantially identical to the left pad electrode **1310**. In a preferred embodiment, the left and right drive pad electrodes, **1310** and **1315**, are positioned substantially equidistant from the axis **630**.

The top support member **1320** is coupled to the bottom plate **1305**, the left support member **1330**, the right support member **1335** and the conductive layer **1340**. The top support member **1320** may have a length, width and height ranging, for example, from about 4000 to 6000 microns, 400 to 600 microns, and 400 to 600 microns. In a preferred embodiment, the top support member **1320** length, width and height are about 4900 microns, 375 microns, and 400 microns.

The left support member **1330** is coupled to the bottom plate **1305**, the top support member **1320**, the bottom support member **1325** and the conductive layer **1340**. The left support member **1330** may have a length, width and height ranging, for example, from about 6000 to 9000 microns, 400 to 600 microns, and 400 to 600 microns. In a preferred embodiment, the left support member **1330** length, width and height are about 6800 microns, 375 microns, and 400 microns.

The bottom support member **1325** is substantially identical to the top support member **1320** and the right support member **1335** is substantially identical to the left support member **1330**.

In a preferred embodiment, the bottom plate **1305**, the top support member **1320**, the bottom support member **1325**, the left support member **1330**, and the right support member **1335** are integrally formed.

The conductive layer **1340** preferably extends around the periphery of the top surface of the base member **220**. The conductive layer **1340** preferably provides a conductive electric path for use in actuating the mirror collection plate **610** of the mirror **210**. The conductive layer **220** may be fabricated from any number of conventional commercially available materials such as, for example, metal, polysilicon or conductive epoxy. In a preferred embodiment, the conductive layer **1340** is fabricated from gold. The conductive layer **1340** may be coupled to the conductive path **1345** using conventional methods.

The base member **220** may be fabricated from any number of conventional commercially available materials such as, for example, ceramic, silicon or glass using any number of conventional fabrication processes.

The base **220** preferably provides electrode access to the mirror collection plate **610** for electrostatic actuation and capacitive position sensing using drive pad electrodes, **1310** and **1315**. The design and operation of the electrostatic actuation and capacitative position sensing are well known in the art.

The metal ring **1340** around the perimeter of the base member **220**, in combination with conductive-epoxy bonding of the base member **220** to the bottom cap **215**, preferably provides electrical contact between the base member **220** and the bottom cap **215**. In a preferred embodiment, the wafer bonding process preferably allows the bottom cap **215** to be in direct electrical contact with the mirror collection plate **610**. Consequently, the mirror collection plate **610** preferably can be electrically accessed, controlled, and monitored using the base member **220**. The electrode drive pad and mirror contact metallization, **1310A**, **1315A**, and **1340**, on the base member **220** are preferably connected to electrical contact pads on the backside of the base member **220**, utilizing conventional thick-film through-hole via technology, which effectively makes the mirror assembly **110** a surface-mount component.

Referring now to **FIG. 16**, a sub-assembly including the top cap **205** and the mirror **210** is illustrated. As illustrated in **FIG. 16**, the travel stops, **310** and **320**, of the top cap **205** protect the mirror collection plate **610** from z-axis shock while also minimizing the shadowing/overlapping of the reflective surface **628** of the mirror collection plate **610**. Furthermore, the side rim cut-outs, **330** and **340**, of the top cap **205** maximize the optical path to the reflective surface **628** of the mirror collection plate **610**.

Referring now to **FIG. 17**, a sub-assembly including the bottom cap **215** and the base member **220** is illustrated. As illustrated in **FIG. 17**, the travel stop fingers, **1010** and **1020**, protect the mirror collection plate **610** from z-axis shock while also maximizing the drive area of the drive pad electrodes, **1310** and **1315**.

Referring now to **FIG. 18**, additional shock protection features of the mirror assembly **110** will be described. As illustrated in **FIG. 18**, preferably all of the interior walls of the top cap **205** and bottom cap **215** include tapered walls. In a preferred embodiment, the mirror collection plate **610** may be rotated out of plane by about 14° in both directions. In a preferred embodiment, the clearance between the mirror collection plate **610** and the interior walls of the top cap **205**, bottom cap **215**, and the support structure of the mirror **210** is about 60 ± 10 microns for rotation ranging from -14° to +14° . As also illustrated in **FIG. 18**, the travel stops, **320** and **1020**, protect the mirror collection plate **610** from z-axis shocks. In a preferred embodiment, the clearance between the mirror collection plate **610** and the travel stops, **320** and **1020**, is about 20-60 microns.

The travel stop fingers' **310** and **320** dimensions are chosen to make them sufficiently compliant in the z-direction to dissipate the Z-axis shock impact energy of the mirror hitting (urging) the travel-stop fingers. This compliancy provides a shock energy dissipation factor (not comprehended in the prior art) makes the resulting mirror assembly more robust to shock loads. The travel-stop fingers **616**, **618**, **620**, and **626** are similarly made to have sufficient compliance in the x-direction to dissipate X-axis shock impact of the mirror plate hitting frame **600**.

As illustrated in **FIG. 18**, the travel-stop fingers, **310** and **320**, of the top cap **205** protect the mirror **210** from Z-axis shock while minimizing the shadowing/overlap of the mirror collection plate **610**, thus providing the external laser optical access to the micromirror. The travel-stop fingers, **310** and **320**, are preferably recessed about 20-60 microns from the surfaces of the top cap **205**, which preferably sets the gap between the mirror collection plate **610** and the travel-stop fingers, **310** and **320**, to be about 20-60 microns in the Z-direction. The tapered walls around the inside perimeter of the top cap **205** are preferably for capturing the mirror collection plate **610** during an input shock while the mirror collection plate **610** is rotated out-of-plane. The left and right rim cut-outs, **330** and **340**, in the top cap **205** preferably provide clipping reduction. The travel-stop fingers, **1010** and **1020**, of the bottom cap **215** preferably protect the mirror collection plate 610 from Z-axis shock while maximizing the area of the drive pad electrodes, **1310** and **1315**. The travel-stop finger arrangement of the top and bottom caps, **205** and **215**, preferably constrain the mirror collection plate **610** from Z-axis translational motion, while promoting torsional rotation of the mirror collection plate **610** about the axis **630**. The bottom cap **215** also preferably includes the beams, **1025**, **1040**, **1045**, and **1050**, for facilitating the handling of defective mirrors during the fabrication process.

As illustrated in **FIGS. 6, 6A, 6B and 6C**, the design of the T-shaped hinges **612** and **614**, decouples the rotational spring constants from the translational spring constants. In this manner, the mirror collection plate 610 is optimally protected from vibration and shock loads.

Referring now to **FIG. 19**, additional features of the mirror assembly **110** for optimizing the reflection of incident laser beams will be described. In an exemplary application of the sensor assembly **110**, an incident laser beam A is directed to the mirror collection plate **610** at an angle of 45° and results in the reflected beam B. For a scanning range of ± 10°, the reflected laser beams are bound by the rays B' and B . In order to avoid laser beam clipping, the tapered walls and rim cut-outs, **330** and **340**, of the top cap **205** minimize clipping of the incident and reflected laser beams. These features are particularly advantageous in the situation where the incident laser beam is displaced resulting in the incident laser beam A' or the reflected laser beam B .

As illustrated in **FIGS. 18 and 19**, the tapered walls of the bottom cap **215** provide optimal shock protection to the mirror collection plate 610, and the tapered walls of the top cap **205** minimize clipping of the incident and reflected laser beams. The rim cut-outs, **330** and **340**, of the top cap **205** further minimize shadowing and clipping of the incident and reflected laser beams.

A mirror assembly has been described that includes a mirror, a top cap and a bottom cap. The mirror includes a mirror support structure, a pair of T-shaped hinges coupled to the mirror support structure and a mirrored plate coupled to the T-shaped hinges. The mirrored plate includes one or more travel stops for limiting movement of the mirrored plate. The top cap is coupled to one side of the mirror. The top cap includes a top cap support structure including an opening for permitting light to reflect off of the mirrored plate and one or more travel stops coupled to the top cap support structure for limiting movement of the mirrored plate. The bottom cap is coupled to another side of the mirror. The bottom cap includes a bottom cap support structure including an opening and one or more travel stops coupled to the bottom cap support structure for limiting movement of the mirrored plate. In a preferred embodiment, the mirror support structure includes a top support member, a bottom support member, a right side support member and a left side support member. In a preferred embodiment, the mirror support structure includes an opening. In a preferred embodiment, the support structure opening includes a pair of oppositely positioned cut-outs. In a preferred embodiment, the support structure opening is complementary shaped with respect to the mirrored plate. In a preferred embodiment, the spacing between the edges of the support structure opening and the mirrored plate ranges from about 15 to 180 microns. In a preferred embodiment, the pair of T-shaped hinges include a top T-shaped hinge and a bottom T-shaped hinge positioned in opposing relation to the top T-shaped hinge. In a preferred embodiment, the mirrored plate includes a plate member including a first side and a second side, a reflective surface coupled to the first side of the plate member, a cavity formed in the second side of the plate member and a pair of travel stops coupled to the second side of the plate member. In a preferred embodiment, the plate member cavity includes a V-shaped cross section. In a preferred embodiment, the mirrored plate includes a plate member and one or more travel stops extending from the plate member. In a preferred embodiment, the travel stops are positioned in the plane of the plate member. In a preferred embodiment, the plate member travel stops that are positioned in the plane of the plate member have a length and thickness ranging from about 500 to 2000 microns and 200 to 600 microns. In a preferred embodiment, the plate member extend from the plane of the plate member. In a preferred embodiment, the plate member travel stops that extend from the plane of the plate member have a length ranging from about 200 to 250 microns. In a preferred embodiment, the mirrored plate includes a plate member and a plurality of travel stops extending from the plate member. In a preferred embodiment, at least one of the plate member travel stops in positioned in the plane of the plate member and at least one of the travel stops extends from the plane of the plate member. In a preferred embodiment, each T-shaped hinge includes a first member and a second member coupled to the first member. In a preferred embodiment, the first and second members are substantially orthogonal. In a preferred embodiment, the length, width and thickness of the first hinge member ranges from about 500 to 4500 microns, 10 to 100 microns and 10 to 100 microns. In a preferred embodiment, the length, width and thickness of the second hinge member ranges from about 400 to 1800 microns, 2 to 35 micron and 2 to 35 microns. In a preferred embodiment, each T-shaped hinge provides a torsional spring. In a preferred embodiment, the spring constant ranges from about $2x10^{-9}$ to $10x10^{-7}$ lbf-ft/radian. In a preferred embodiment, the top cap travel stops are positioned in the plane of the top cap support structure. In a preferred embodiment, the thickness of the top cap travel stops are less than the thickness of the top cap support structure. In a preferred embodiment, the opening in the top cap support structure includes a pair of oppositely positioned cut-outs. In a preferred embodiment, the cut-outs include tapered walls. In a preferred embodiment, the taper angle of the tapered walls ranges from about 55 to 60 degrees. In a preferred embodiment, the top cap opening includes tapered walls. In a preferred embodiment, the taper angle of the tapered walls ranges from about 55 to 60 degrees. In a preferred embodiment, the bottom cap travel stops are positioned in the plane of the bottom cap support structure. In a preferred embodiment, the thickness of the bottom cap travel stops are less than the thickness of the bottom cap support structure. In a preferred embodiment, the bottom cap opening includes tapered walls. In a preferred embodiment, the taper angle of the tapered walls ranges from about 55 to 60 degrees. In a preferred embodiment, the mirror assembly further includes a base member coupled to the bottom cap. In a preferred embodiment, the base member includes one or more drive pads for actuating the mirrored plate. In a preferred embodiment, the base member includes one or more sensing members for sensing the position of the mirrored plate. In a preferred embodiment, the bottom cap further includes one or more support members for supporting the mirrored plate during the manufacturing process. In a preferred embodiment, the length and thickness of the top cap travel stops range from about 800 to 2800 microns and 340 to 580 microns. In a preferred embodiment, the length and thickness of the bottom cap travel stops range from about 800 to 2800 microns and 340 to 580 microns. In a preferred embodiment, one or more of the T-shaped hinges include a first member and a second member coupled to the first member, wherein the second member is perpendicular to the first member. In a preferred embodiment, one or more of the T-shaped hinges include a first member and a second member coupled to the first member, wherein the second member is serpentine. In a preferred embodiment, one or more of the T-shaped hinges include a first member and a second member coupled to the first member, wherein the second member is offset from the center of the first member. In a preferred embodiment, one or more of the T-shaped hinges include a first member and a second member coupled to the first member, wherein the second member intersects the first member at an acute angle. In a preferred embodiment, each T-shaped hinge includes a translational spring constant and a rotational spring constant that are decoupled from one another.

A mirror assembly has also been described that includes a support structure, a pair of T-shaped hinges coupled to the support structure and a mirrored plate coupled to the T-shaped hinges. The mirrored plate includes one or more travel stops for limiting movement of the mirrored plate. In a preferred embodiment, each T-shaped hinge includes a rotational spring constant and a translational spring constant that are decoupled. In a preferred embodiment, the support structure includes a top support member, a bottom support member, a right side support member and a left side support member. In a preferred embodiment, the support structure includes an opening. In a preferred embodiment, the opening includes a pair of oppositely positioned cut-outs. In a preferred embodiment, the opening is complementary shaped with respect to the mirrored plate. In a preferred embodiment, the spacing between the edges of the opening and the mirrored plate ranges from about 15 to 180 microns. In a preferred embodiment, the pair of T-shaped hinges include a top T-shaped hinge and a bottom T-shaped hinge positioned in opposing relation to the top T-shaped hinge. In a preferred embodiment, the mirrored plate includes a plate member including a first side and a second side, a reflective surface coupled to the first side of the plate member, a cavity formed in the second side of the plate member and a pair of travel stops coupled to the second side of the plate member. In a preferred embodiment, the cavity includes a V-shaped cross section. In a preferred embodiment, the mirrored plate includes a plate member and one or more travel stops extending from the plate member. In a preferred embodiment, the travel stops are positioned in the plane of the plate member. In a preferred embodiment, the travel stops that are positioned in the plane of the plate member have a length and thickness that range from about 500 to 2000 microns and 200 to 600 microns. In a preferred embodiment, the travel stops extend from the plane of the plate member. In a preferred embodiment, the travel stops that extend from the plane of the plate member have a length that extends from about 200 to 250 microns. In a preferred embodiment, the mirrored plate includes a plate member and a plurality of travel stops extending from the plate member. In a preferred embodiment, at least one of the travel stops in positioned in the plane of the plate member and at least one of the travel stops extends from the plane of the plate member. In a preferred embodiment, each T-shaped hinge includes a first member and a second member coupled to the first member. In a preferred embodiment, the first and second members are substantially orthogonal. In a preferred embodiment, the length, width and thickness of the first member ranges from about 500 to 4500 microns, 10 to 100 microns and 10 to 100 microns. In a preferred embodiment, the length, width and thickness of the second member ranges from about 400 to 1800 microns, 20 to 35 microns and 2 to 35 microns. In a preferred embodiment, each T-shaped hinge provides a torsional spring. In a preferred embodiment, the spring constant ranges from about $2x10^{-9}$ to $10x10^{-7}$ lbf-ft/radian. In a preferred embodiment, one or more of the T-shaped hinges include a first member and a second member coupled to the first member, wherein the second member is perpendicular to the first member. In a preferred embodiment, one or more of the T-shaped hinges include a first member and a second member coupled to the first member, wherein the second member is serpentine. In a preferred embodiment, one or more of the T-shaped hinges include a first member and a second member coupled to the first member, wherein the second member is offset from the center of the first member. In a preferred embodiment, one or more of the T-shaped hinges include a first member and a second member coupled to the first member, wherein the second member intersects the first member at an acute angle.

An apparatus has also been described that includes one or more T-shaped springs and a mass coupled to the T-shaped springs. In a preferred embodiment, the mass includes a reflective surface. In a preferred embodiment, the mass includes one or more travel stops for limiting movement of the mass. In a preferred embodiment, the apparatus further includes a top cap coupled to the top of the mass, wherein the top cap includes one or more travel stops for limiting movement of the mass. In a preferred embodiment, the apparatus further includes a bottom cap coupled to bottom of the mass, wherein the bottom cap includes one or more travel stops for limiting movement of the mass. In a preferred embodiment, the apparatus further includes a top cap coupled to the top of the mass and a bottom cap coupled to the bottom of the mass, wherein the top and bottom caps each include one or more travel stops for limiting movement of the mass. In a preferred embodiment, each T-shaped hinge includes a rotational spring constant and a translational spring constant that are decoupled. In a preferred embodiment, the apparatus comprises an accelerometer. In a preferred embodiment, the apparatus comprises a gyroscope.

An apparatus also has been described that includes a housing, a mass, and one or more springs for coupling the mass to the housing. Each spring includes a rotational spring constant and a translational spring constant. The rotational spring constant is decoupled from the translational spring constant. In a preferred embodiment, the springs are fabricated by a process including micromachining a substrate. In a preferred embodiment, the housing, mass and springs are fabricated by a process including micromachining a substrate. In a preferred embodiment, each spring comprises a plurality of springs. In a preferred embodiment, each spring is T-shaped. In a preferred embodiment, the apparatus further includes a top cap coupled to the top of the housing including a top cap cutout and a bottom cap coupled to the bottom of the housing including a bottom cap cutout. The top and bottom cap cutouts limit movement of the mass when the mass is rotated away from its rest position. In a preferred embodiment, each cutout includes tapered side walls. In a preferred embodiment, the tapered side walls are rotated from the vertical direction at an angle ranging from about 15 to 45 degrees.

A method of resiliently supporting a mass in a housing also has been described that includes coupling the mass to the housing using one or more springs having translational spring constants and rotational spring constants and decoupling the translational spring constants from the rotational spring constants. In a preferred embodiment, the springs are fabricated by a process including micromachining a substrate. In a preferred embodiment, the housing, mass and springs are fabricated by a process including micromachining a substrate. In a preferred embodiment, each spring comprises a plurality of springs. In a preferred embodiment, each spring is

T-shaped. In a preferred embodiment, method further includes limiting movement of the mass when it is rotated from a rest position. In a preferred embodiment, limiting movement of the mass when it is rotated from a rest position includes limiting translation of the mass when it is rotated from the rest position.

A method of resiliently supporting a mass in a housing also has been described that includes limiting translational movement of the mass in the X, Y and Z directions and limiting rotational movement of the mass. In a preferred embodiment, the housing and mass are fabricated by a process including micromachining a substrate. In a preferred embodiment, the method further includes limiting movement of the mass when it is rotated from a rest position. In a preferred embodiment, limiting movement of the mass when it is rotated from a rest position includes limiting translation of the mass when it is rotated from the rest position.

An apparatus also has been described that includes a housing and a mass resiliently coupled to the housing, the mass including one or more travel stops for limiting rotational and translational movement of the mass. In a preferred embodiment, the housing includes an opening for receiving the mass that limits the translational movement of the mass. In a preferred embodiment, the apparatus further includes a top cap coupled to the top of the housing and a bottom cap coupled to the bottom of the housing. The top and bottom caps limit movement of the mass when it is rotated out of its rest position within the housing. In a preferred embodiment, the top and bottom caps includes cutouts. In a preferred embodiment, each cutout includes tapered side walls. In a preferred embodiment, the tapered side walls are rotated from the vertical direction at an angle ranging from about 15 to 45 degrees.

An apparatus also has been described that includes a housing including an opening, the opening including one or more cutouts and a reflective surface resiliently coupled to the housing. In a preferred embodiment, each cutout includes tapered side walls. In a preferred embodiment, the tapered side walls are rotated from the vertical direction at an angle ranging from about 15 to 45 degrees. In a preferred embodiment, the housing and reflective surface are fabricated by a process including micromachining a substrate.

A method of reflecting rays of light also has been described that includes providing a reflective surface and providing an optical pathway for accessing the reflective surface including one or more cutouts for minimizing clipping of the incident and reflected light rays. In a preferred embodiment, the optical pathway includes sidewalls that are rotated from the vertical direction at an angle ranging from about 15 to 45 degrees. In a preferred embodiment, the optical pathway and reflective surface are fabricated by a process including micromachining a substrate.

Although illustrative embodiments of the invention have been shown and described, a wide range of modification, changes and substitution is contemplated in the foregoing disclosure. In some instances, some features of the present invention may be employed without a corresponding use of the other features. Accordingly, it is appropriate that the appended claims be construed broadly and in a manner consistent with the scope of the invention.

WHAT IS CLAIMED IS:

1. A mirror assembly, comprising:
a mirror including:
a mirror support structure;
a pair of T-shaped hinges coupled to the mirror support structure; and
a mirrored plate coupled to the T-shaped hinges, the mirrored plate including:
one or more travel stops for limiting movement of the mirrored plate;
a top cap coupled to one side of the mirror, the top cap including:
a top cap support structure including:
an opening for permitting light to reflect off of the mirrored plate; and
one or more travel stops coupled to the top cap support structure for limiting movement of the mirrored plate; and
a bottom cap coupled to another side of the mirror, the bottom cap including:
a bottom cap support structure including an opening; and
one or more travel stops coupled to the bottom cap support structure for limiting movement of the mirrored plate.

2. The mirror assembly of claim 1, wherein one or more of the T-shaped hinges include:
a first member; and
a second member coupled to the first member;
wherein the second member is perpendicular to the first member.

3. The mirror assembly of claim 1 wherein one or more of the T-shaped hinges include:
a first member; and
a second member coupled to the first member; wherein the second member is serpentine.

4. The mirror assembly of claim 1 wherein one or more of the T-shaped hinges include:

a first member; and

a second member coupled to the first member;

wherein the second member is offset from the center of the first member.

5. The mirror assembly of claim 1, wherein one or more of the T-shaped hinges include:

a first member; and

a second member coupled to the first member;

wherein the second member intersects the first member at an acute angle.

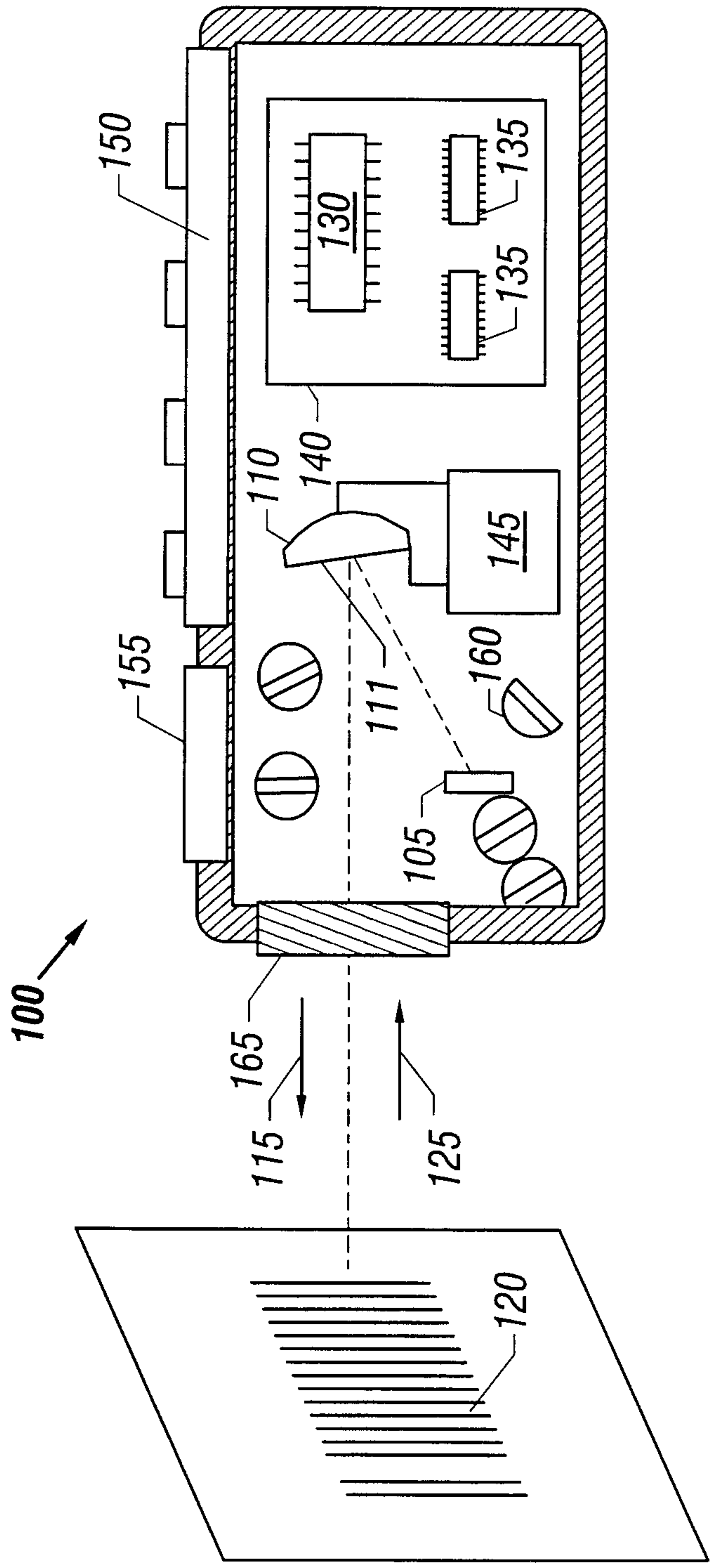


FIG. 1

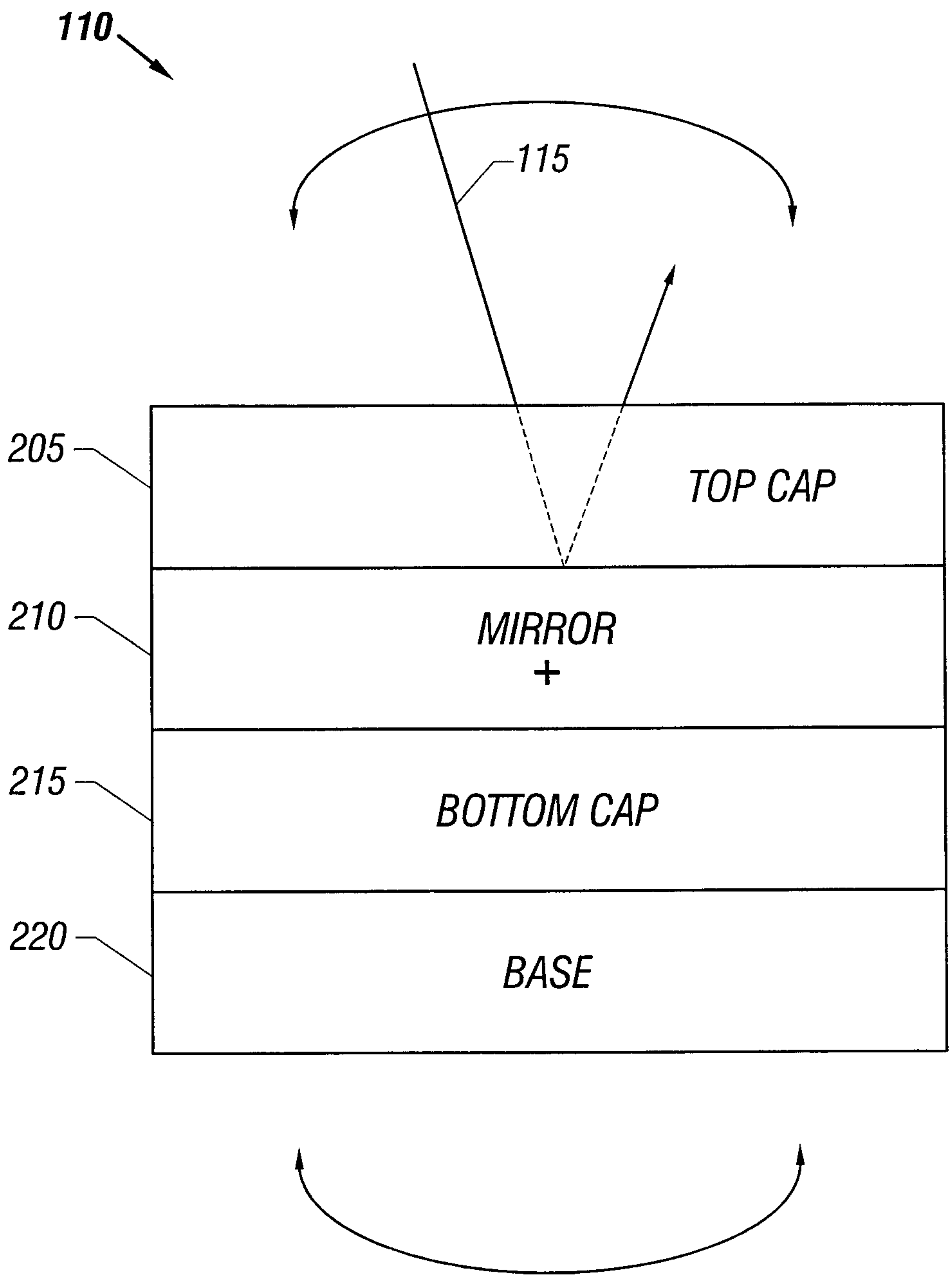


FIG. 2

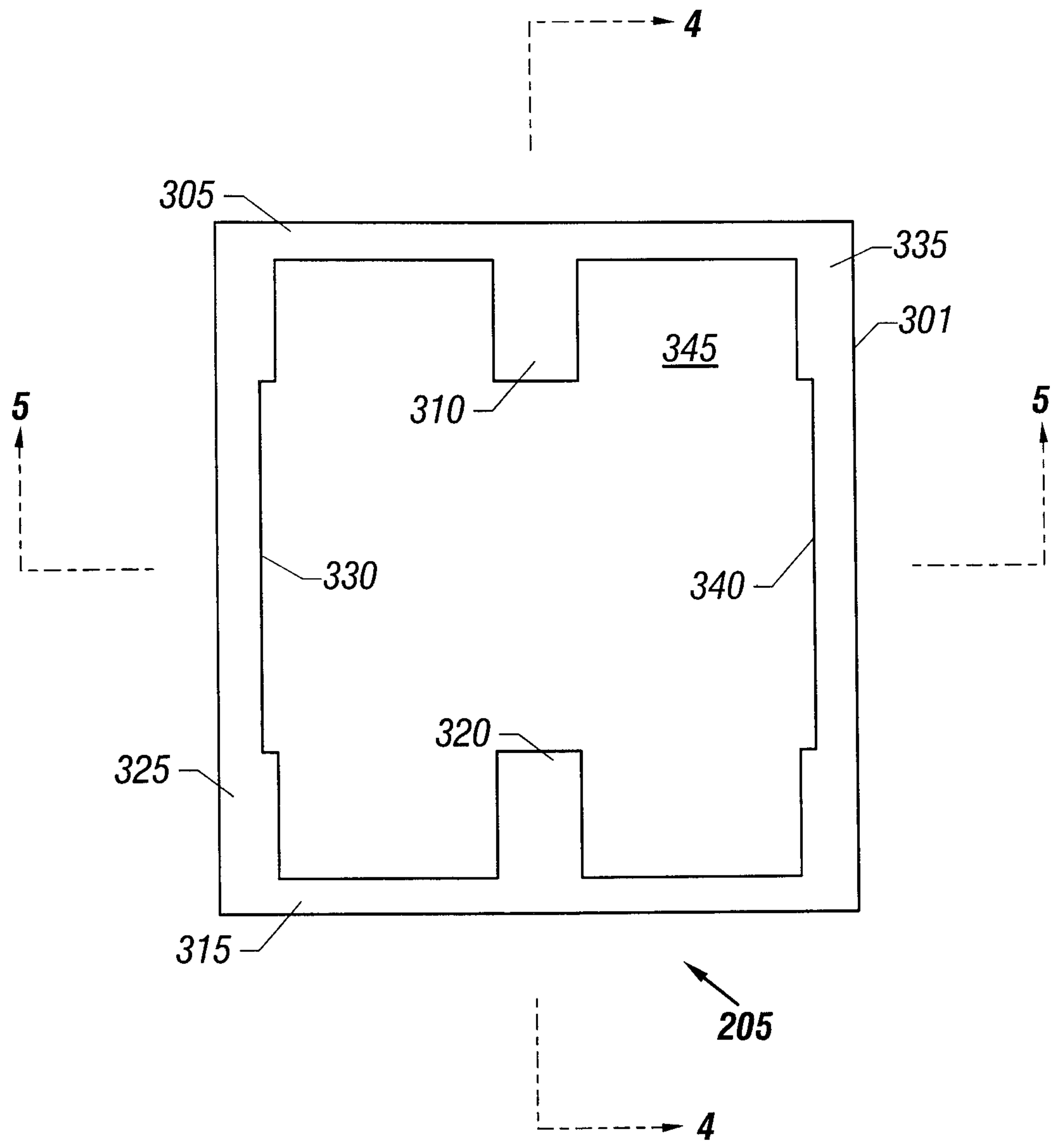


FIG. 3

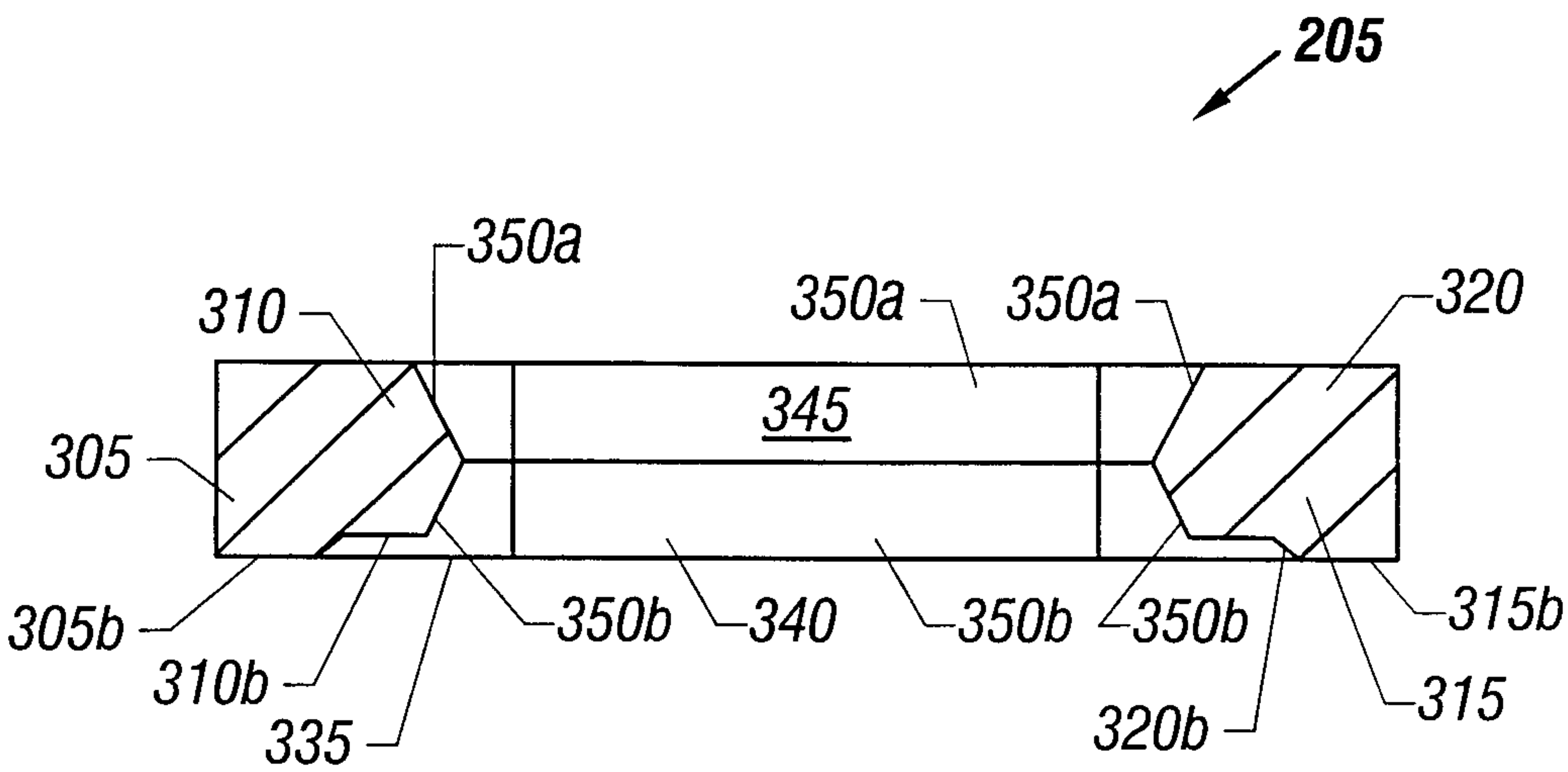

205
350a
310
350a
350a
320
345
305
305b
310b
335
350b
340
350b
350b
315b
315
320b

FIG. 4

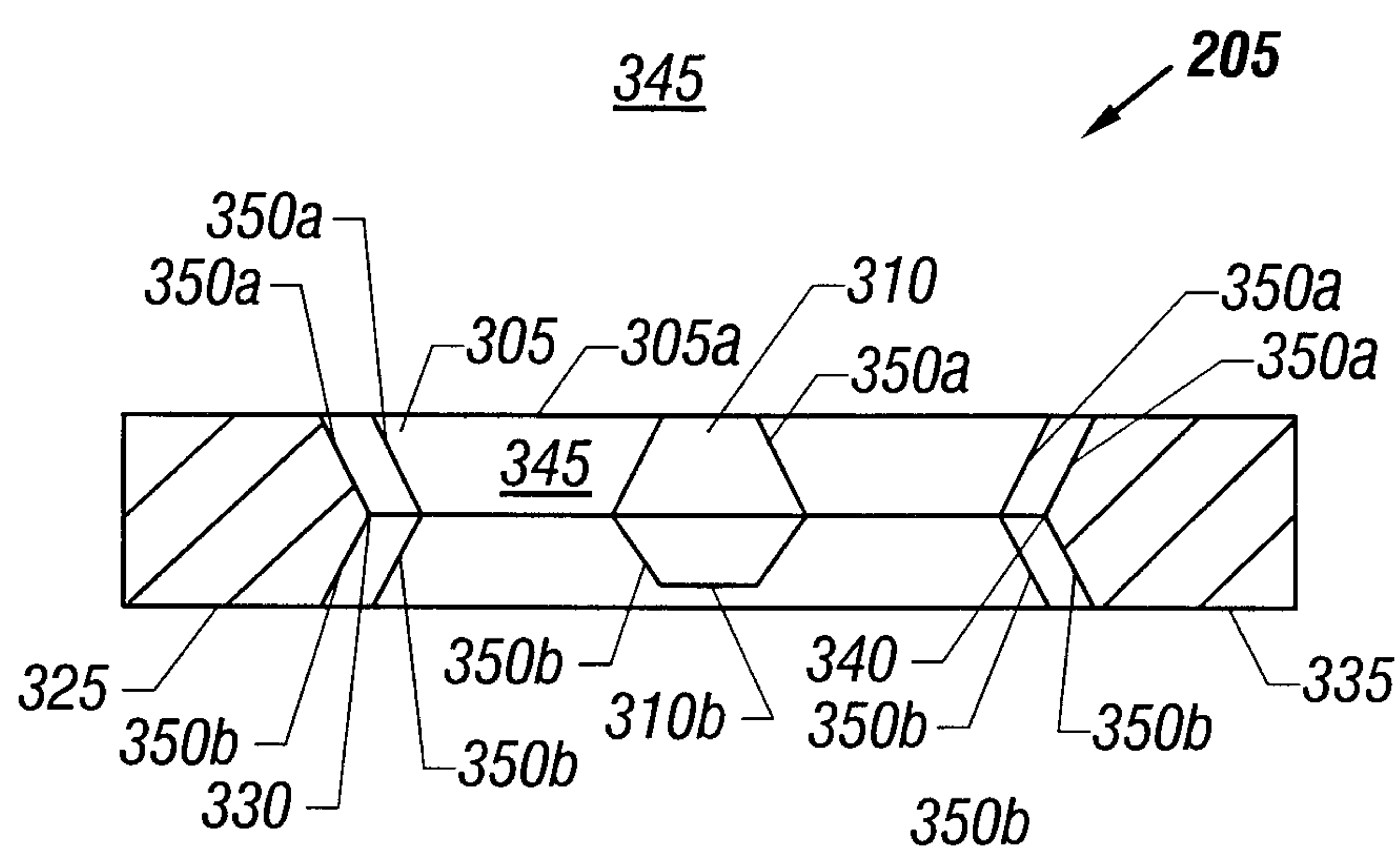

345
205
350a
350a
305
305a
310
350a
350a
350a
345
325
350b
330
350b
350b
310b
340
350b
350b
335
350b

FIG. 5

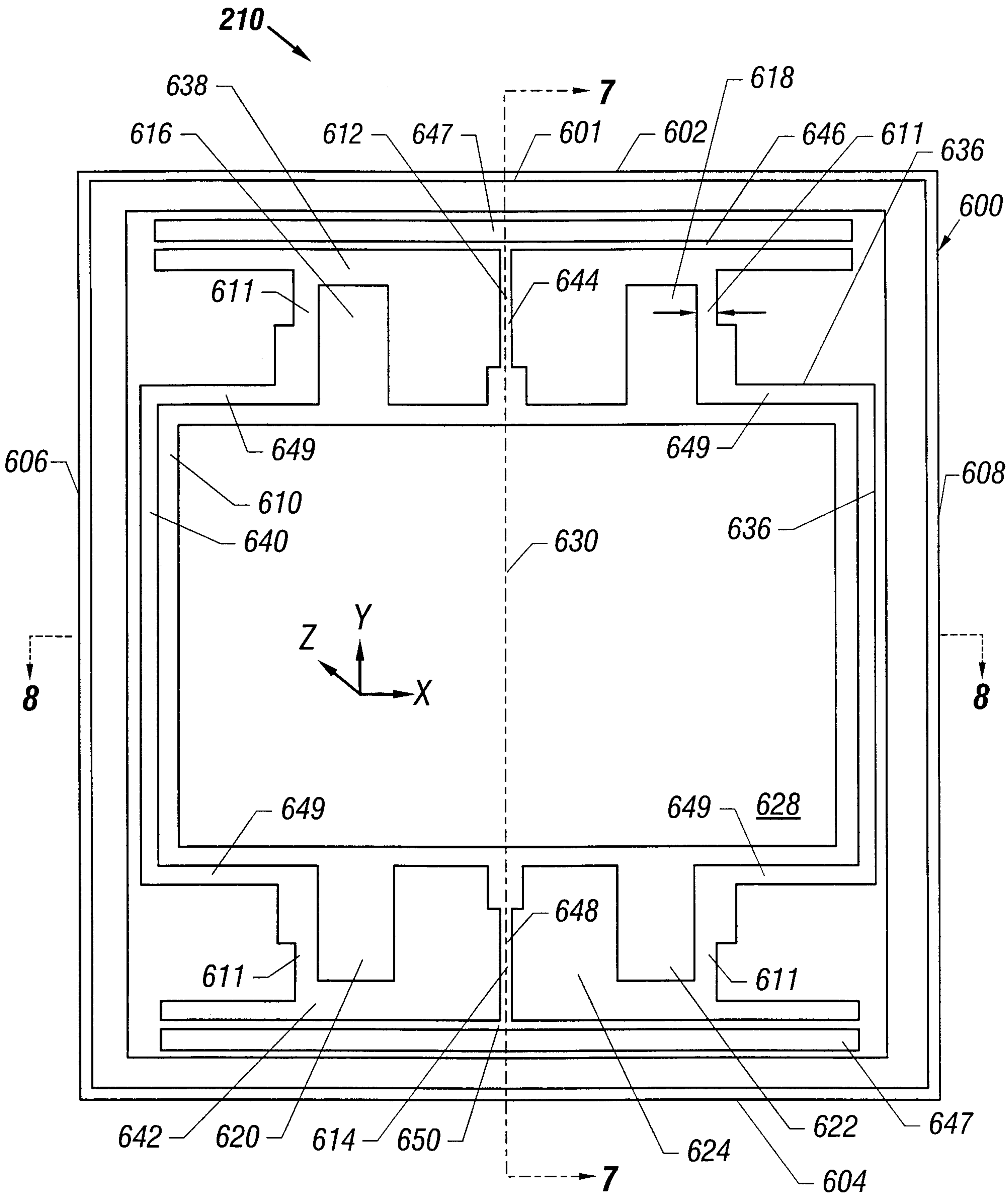

210
638
7
618
616
612
647
601
602
646
611
636
600
611
644
649
649
606
610
608
640
630
636
Z
Y
X
8
8
649
649
628
648
611
611
642
620
614
650
622
647
624
7
604

FIG. 6

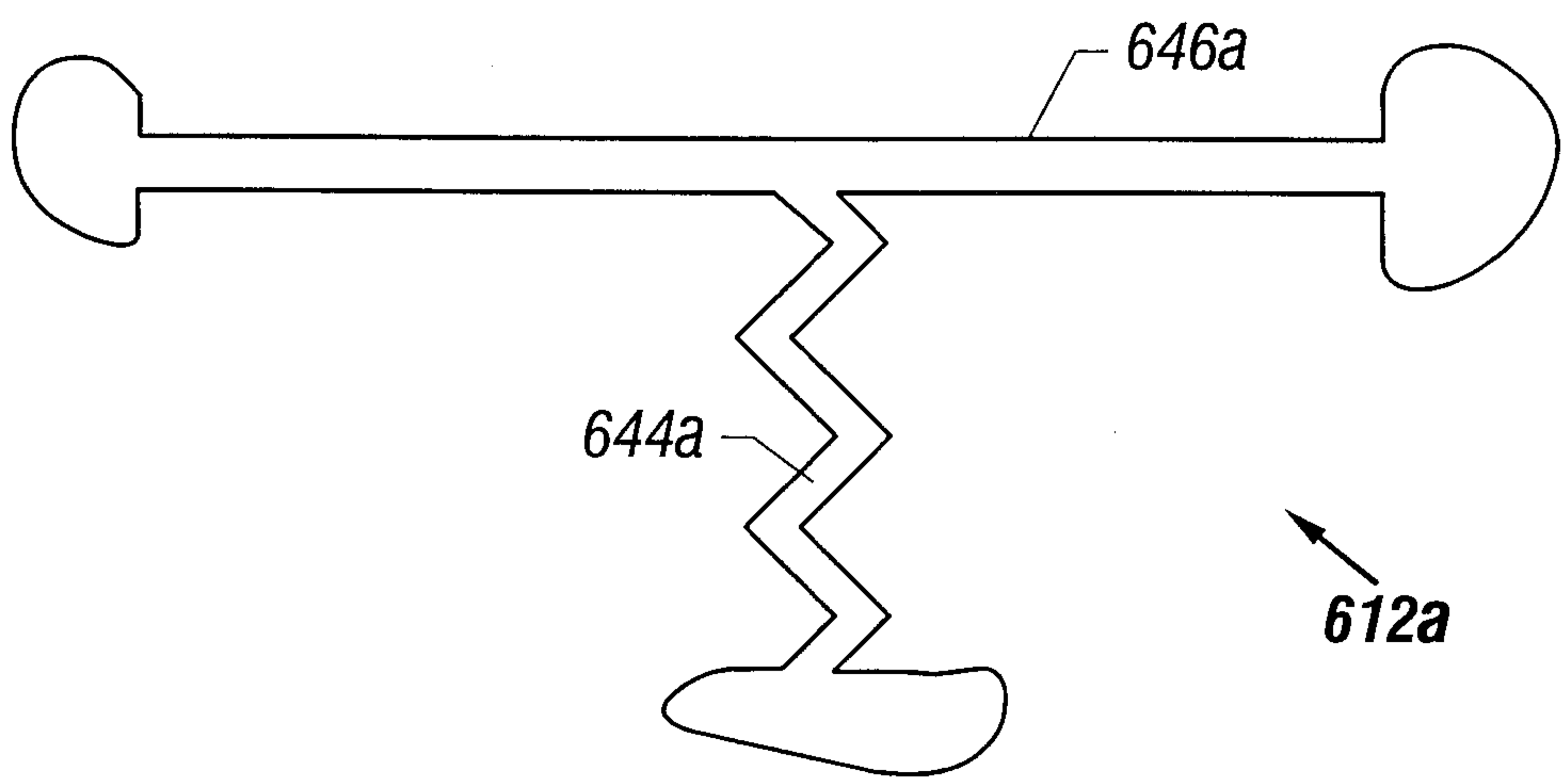


FIG. 6A

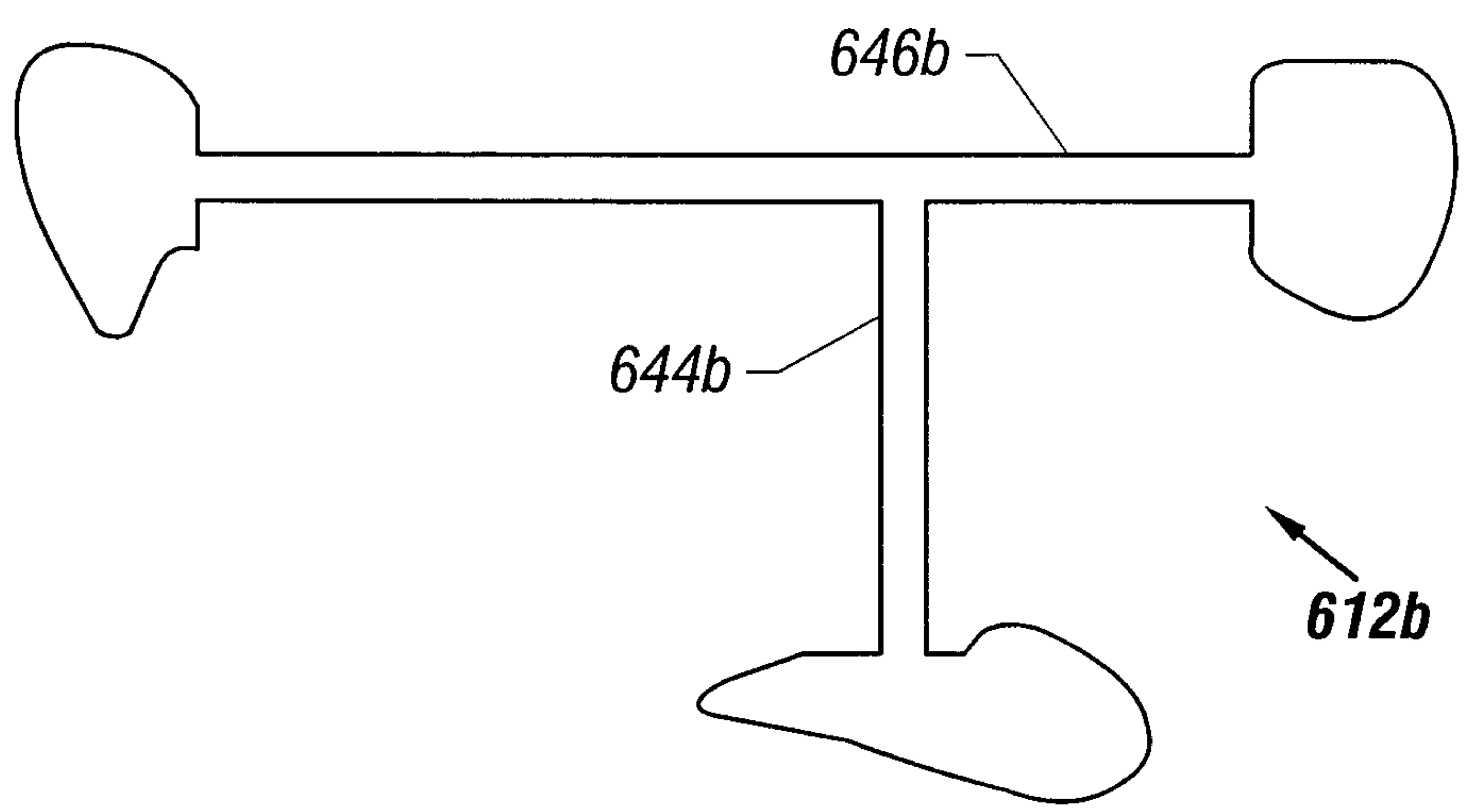


FIG. 6B

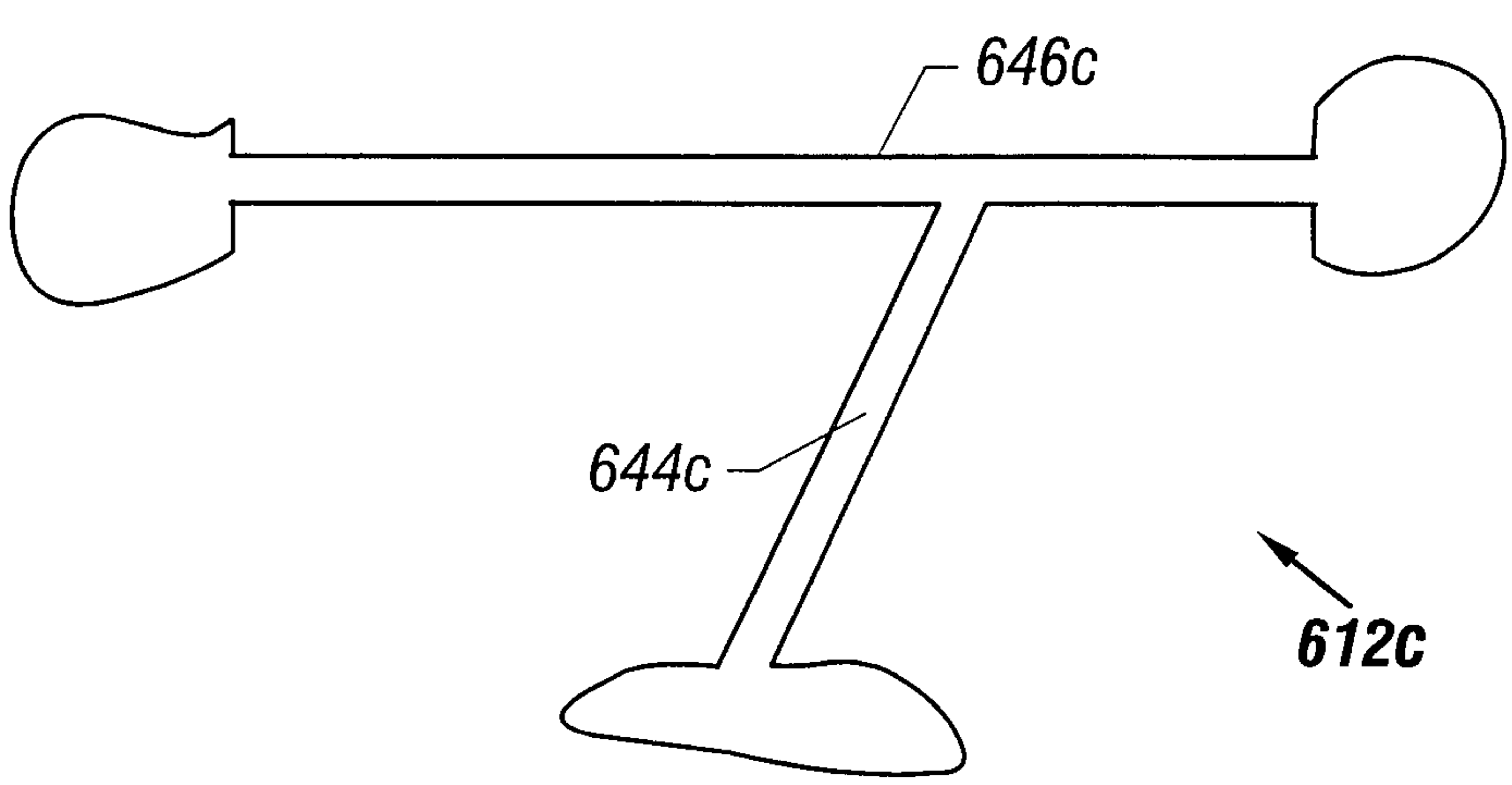


FIG. 6C

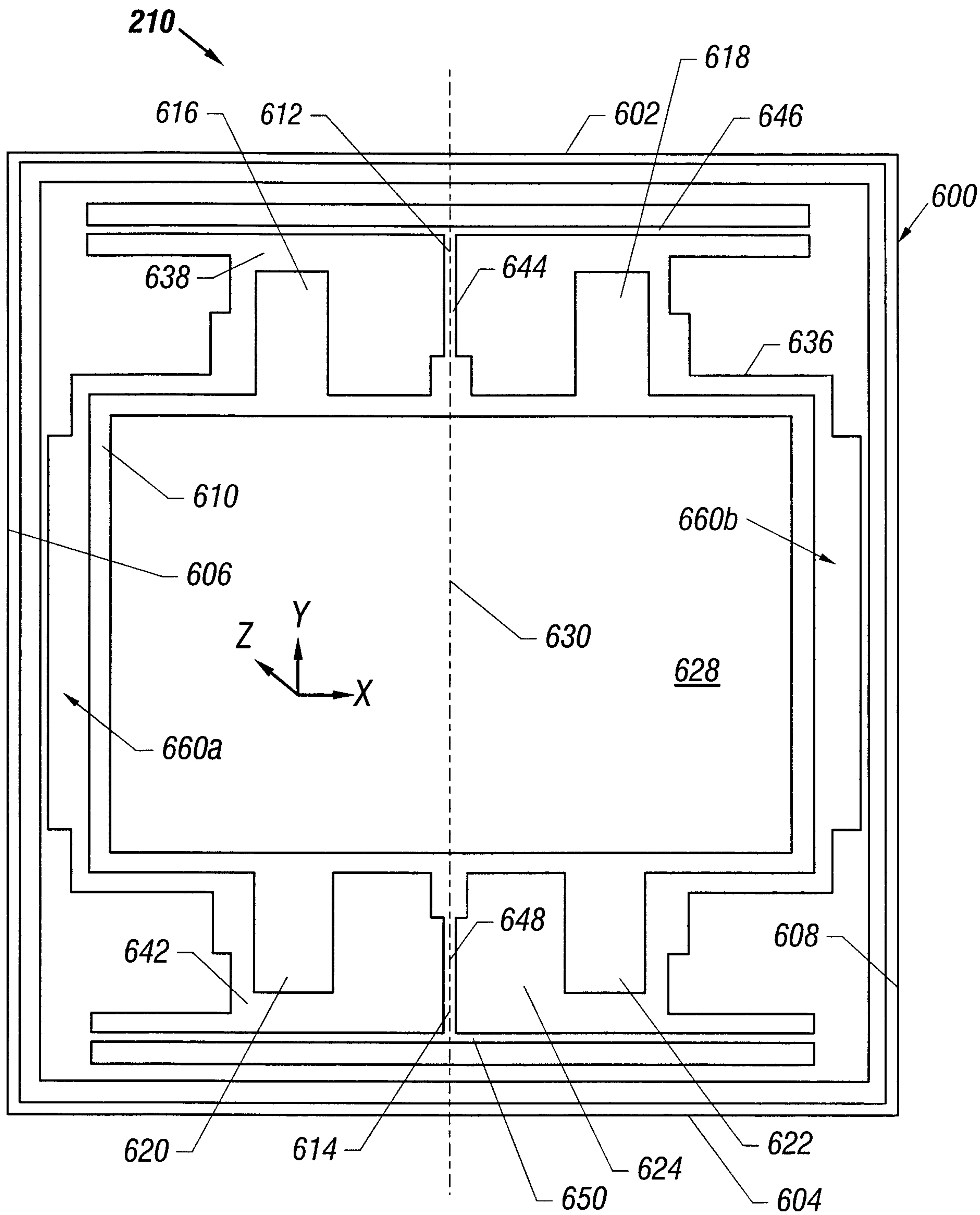

210
618
616
612
602
646
600
638
644
636
610
660b
606
630
Y
Z
X
628
660a
648
642
608
620
614
622
624
650
604

FIG. 6D

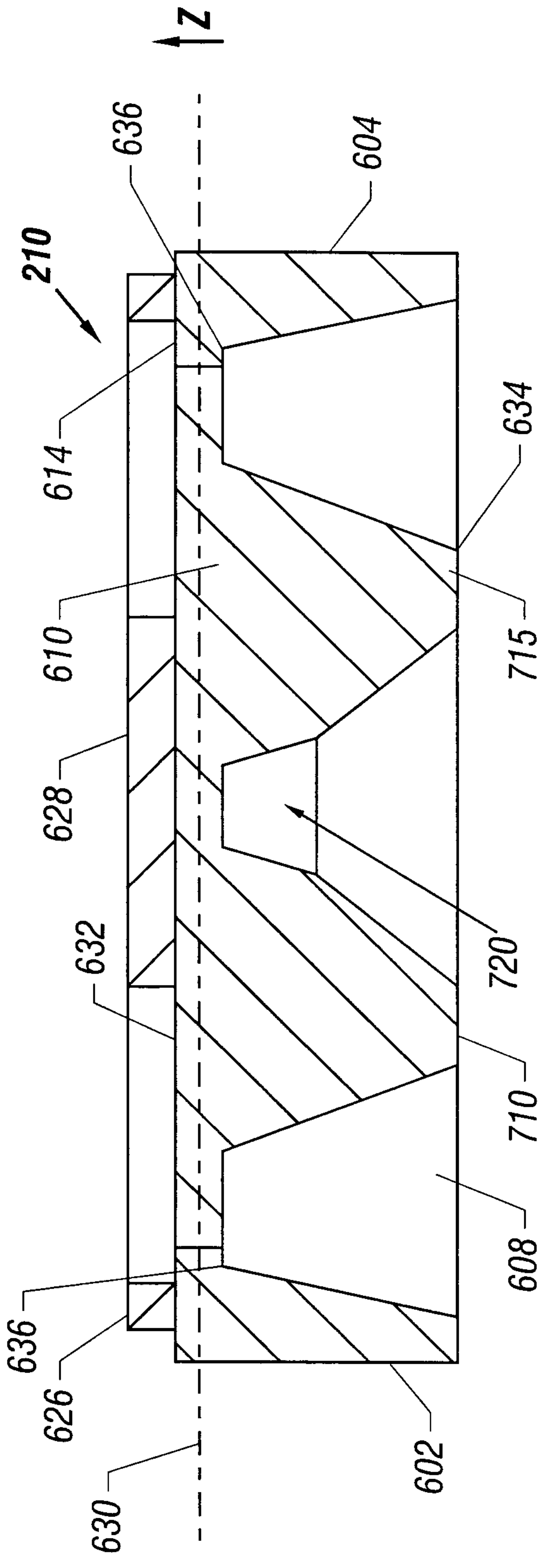

Z
210
636
604
614
634
610
715
628
720
632
710
608
636
626
602
630

FIG. 7

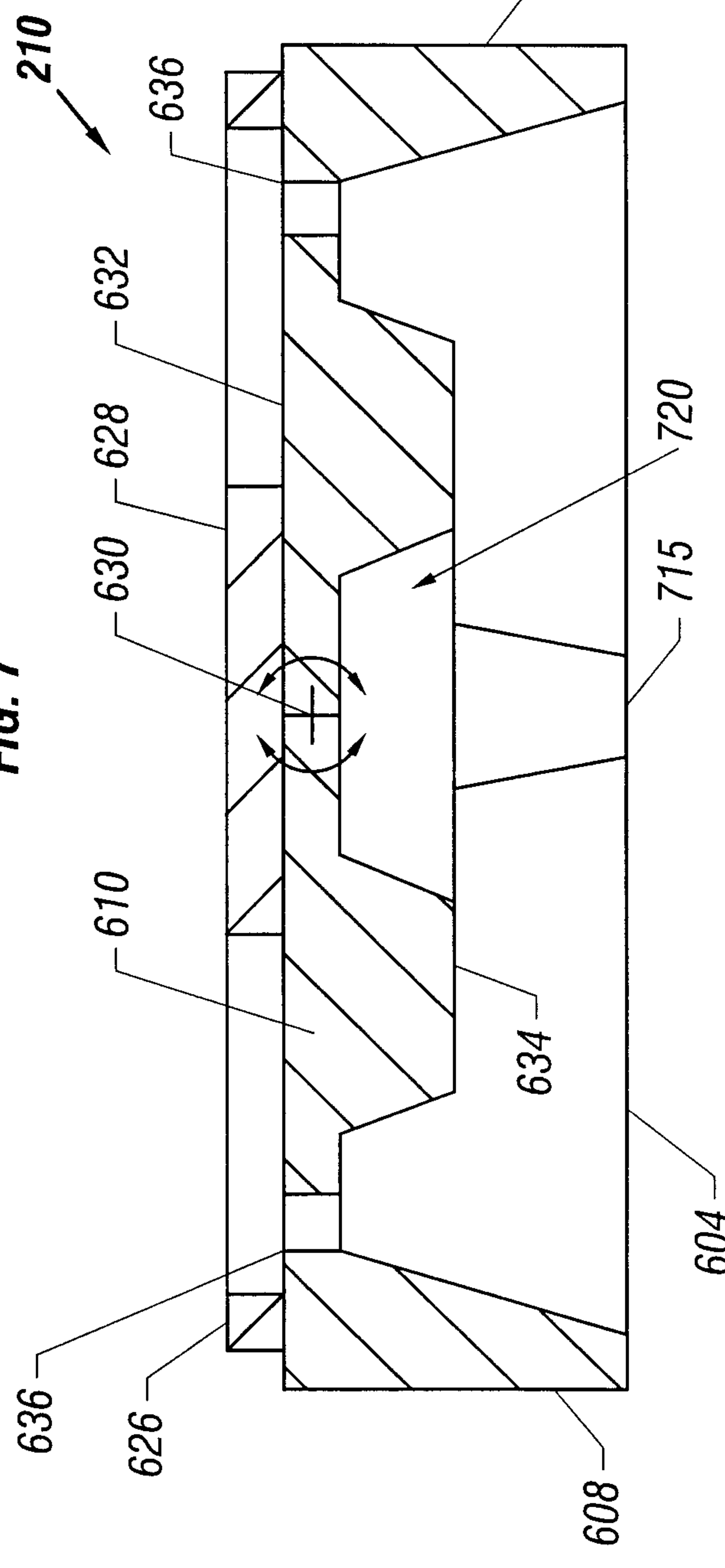

210
636
606
632
628
720
630
715
610
634
604
636
626
608

FIG. 8

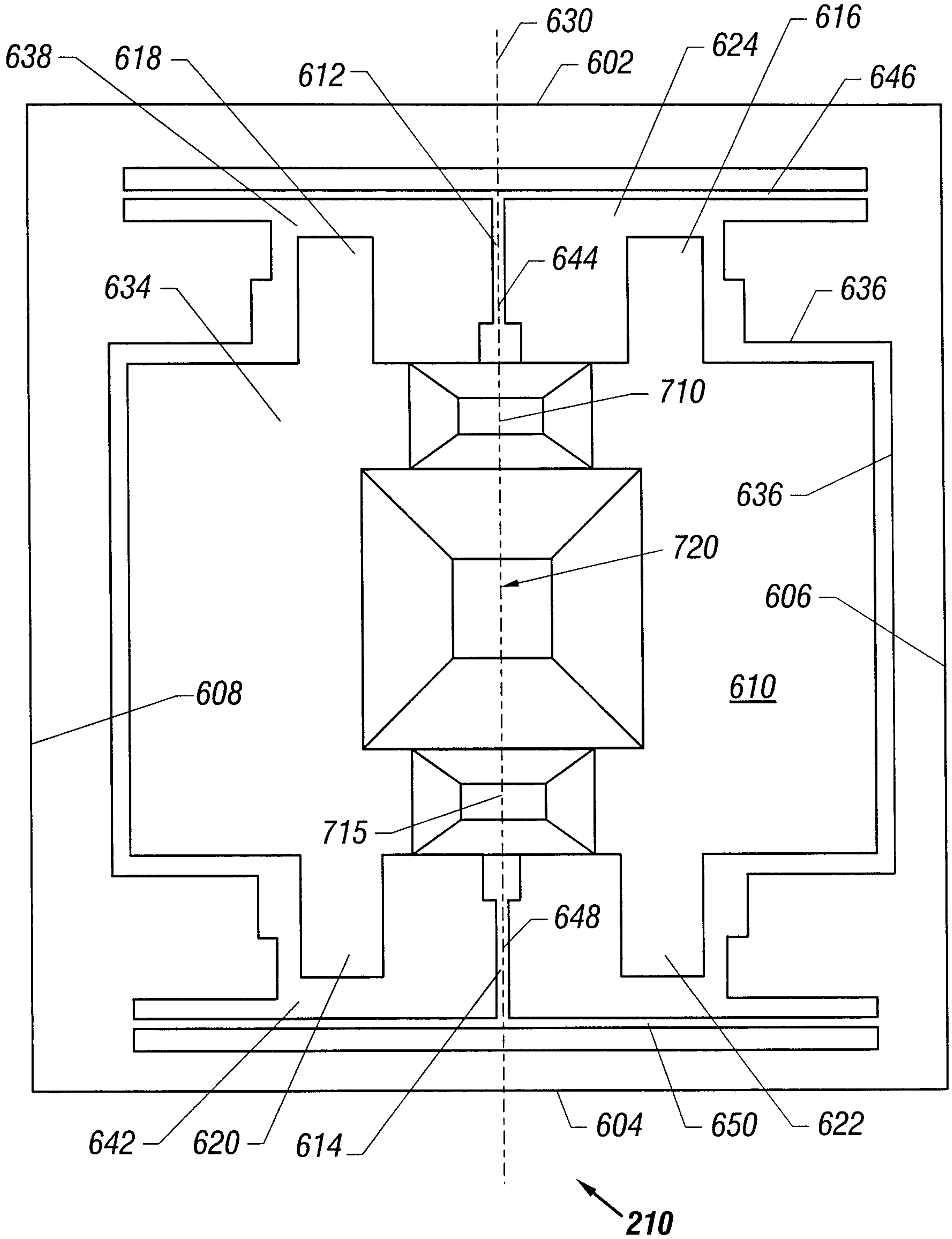

630
616
624
602
646
638
618
612
644
634
636
710
636
720
606
608
610
715
648
642
620
614
604
650
622
210

FIG. 9

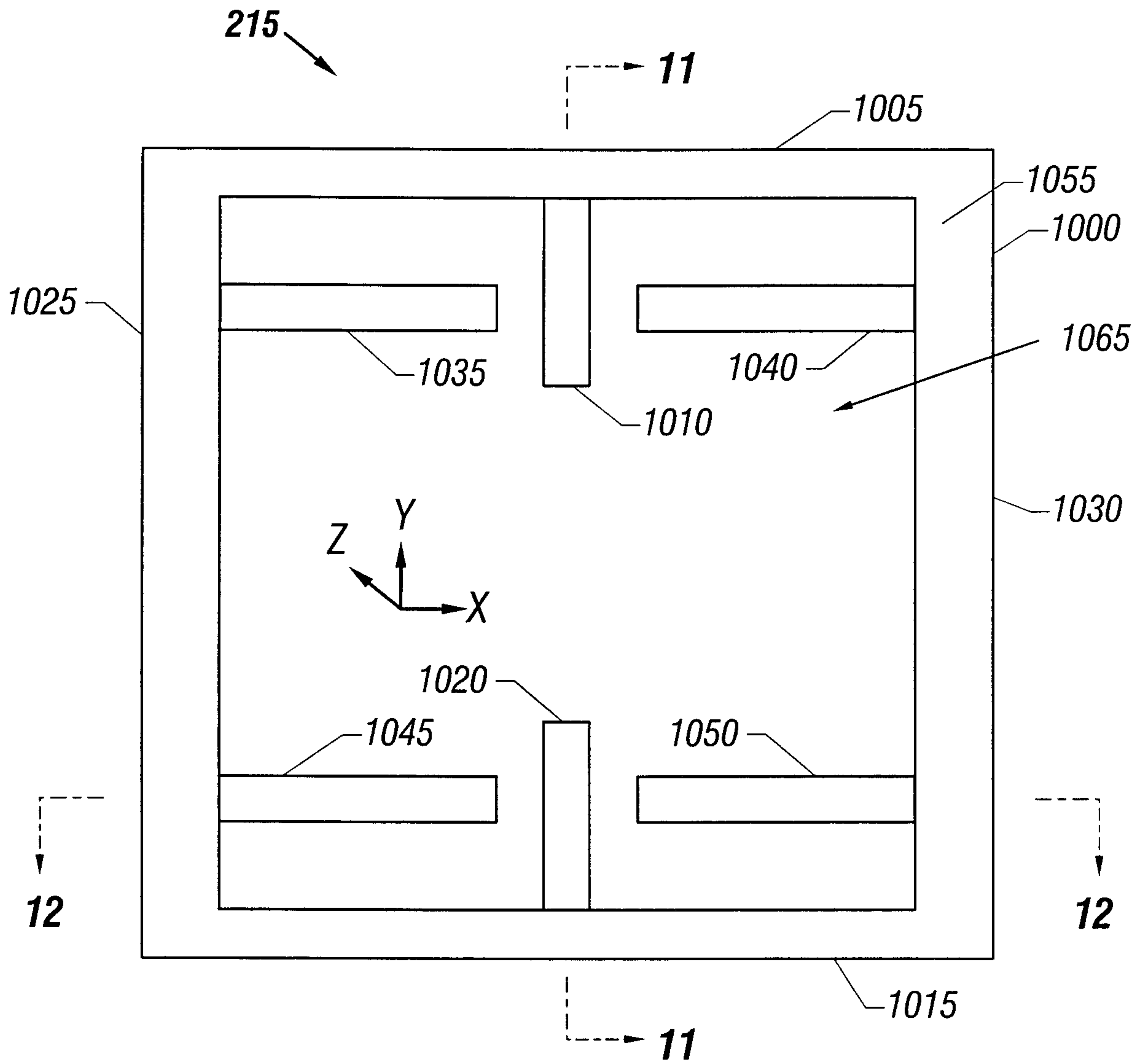

215
11
1005
1055
1000
1025
1035
1040
1065
1010
1030
Z
Y
X
1020
1045
1050
12
12
1015
11

FIG. 10

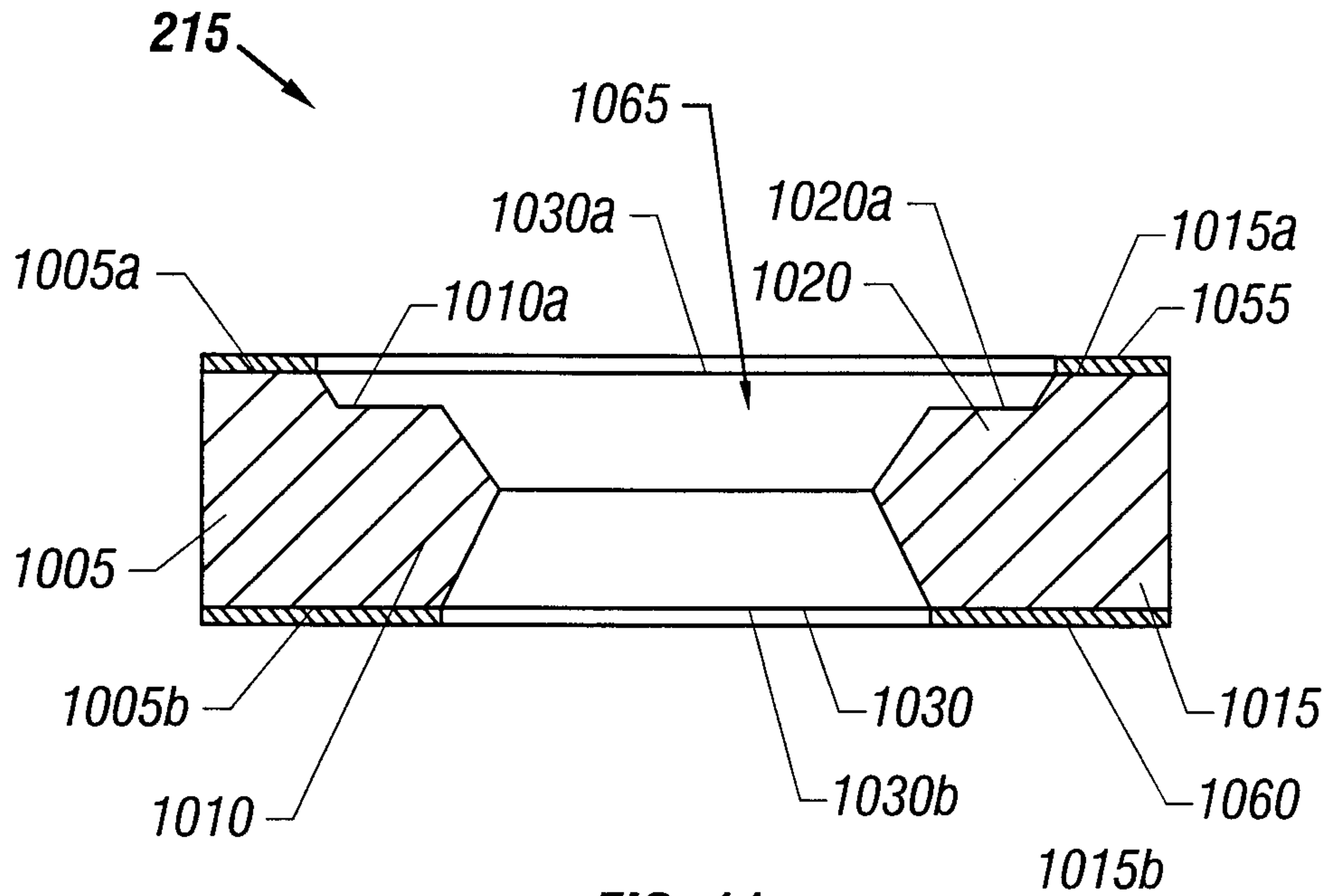

215
1065
1030a
1020a
1015a
1005a
1010a
1020
1055
1005
1005b
1030
1015
1010
1030b
1060
1015b

FIG. 11

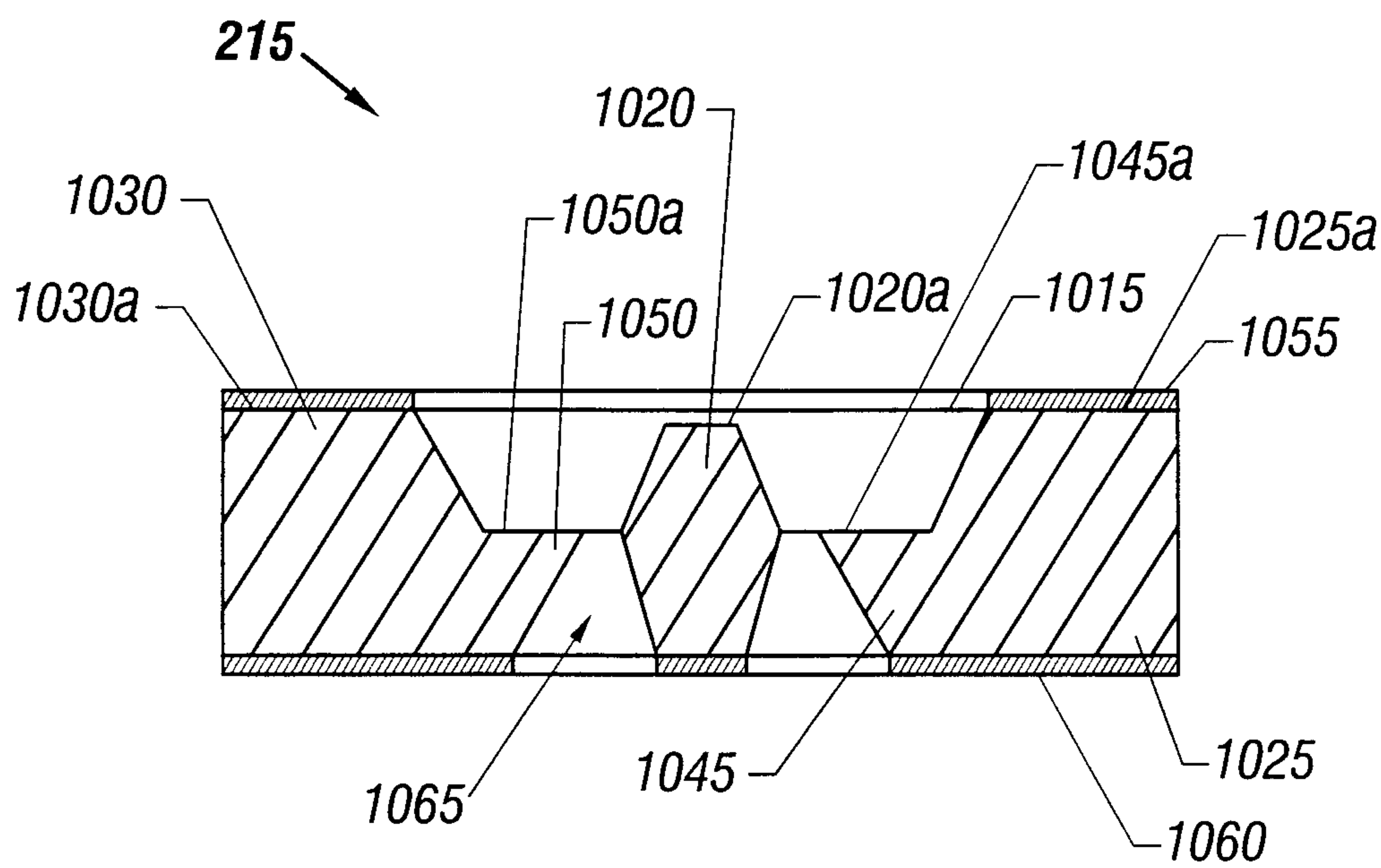

215
1020
1045a
1030
1050a
1025a
1030a
1020a
1015
1050
1055
1025
1045
1065
1060

FIG. 12

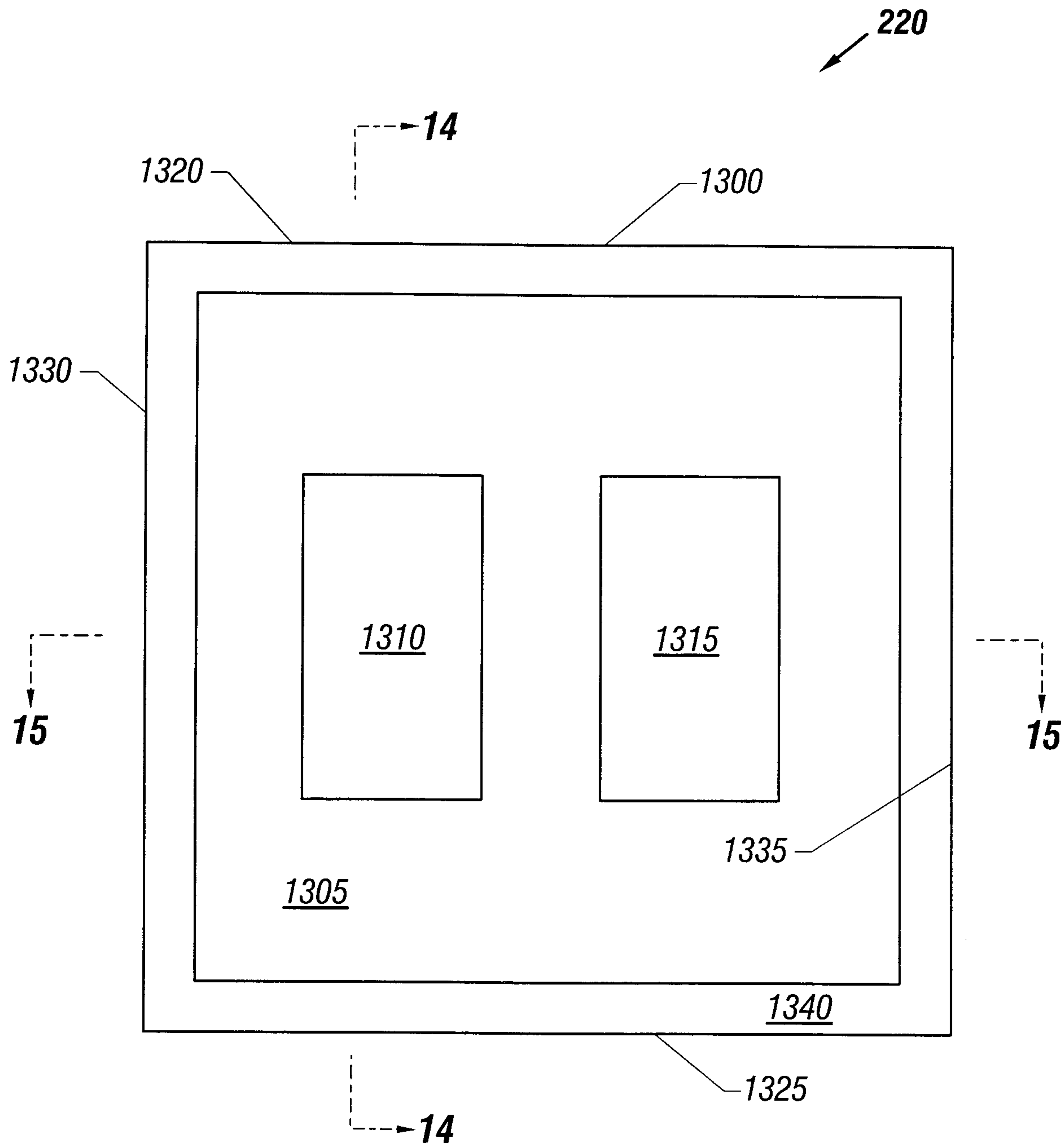


FIG. 13

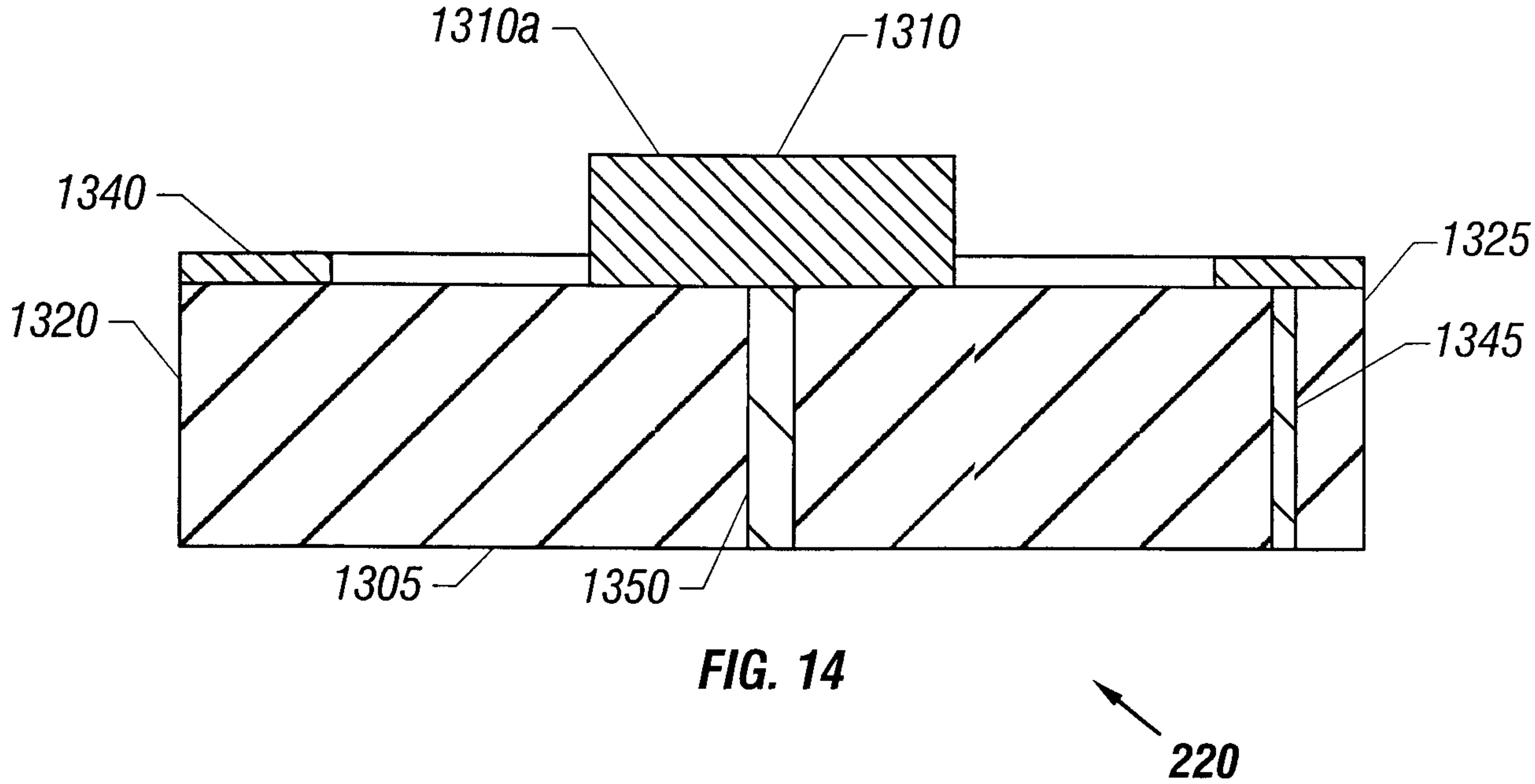

1310a
1310
1340
1325
1320
1345
1305
1350
220

FIG. 14

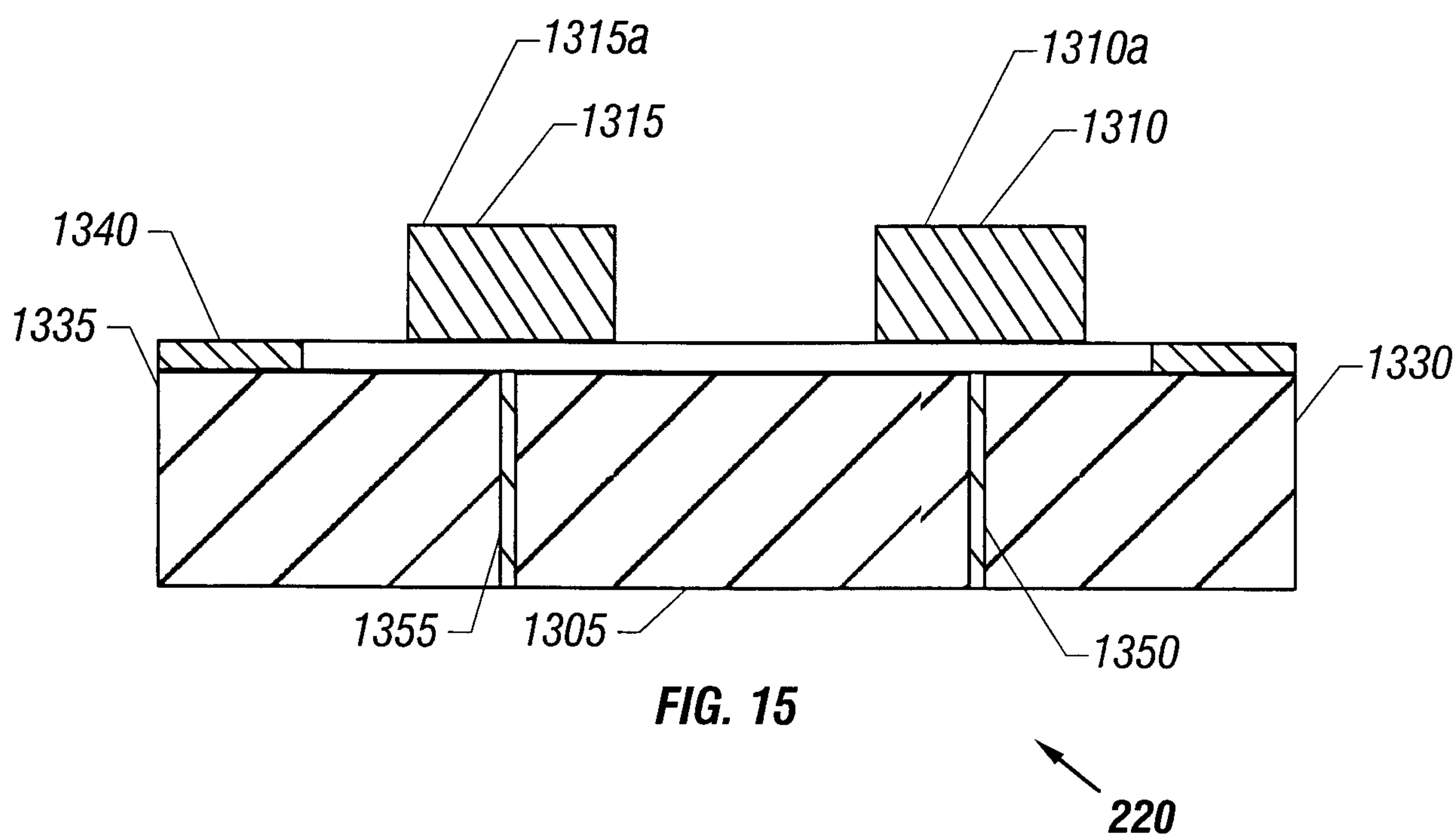

1315a
1310a
1315
1310
1340
1335
1330
1355
1305
1350
220

FIG. 15

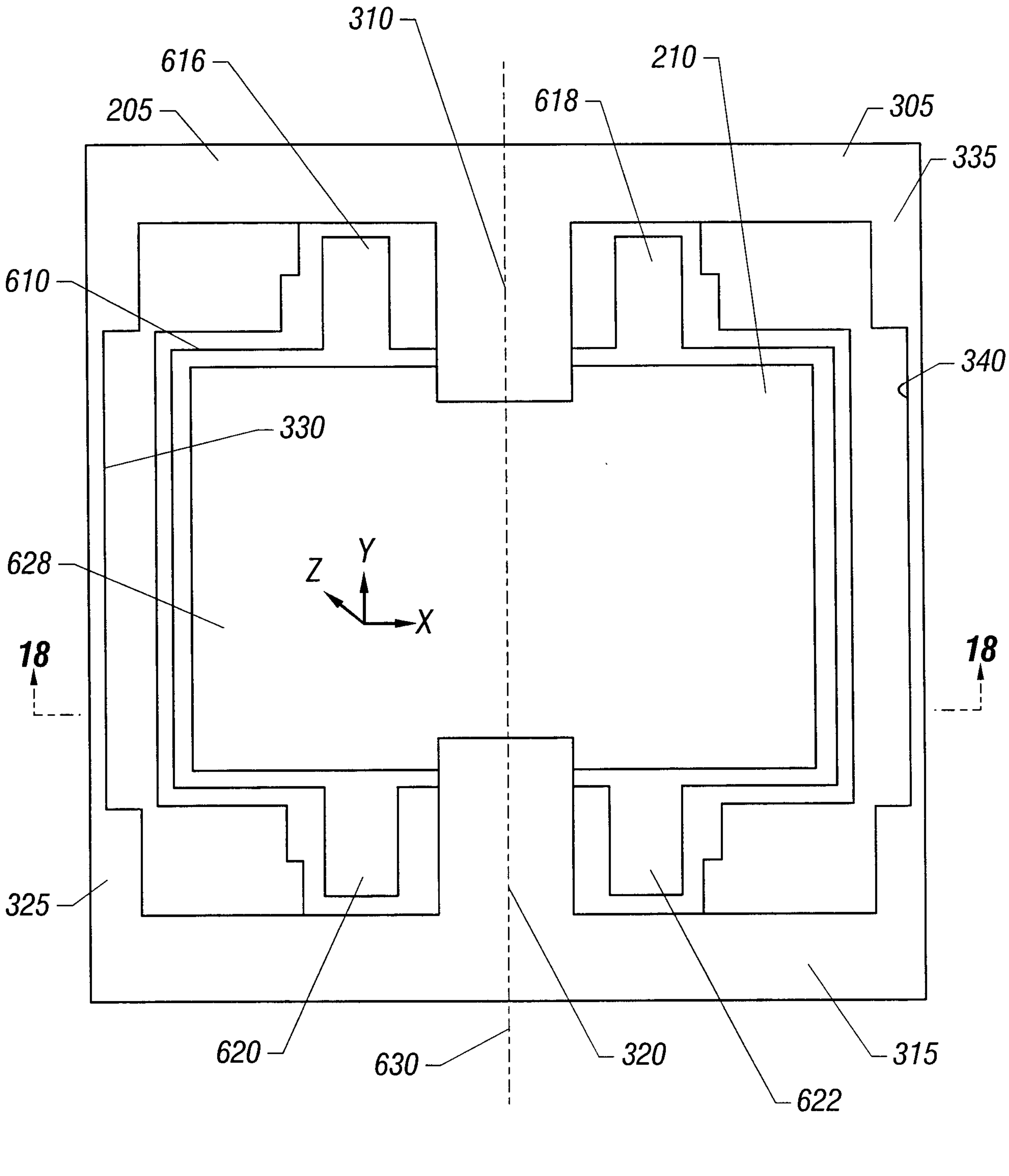

310
616
210
618
205
305
335
610
340
330
628
Y
Z
X
18
18
325
620
630
320
315
622

FIG. 16

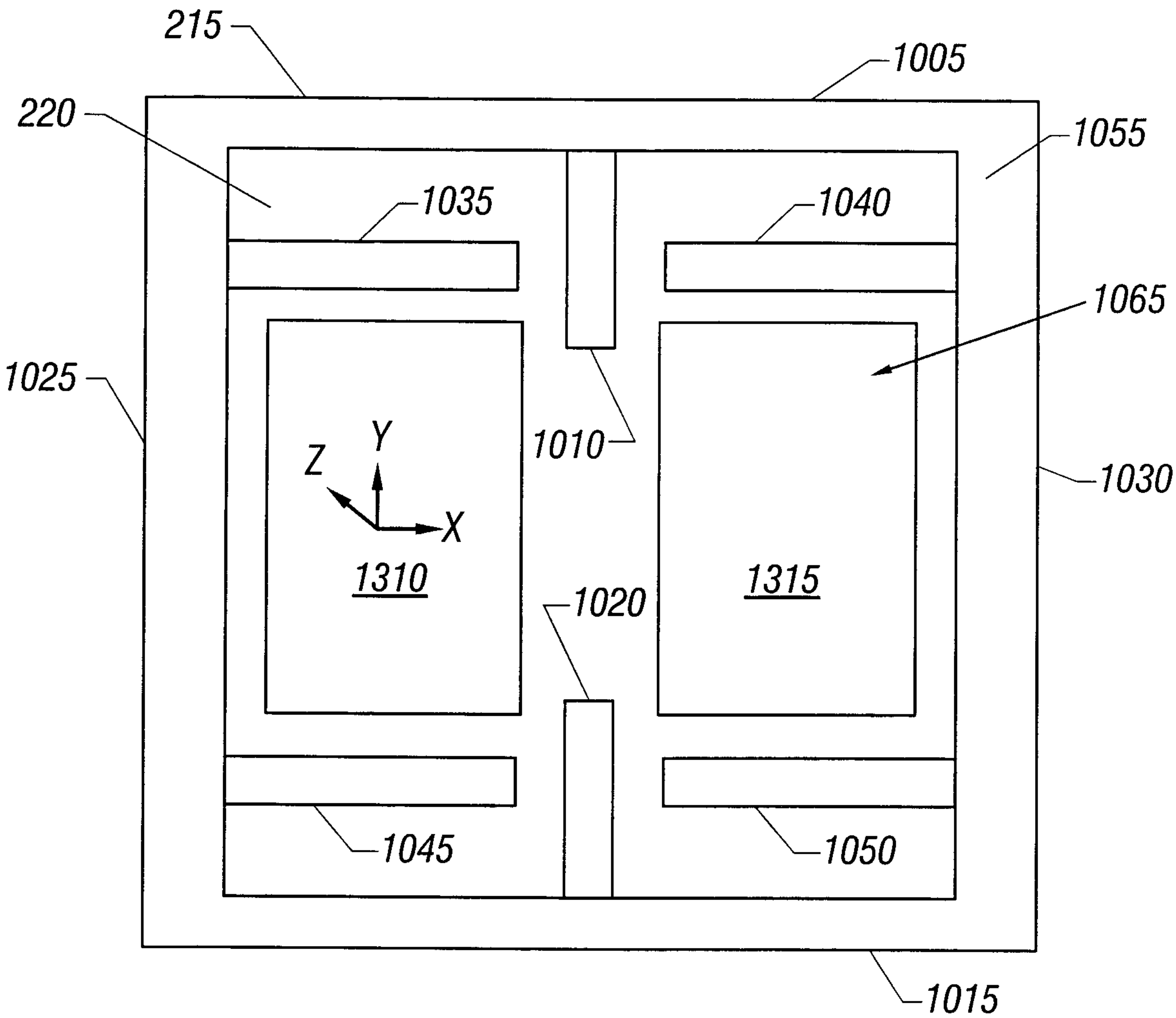

215
1005
220
1055
1035
1040
1065
1025
1010
1030
Z
Y
X
1310
1315
1020
1045
1050
1015

FIG. 17

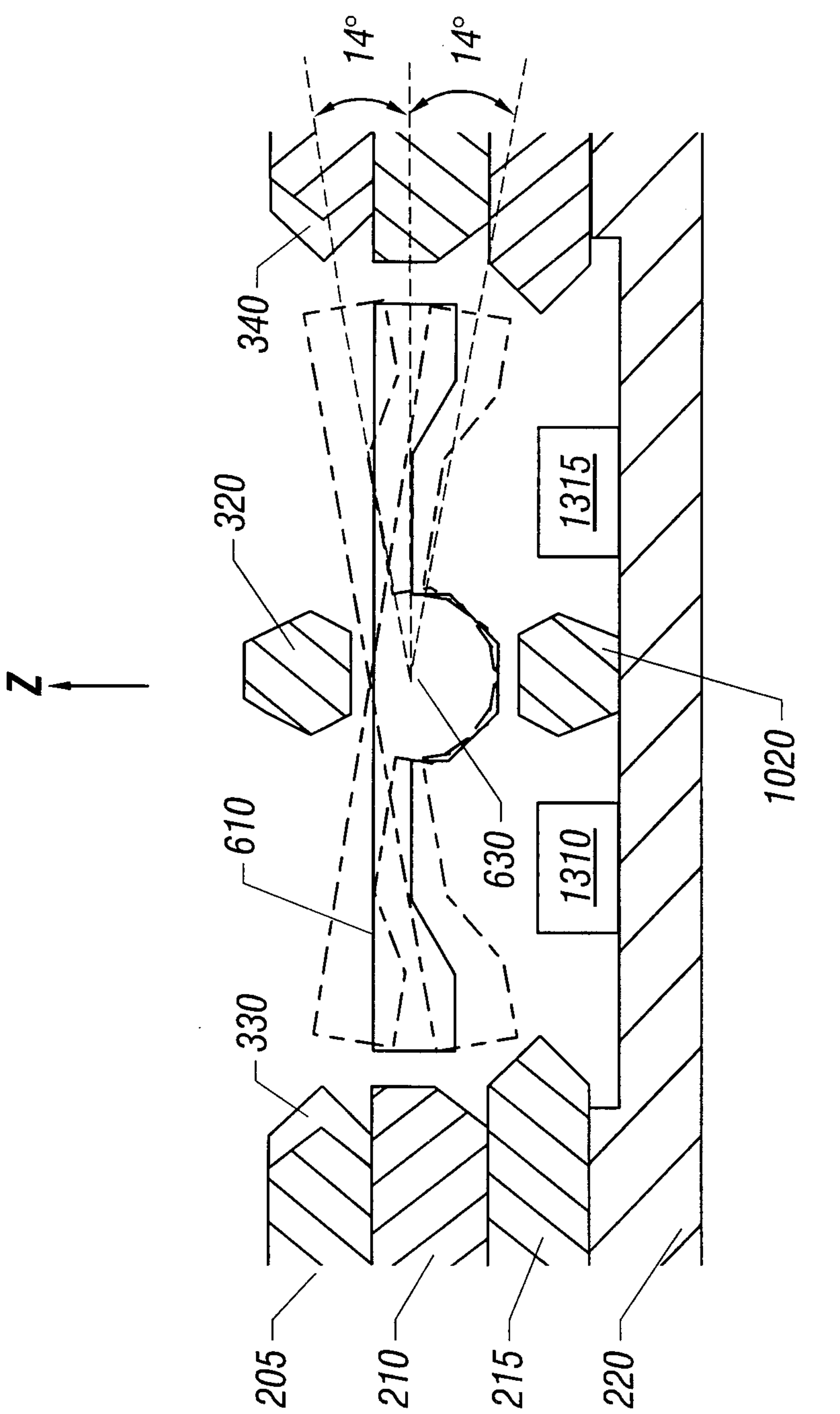


FIG. 18

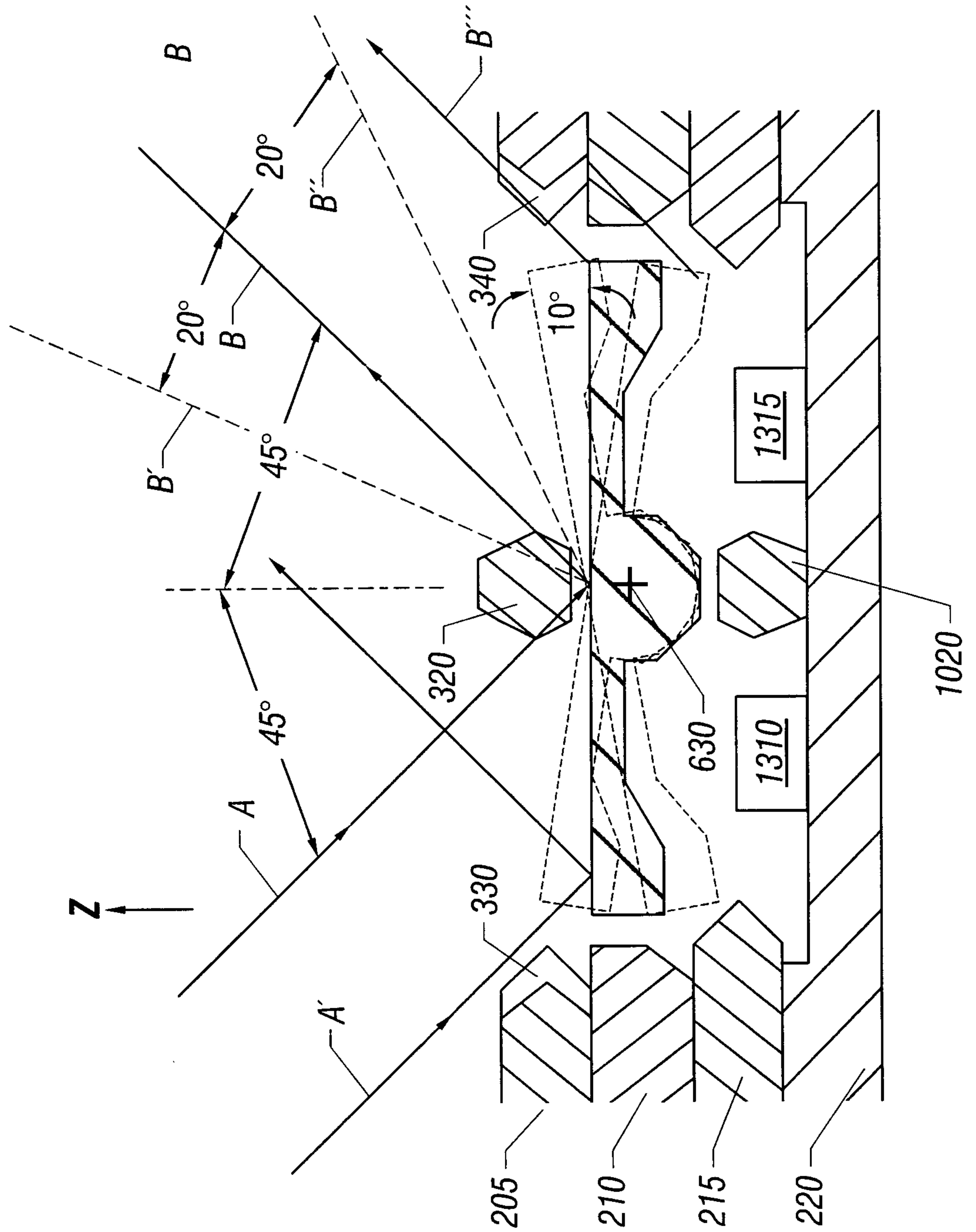
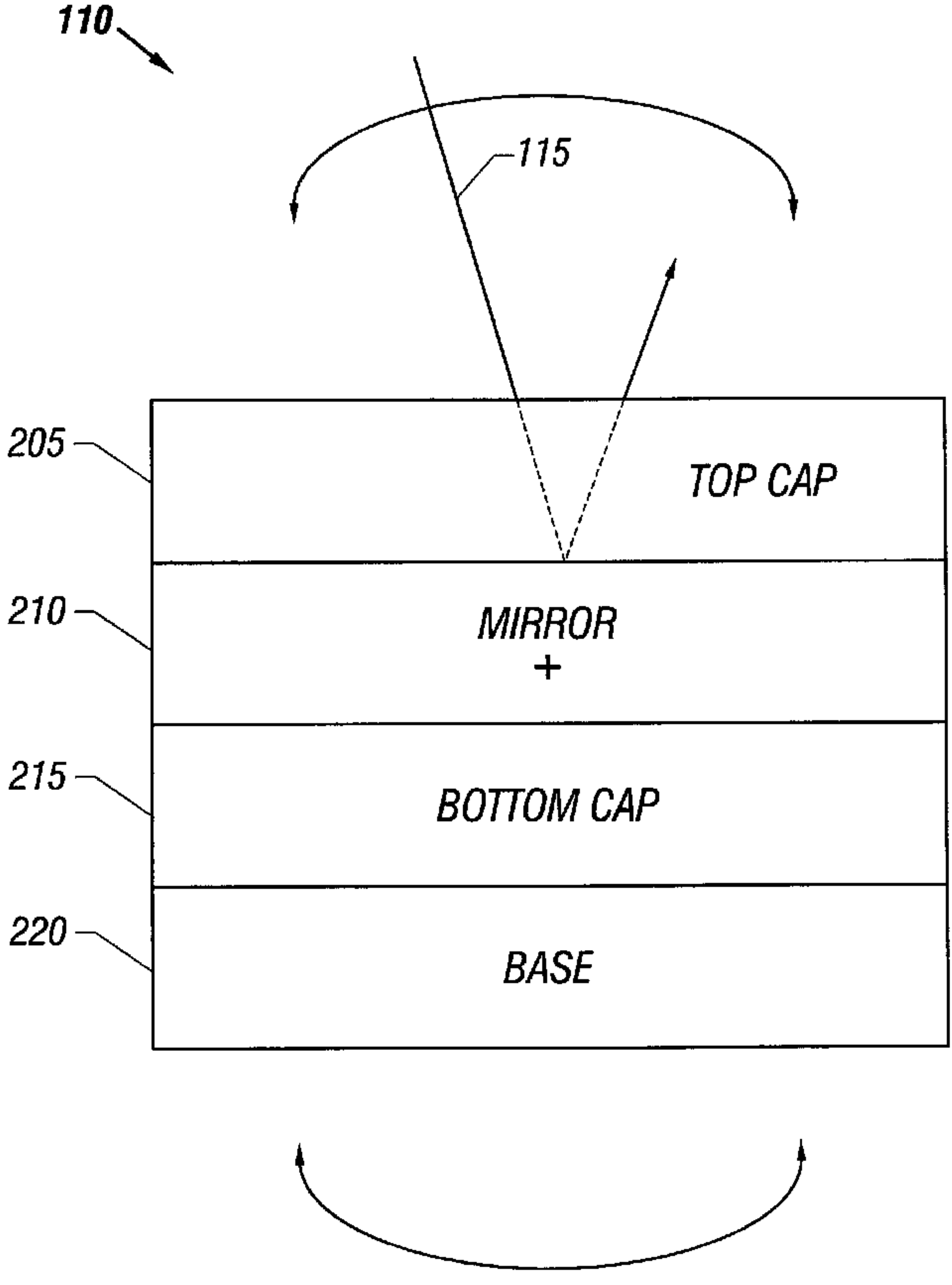

Z
A
A′
B
B′
B″
B‴
20°
20°
45°
45°
10°
205
210
215
220
320
330
340
630
1310
1315
1020

FIG. 19


110
115
205
TOP CAP
210
MIRROR
+
215
BOTTOM CAP
220
BASE