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(54) TUNABLE LENS WITH ACTUATOR BRAKES

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Publication Classification

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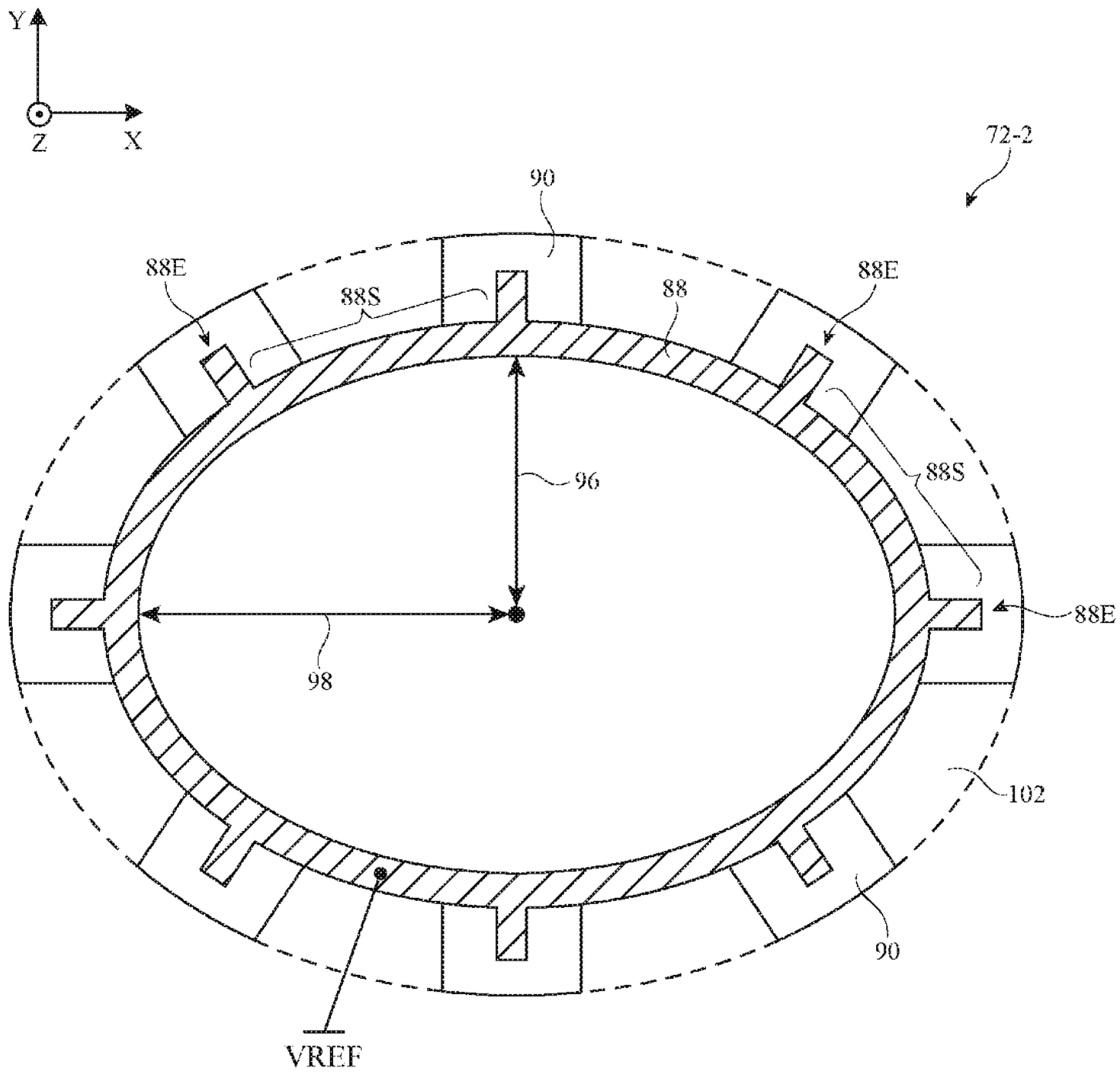
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F16D 55/225	(2006.01)
F16D 65/00	(2006.01)
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(57) **ABSTRACT**

An electronic device may include a lens module with a tunable lens. The tunable lens may include a flexible lens element and a lens shaping structure attached to the flexible lens element. The lens shaping structure may include tabs that are each coupled to a respective actuator. The actuator may move the tab up and down along an axis of displacement. The actuator may have a structure that is configured to rotate about a pivot axis. When it is not desired to adjust the tunable lens, a brake assembly in the actuator may apply a force to the structure in a direction parallel to the pivot axis. The brake assembly may include one or more brake calipers with wedge-shaped surfaces, brake cams, L-shaped brake structures, flexures, and/or piezoelectric members to apply the force to the structure.



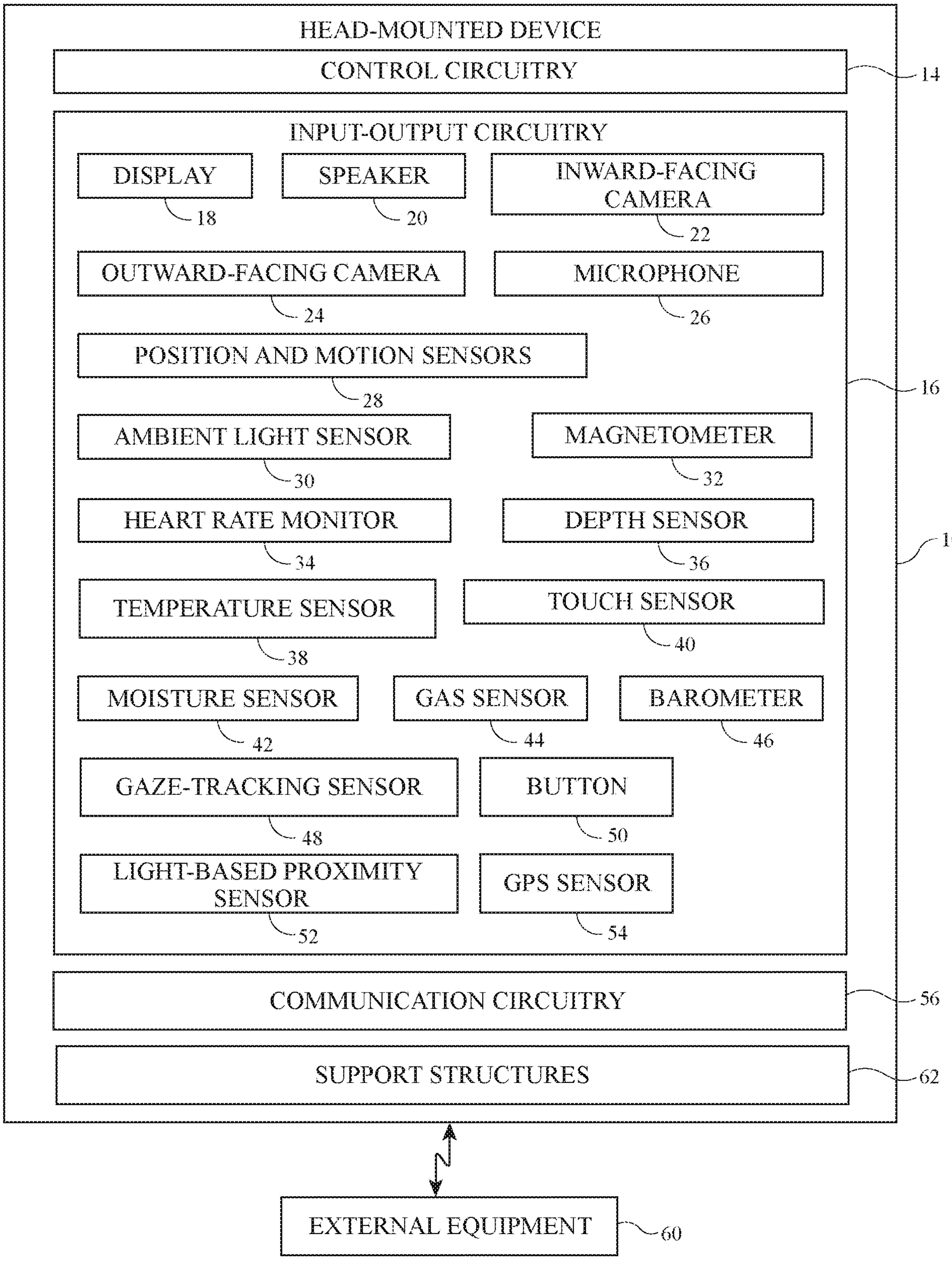

HEAD-MOUNTED DEVICE
CONTROL CIRCUITRY
14
INPUT-OUTPUT CIRCUITRY
DISPLAY
18
SPEAKER
20
INWARD-FACING CAMERA
22
OUTWARD-FACING CAMERA
24
MICROPHONE
26
POSITION AND MOTION SENSORS
28
AMBIENT LIGHT SENSOR
30
MAGNETOMETER
32
HEART RATE MONITOR
34
DEPTH SENSOR
36
TEMPERATURE SENSOR
38
TOUCH SENSOR
40
MOISTURE SENSOR
42
GAS SENSOR
44
BAROMETER
46
GAZE-TRACKING SENSOR
48
BUTTON
50
LIGHT-BASED PROXIMITY SENSOR
52
GPS SENSOR
54
16
10
COMMUNICATION CIRCUITRY
56
SUPPORT STRUCTURES
62
N
EXTERNAL EQUIPMENT
60

FIG. 1

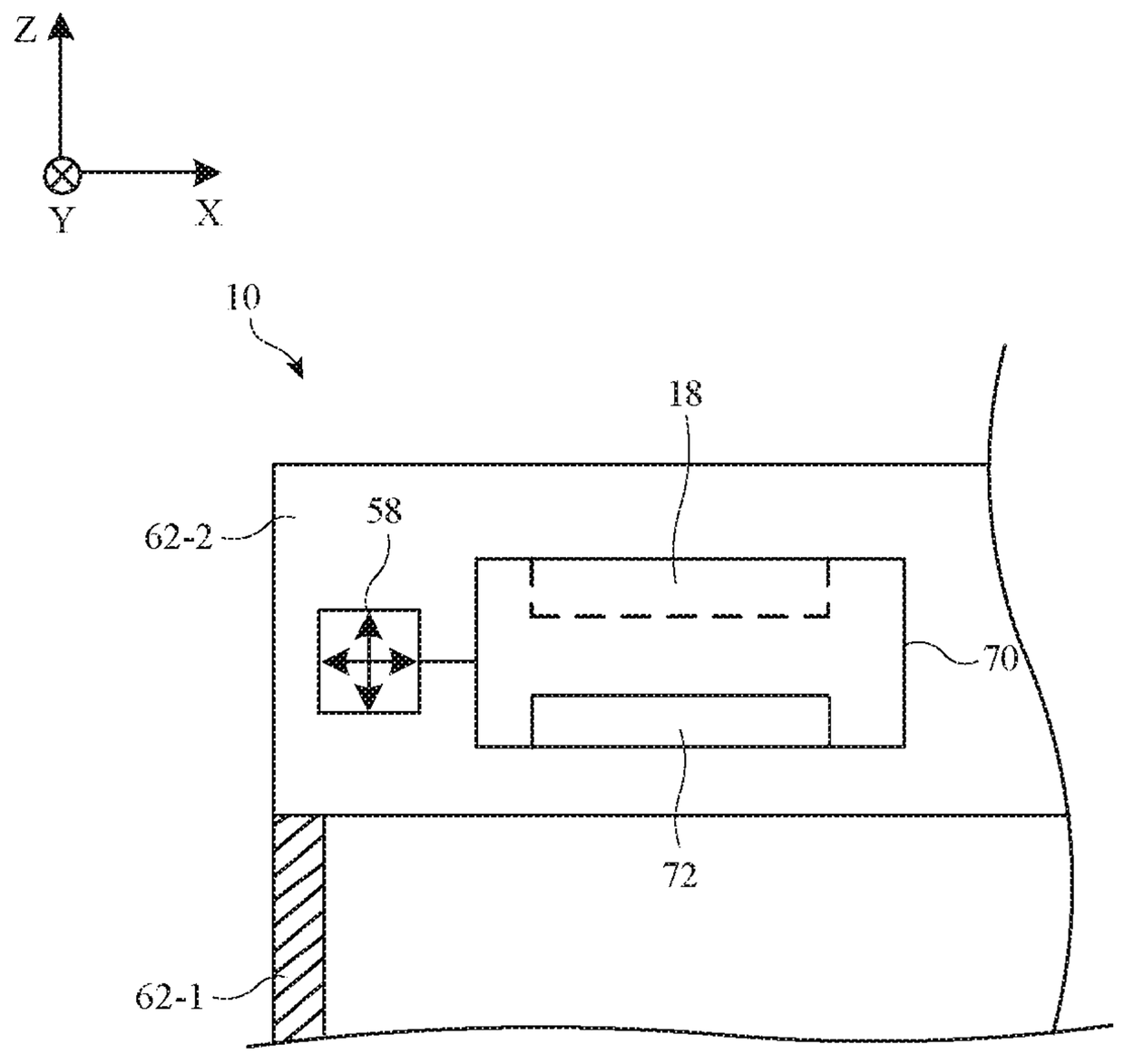


FIG. 2

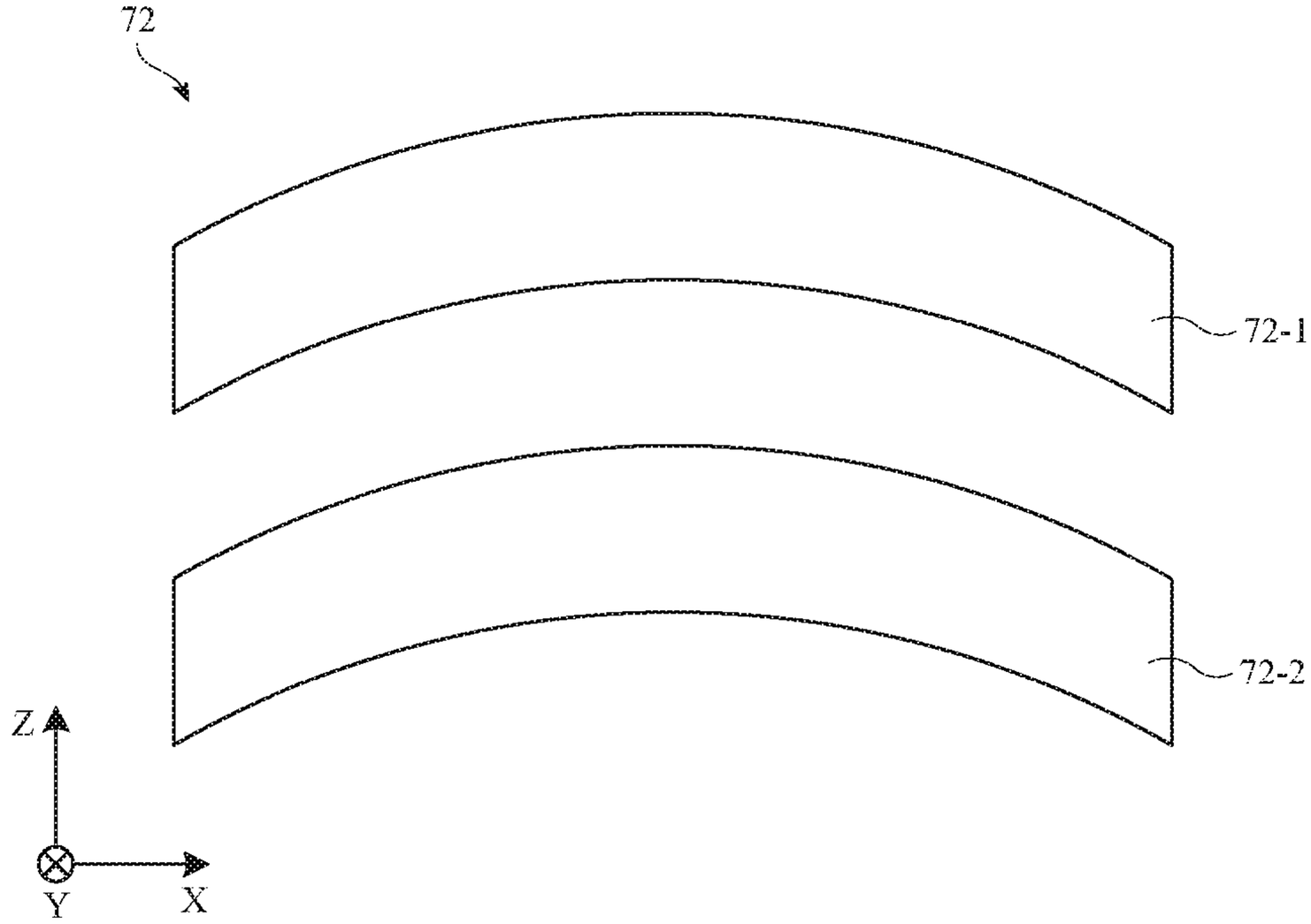


FIG. 3

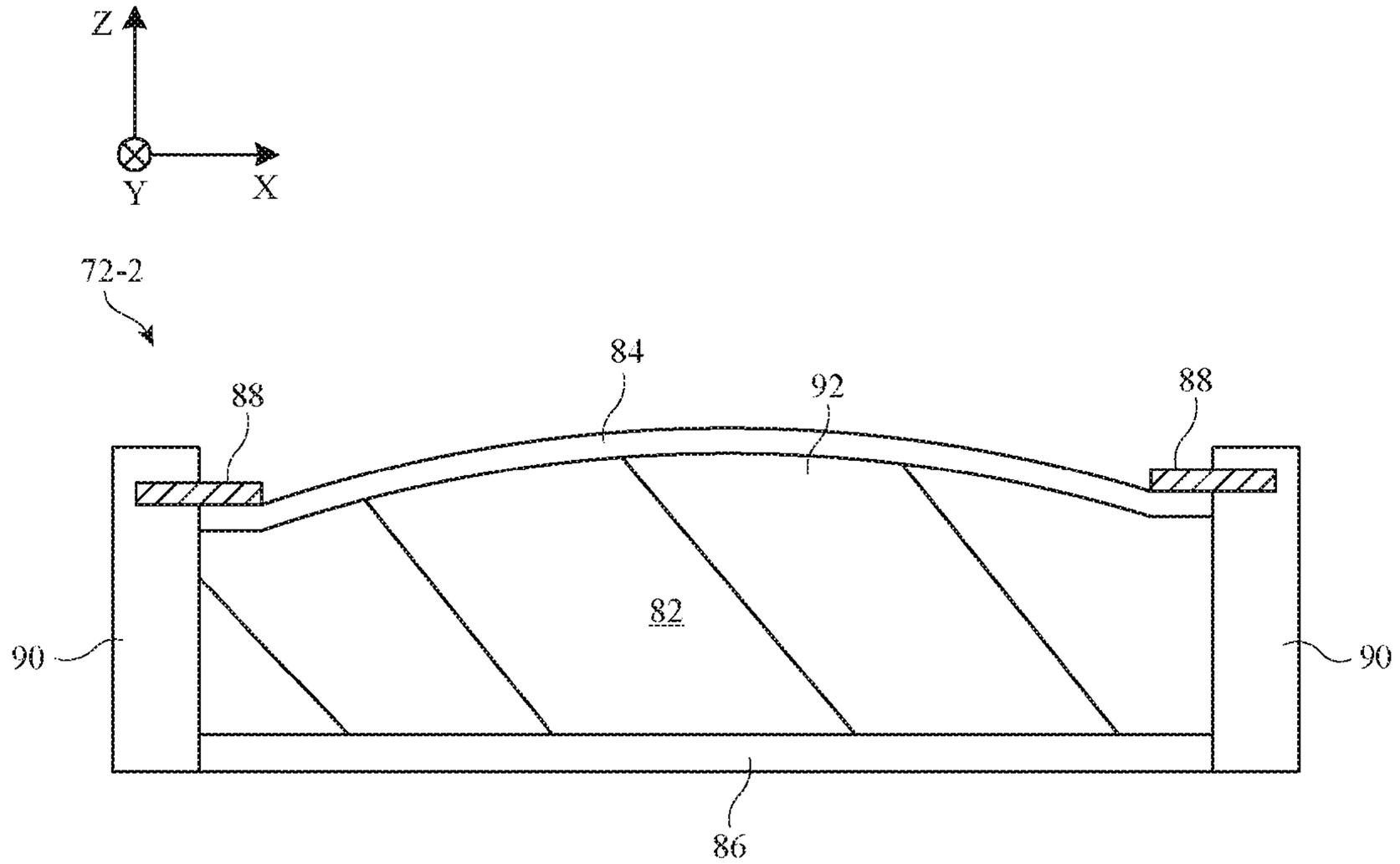


FIG. 4

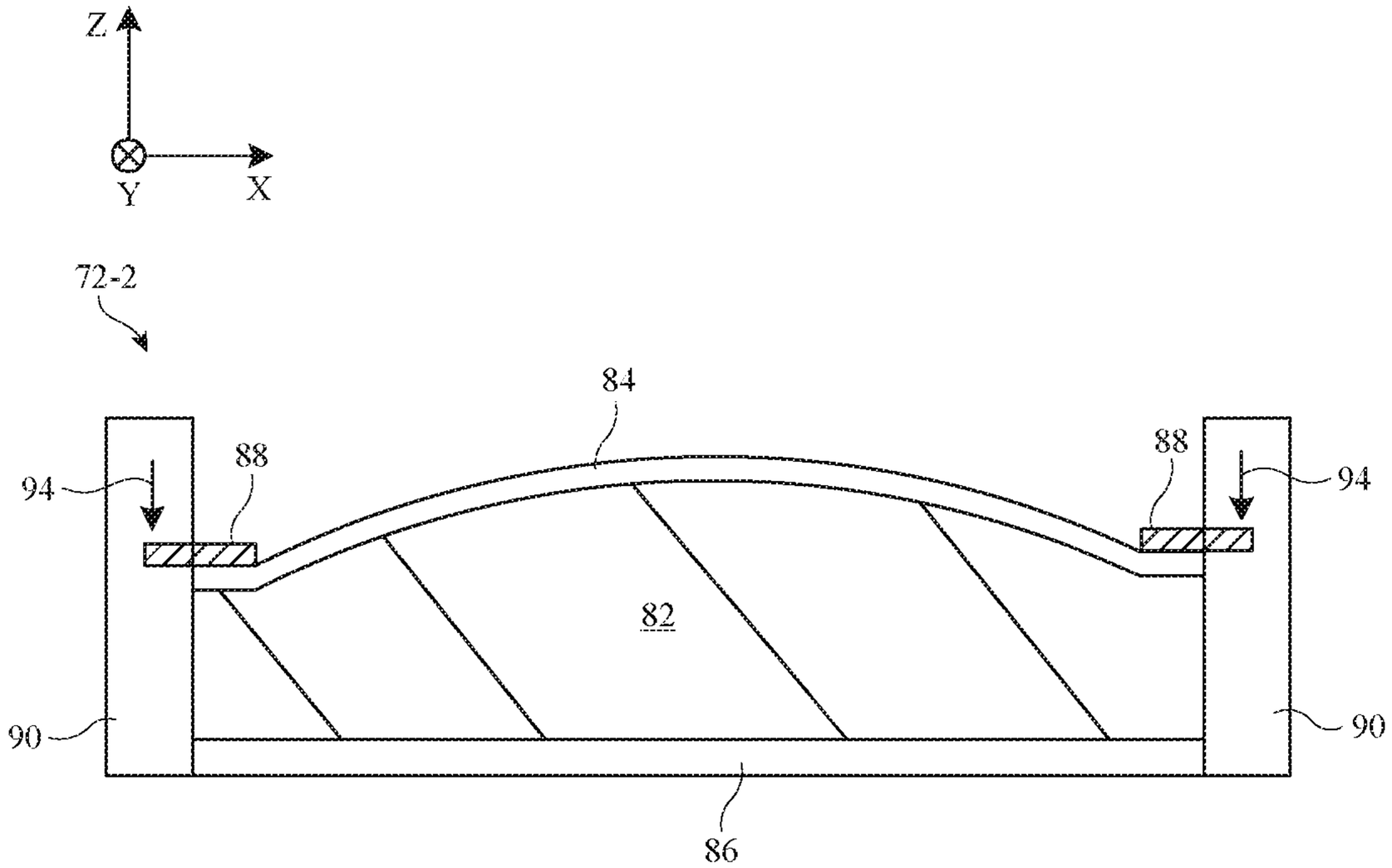


FIG. 5

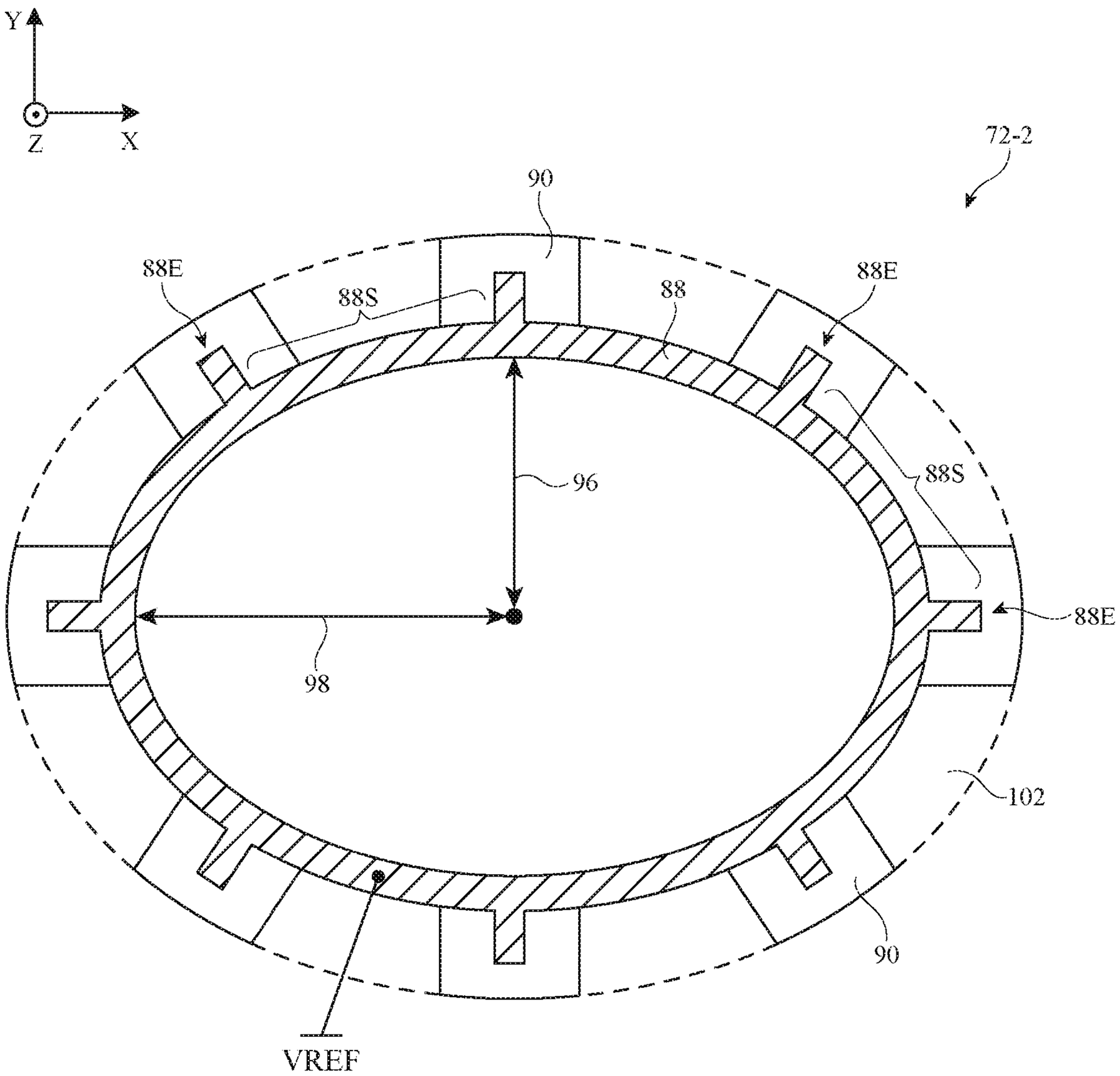


FIG. 6

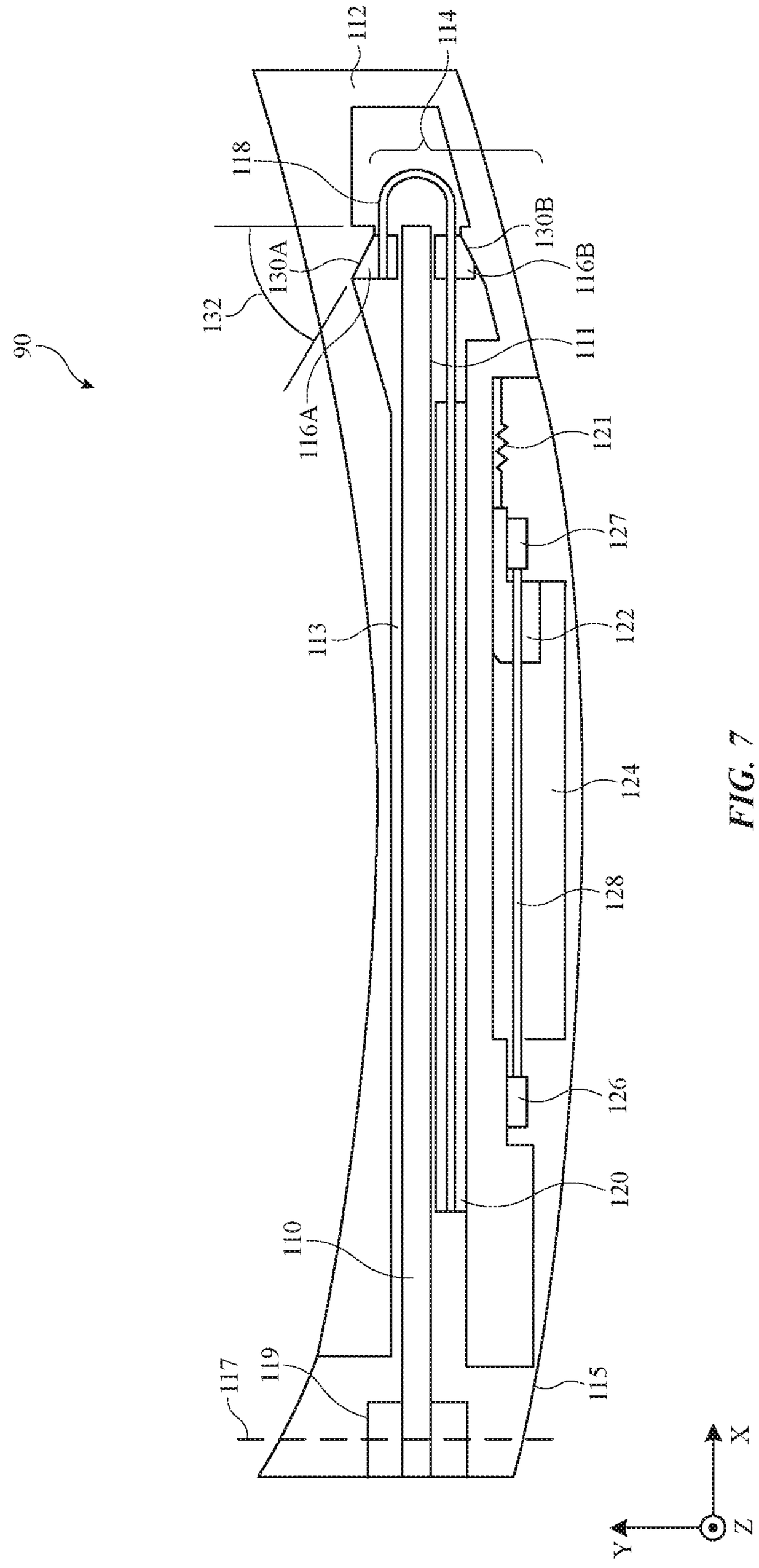

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130B
130A
116B
132
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116A
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Z

FIG. 7

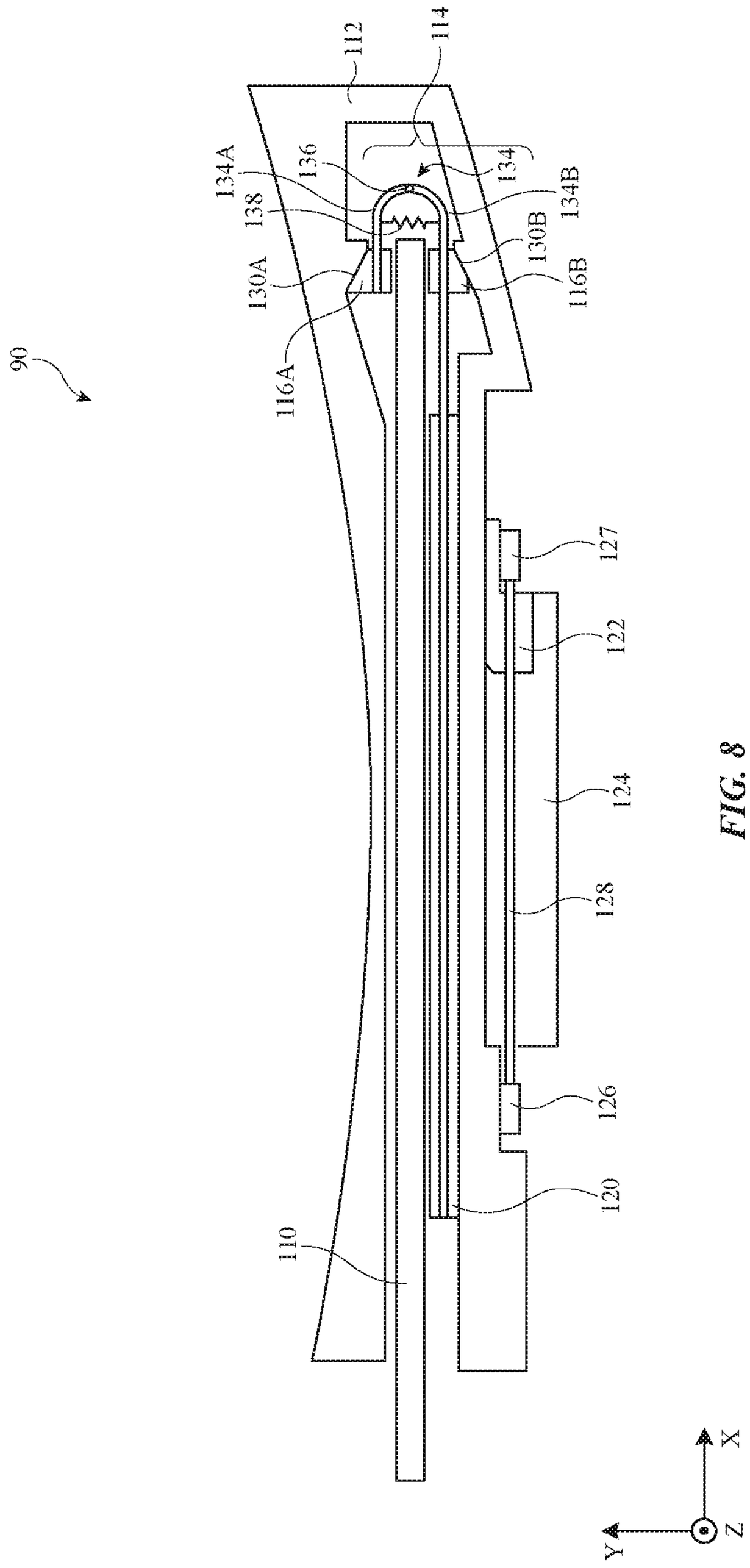

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134A
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Y
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FIG. 8

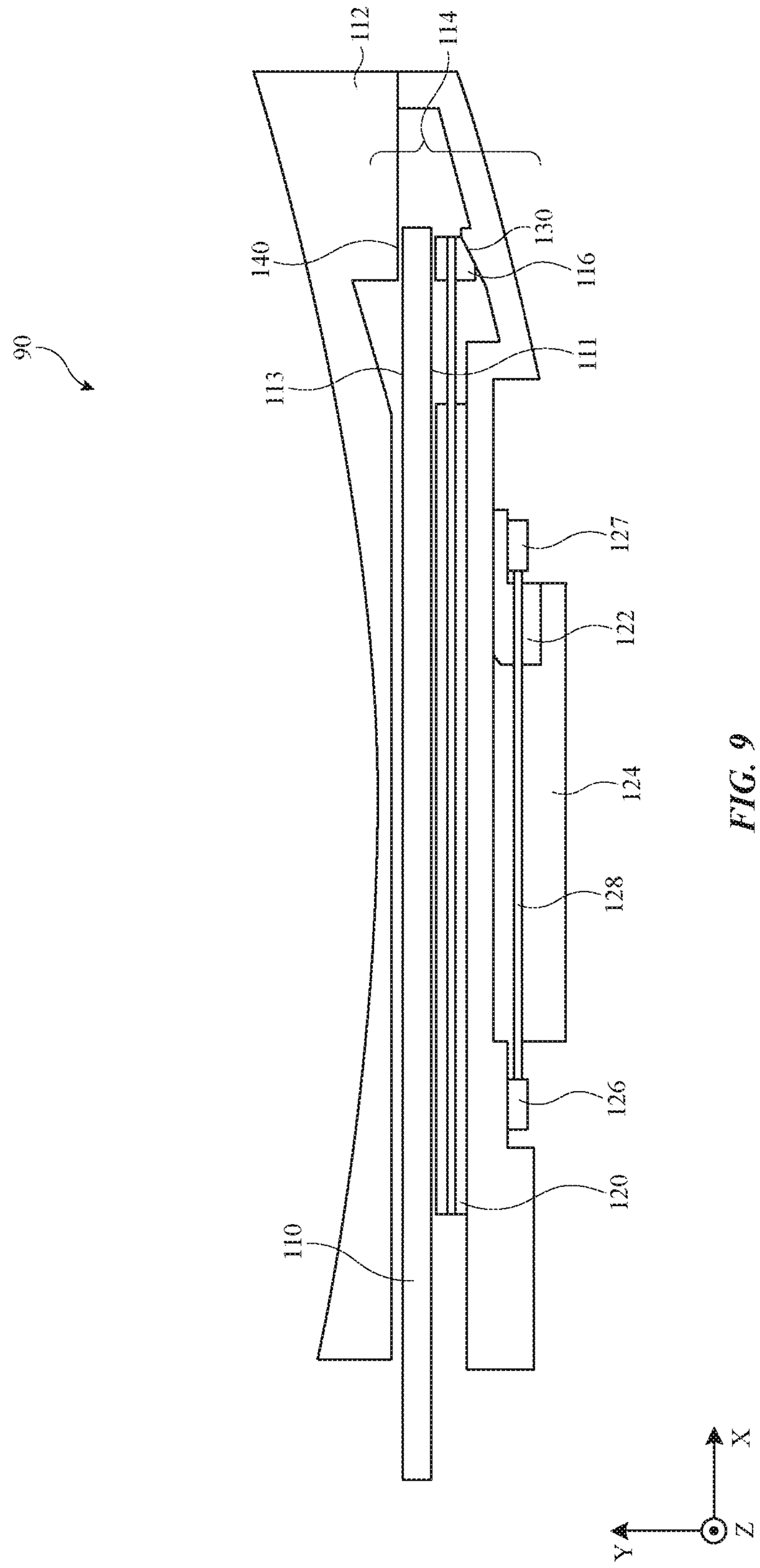


FIG. 9

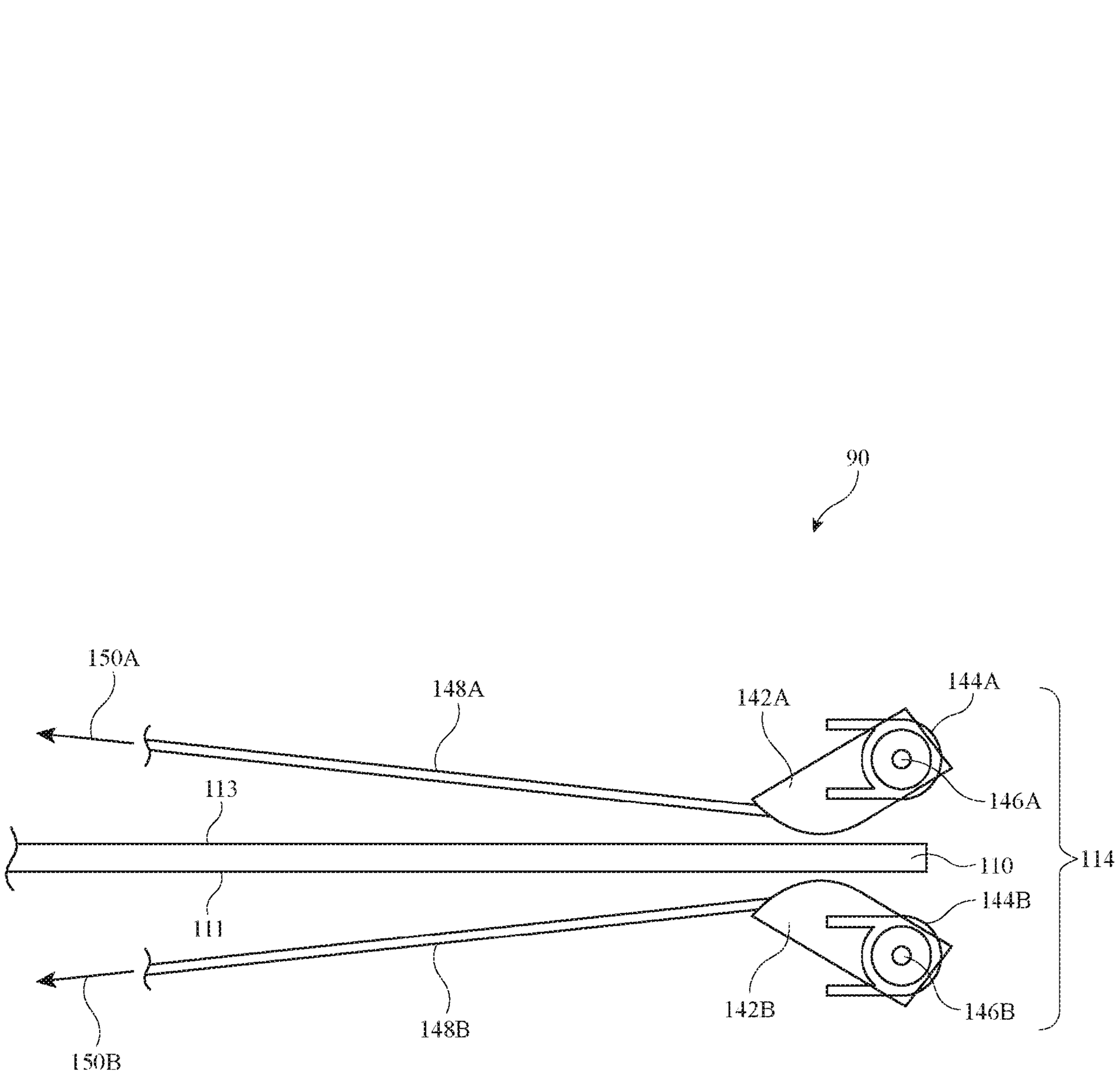

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142A
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146A
113
110
114
144B
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148B
150B

FIG. 10A

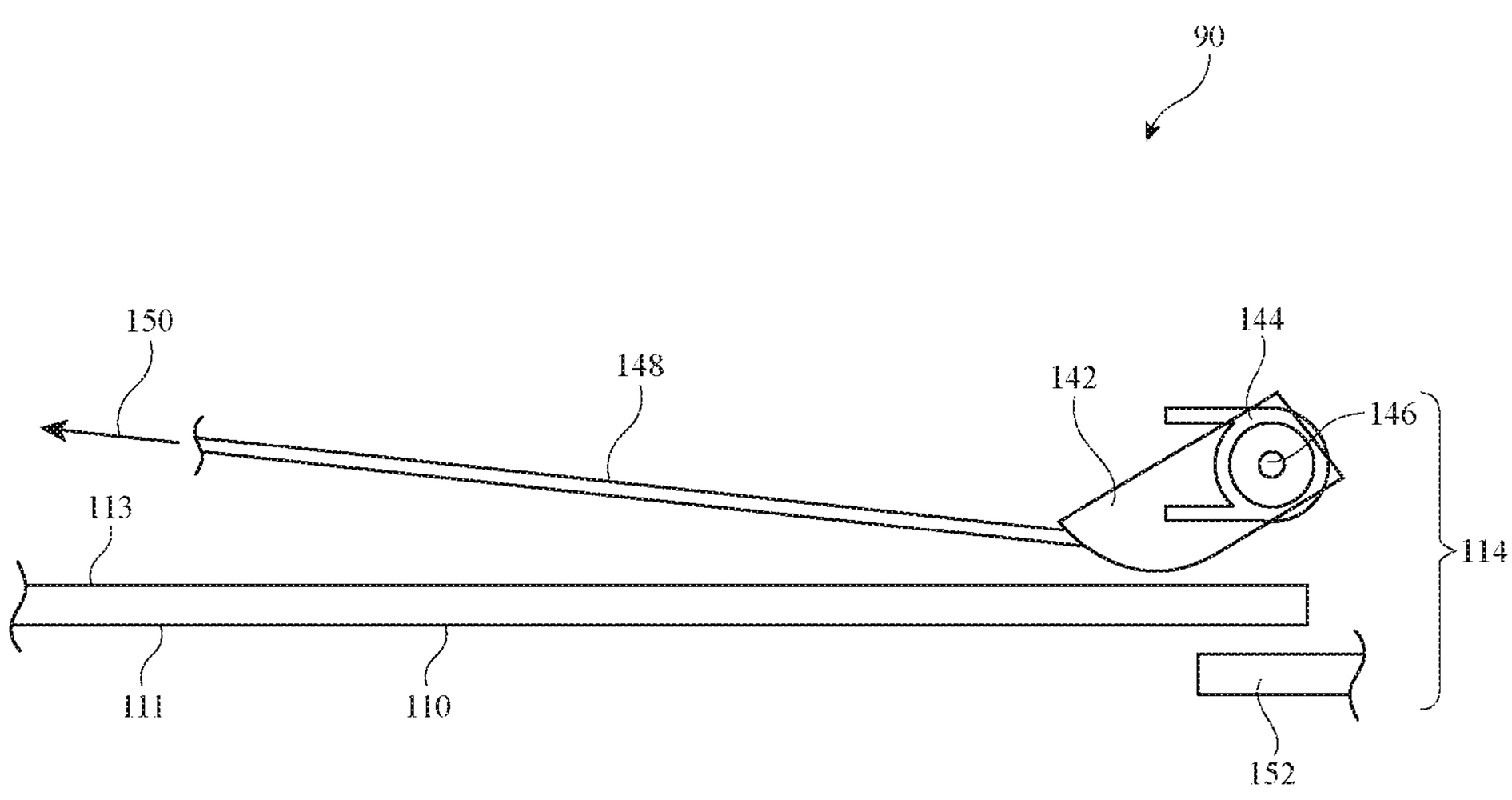


FIG. 10B

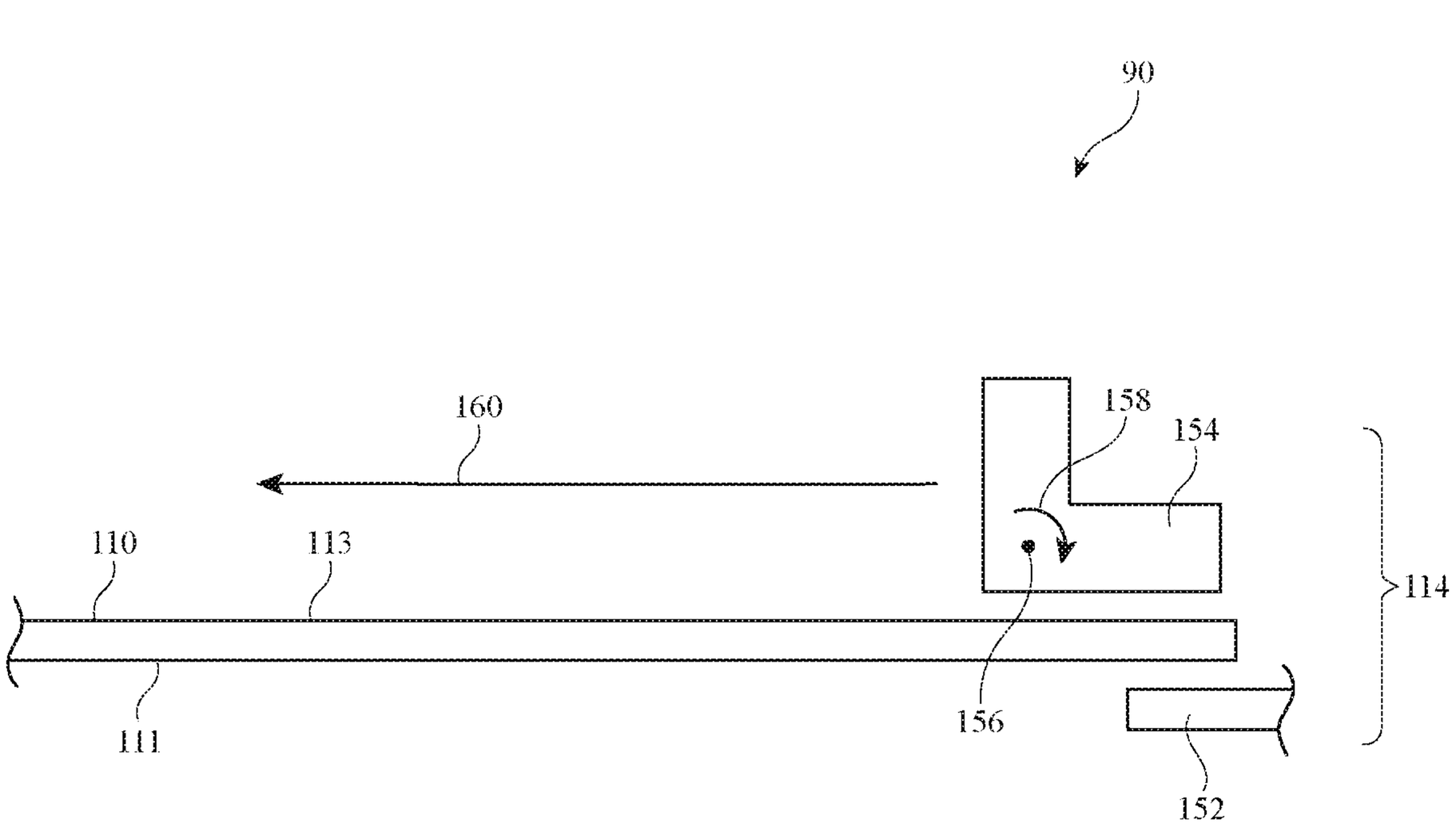


FIG. 10C

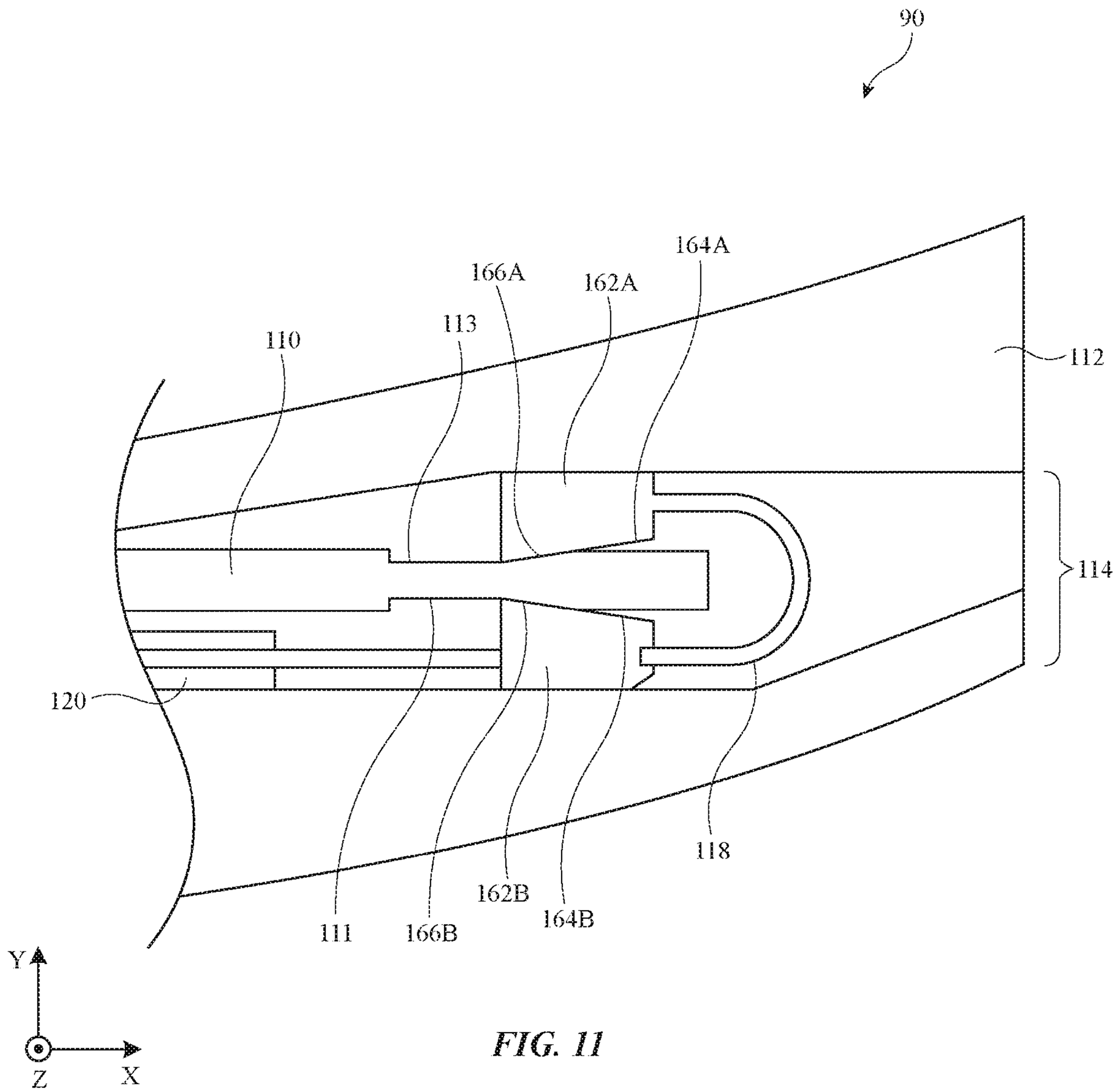

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164A
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162A
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114
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118
162B
164B
111
166B
Y
Z
X

FIG. 11

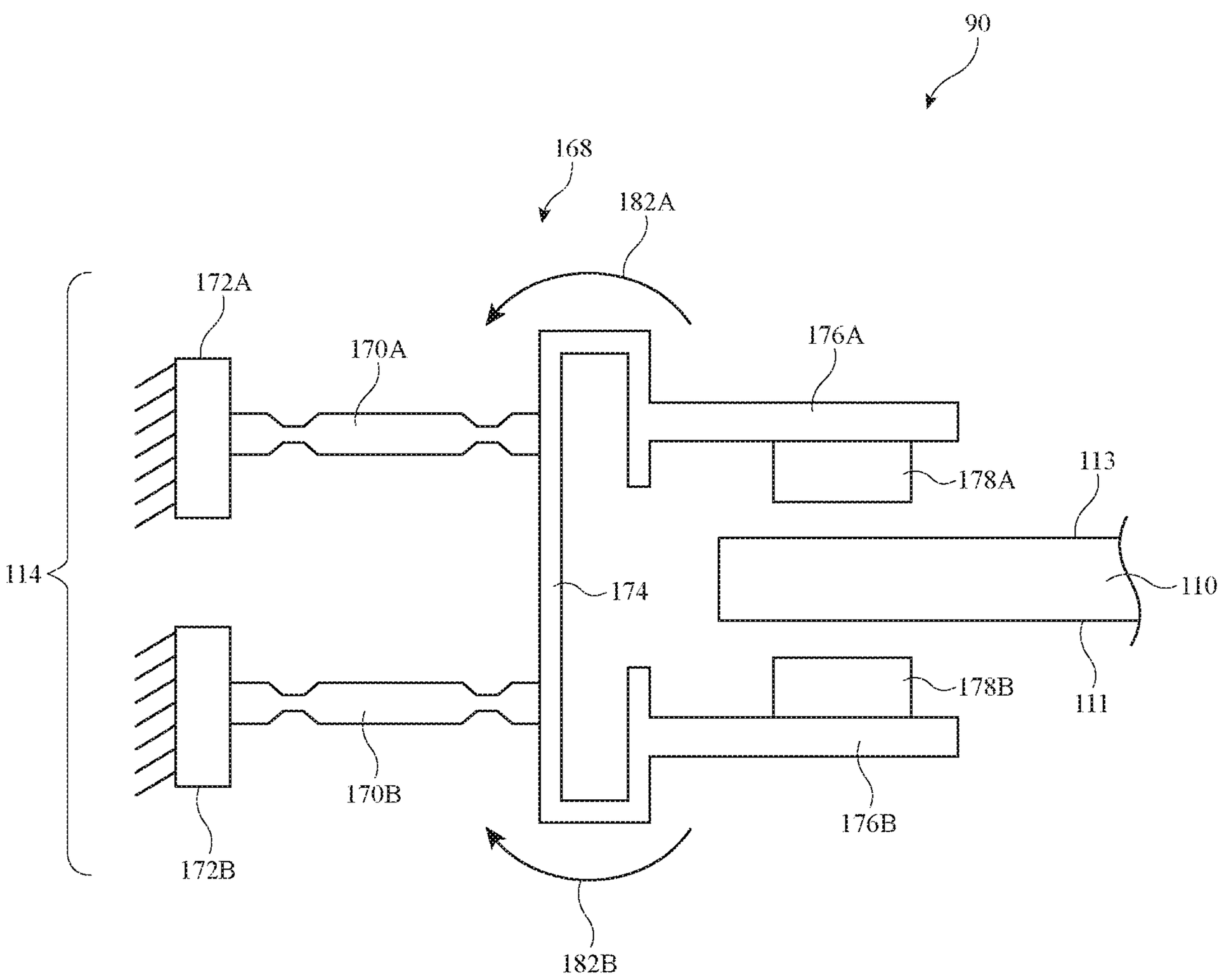

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172A
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176A
178A
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174
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178B
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170B
176B
172B
182B

FIG. 12A

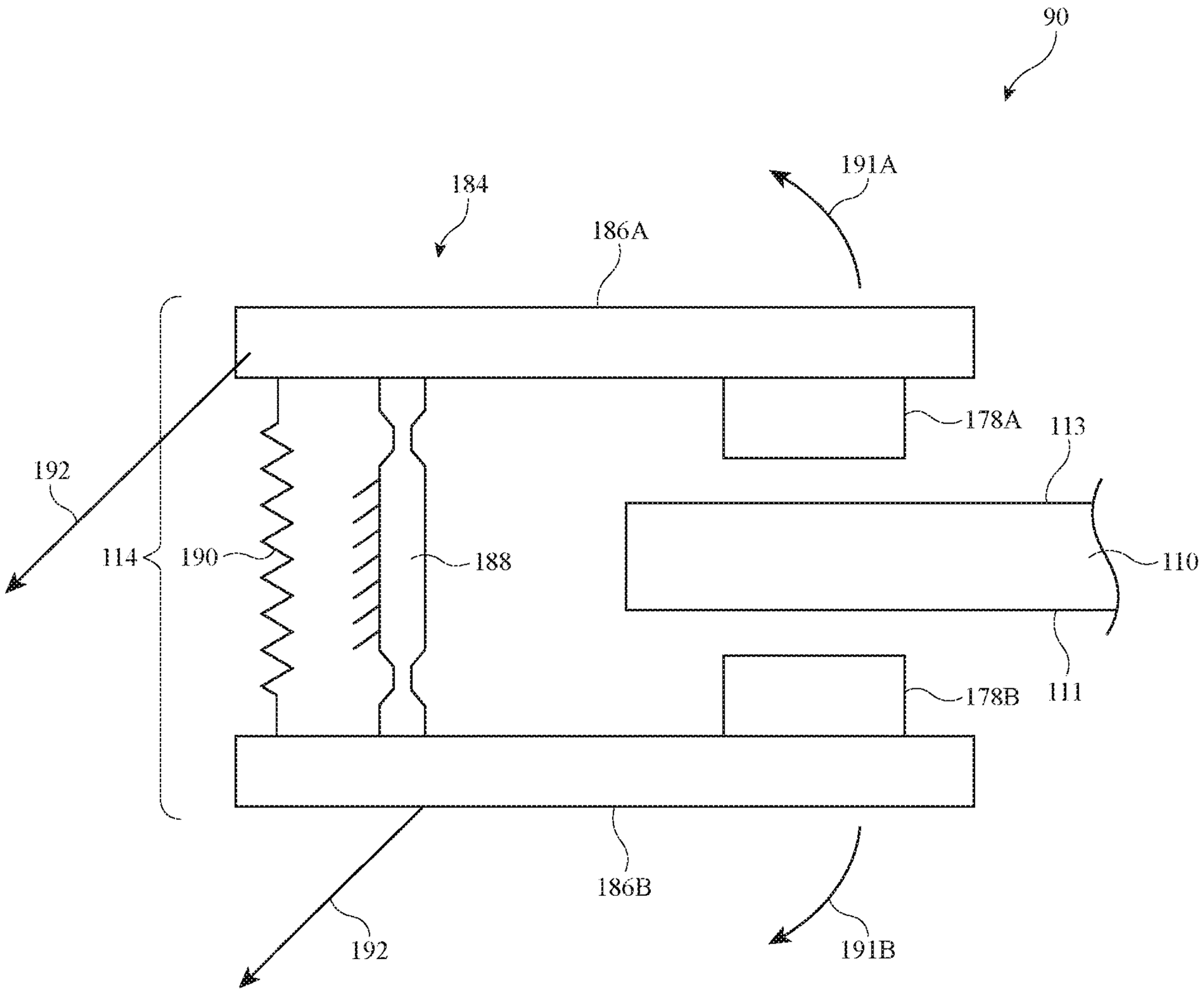

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191A
178A
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192
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188
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178B
186B
192
191B

FIG. 12B

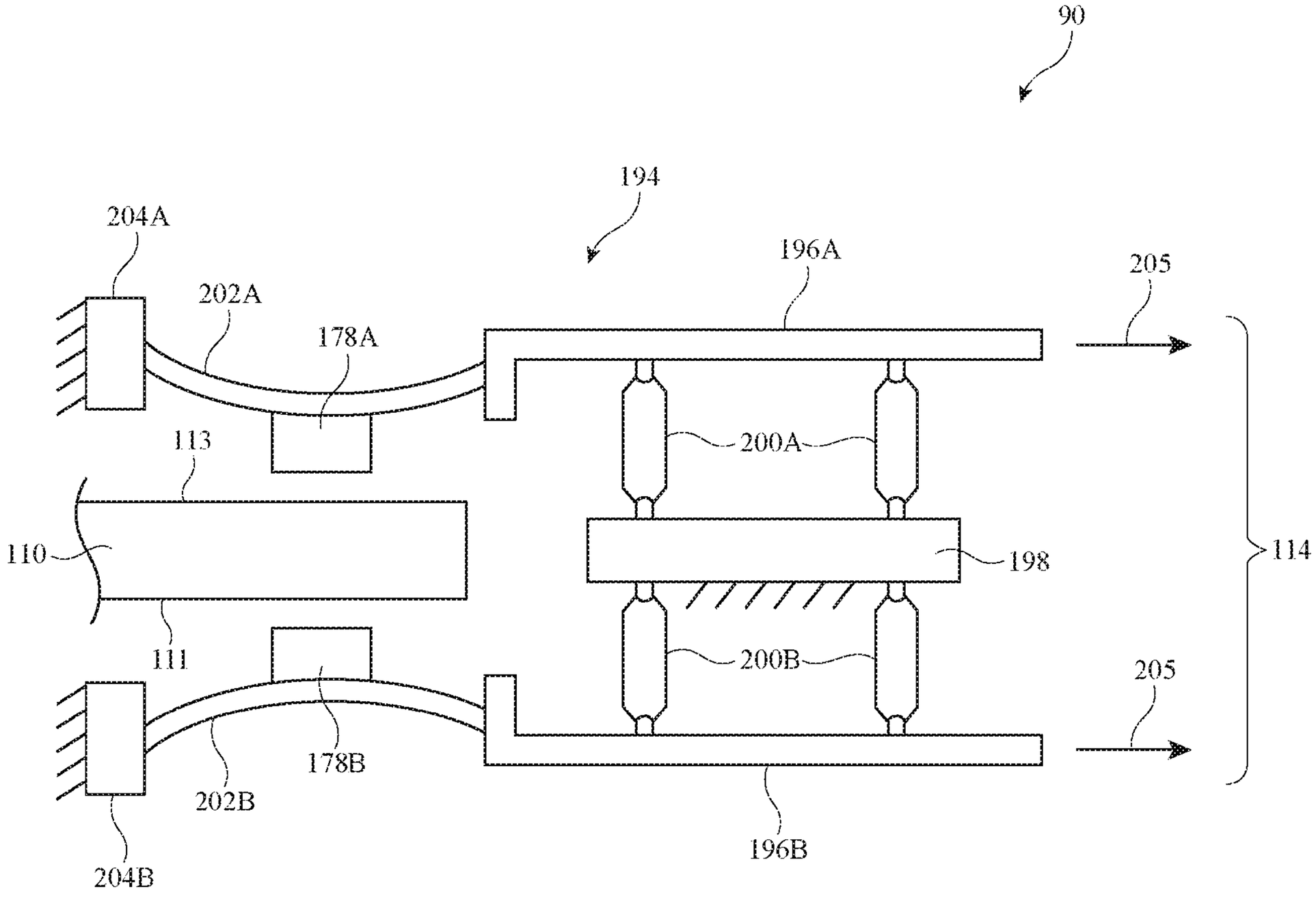

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204A
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178A
196A
205
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200A
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198
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200B
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178B
202B
196B
204B

FIG. 12C

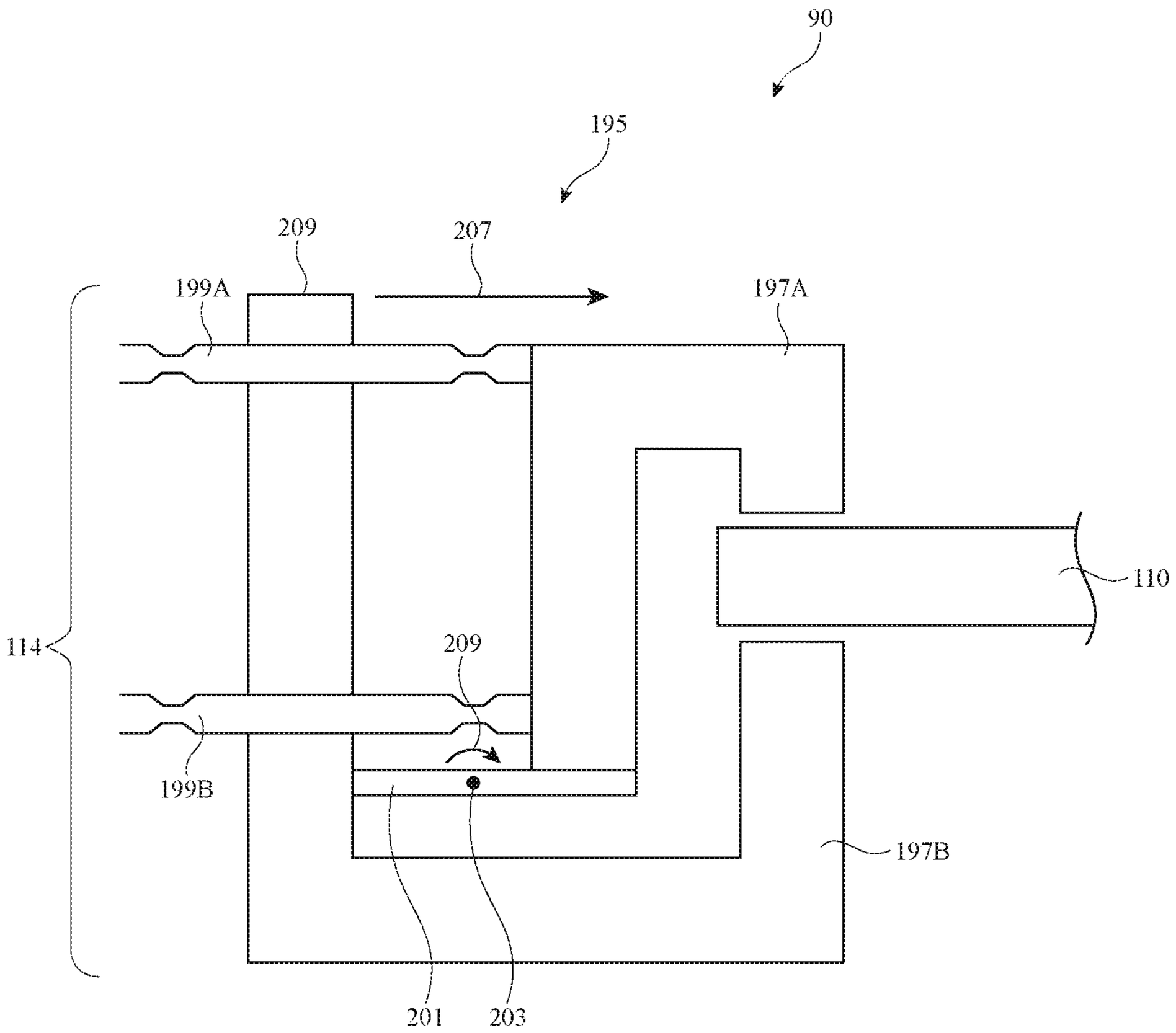


FIG. 12D

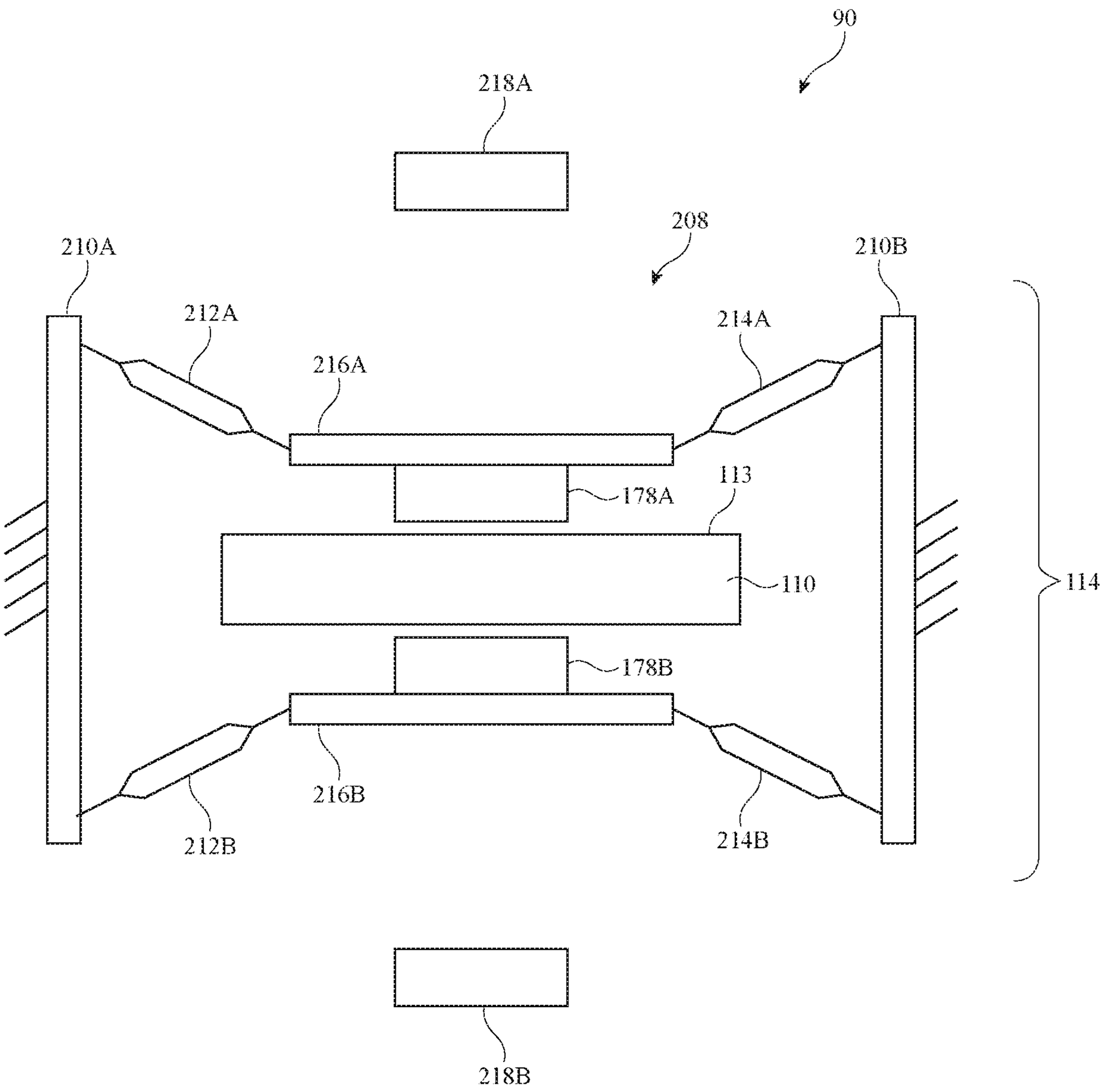

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218A
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210A
210B
212A
214A
216A
178A
113
110
114
178B
216B
212B
214B
218B

FIG. 13A

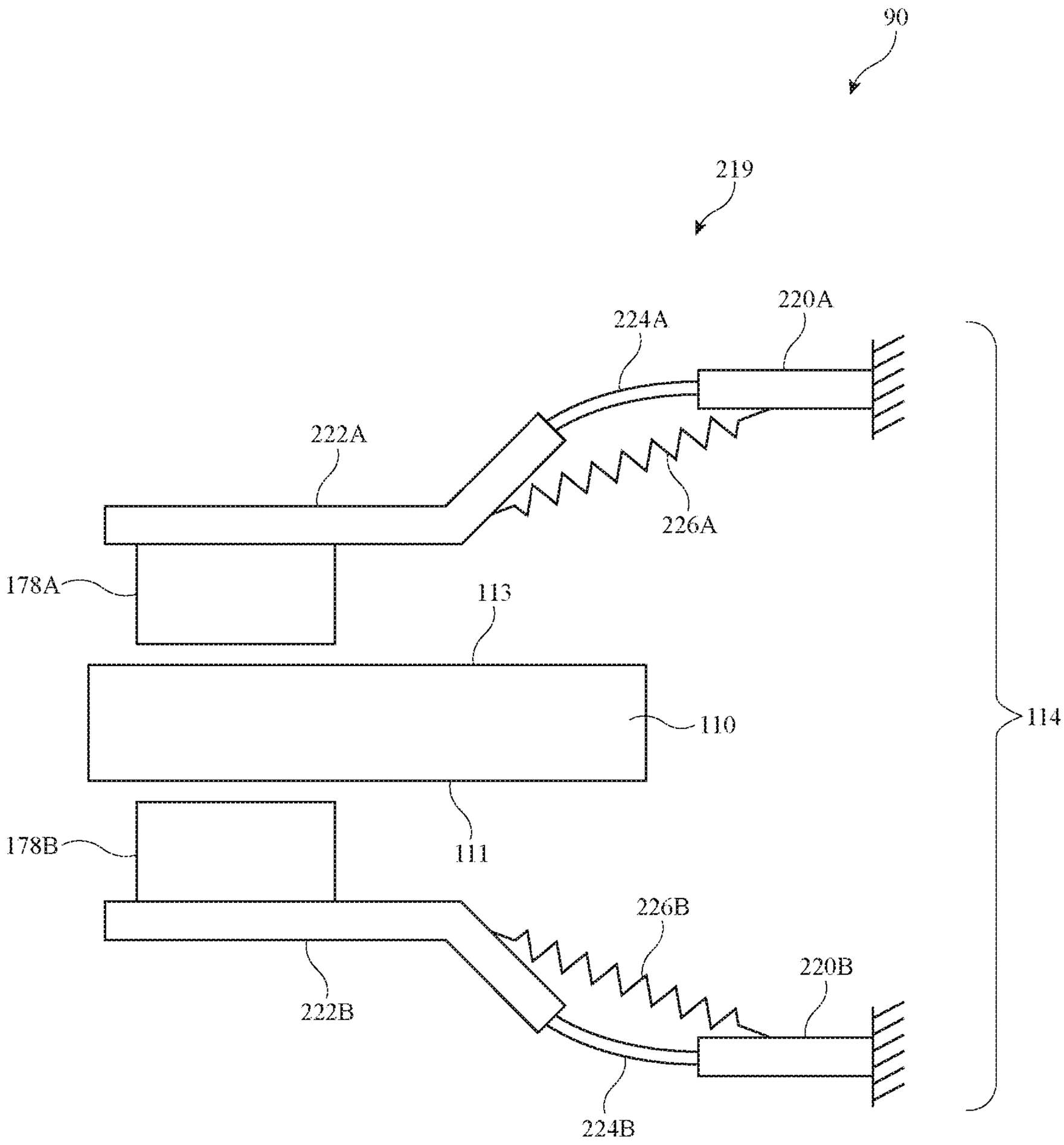

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219
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222A
226A
178A
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178B
226B
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222B
224B

FIG. 13B

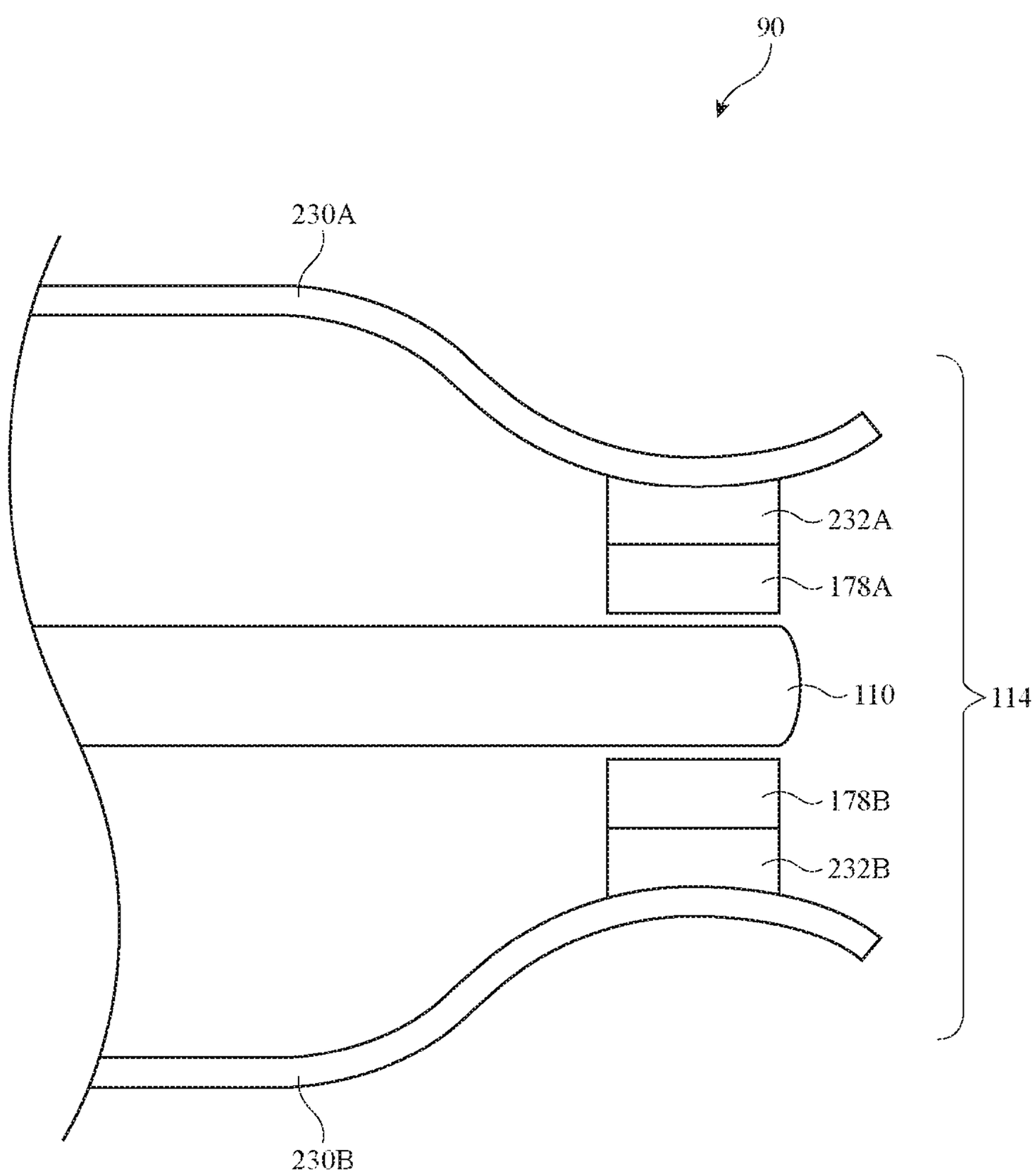


FIG. 14

TUNABLE LENS WITH ACTUATOR BRAKES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. provisional patent application No. 63/764,822, filed February 28, 2025, which is hereby incorporated by reference herein in its entirety.

BACKGROUND

[0002] This relates generally to electronic devices and, more particularly, to wearable electronic device systems.

[0003] Electronic devices are sometimes configured to be worn by users. For example, head-mounted devices are provided with head-mounted structures that allow the devices to be worn on users' heads. The head-mounted devices may include optical systems with lenses.

[0004] Head-mounted devices typically include lenses with fixed shapes and properties. If care is not taken, it may be difficult to adjust these types of lenses to optimally present content to each user of the head-mounted device.

SUMMARY

[0005] An actuator may include a main structure, an actuating component that is coupled to the main structure and is configured to selectively rotate the main structure about a pivot axis, and a brake assembly that is configured to selectively fix a position of the main structure. The brake assembly may include a brake that is configured to apply a force to the main structure in a direction parallel to the pivot axis.

[0006] An actuator may include a housing comprising first and second wedges, a main structure in the housing, the main structure including opposing first and second surfaces, an actuating component in the housing that is configured to selectively rotate the main structure about a pivot axis, and a brake assembly in the housing that is configured to selectively fix a position of the main structure. The brake assembly may include a first brake caliper that is configured to move along the first wedge of the housing to apply a first force to the first surface of the main structure in a first direction parallel to the pivot axis, a second brake caliper that is configured to move along the second wedge of the housing to apply a second force to the second surface of the main structure in a second direction parallel to the pivot axis, a spring that is configured to bias the first and second brake calipers toward the main structure to maintain the first and second forces on the main structure, and a spring actuation component configured to selectively engage the spring to move the first and second brake calipers along the first and second wedges and away from the main structure.

[0007] An actuator may include a housing, a structure in the housing, the structure including opposing first and second surfaces, an actuating component in the housing is configured to selectively rotate the structure about a pivot axis, and a brake assembly in the housing that is configured to selectively fix a position of the structure. The brake assembly includes a first brake pad that is configured to apply a first force to the first surface of the structure in a first direction parallel to the pivot axis, a second brake pad that is configured to apply a second force to the second surface of the structure in a second direction parallel to the pivot axis, a flexure to which the first and second brake pads are coupled, and a flexure actuation component that is configured to move at least a portion of the flexure to move the first and second brake pads away from the structure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] FIG. **1** is a schematic diagram of an illustrative electronic device in accordance with some embodiments.

[0009] FIG. **2** is a top view of an illustrative head-mounted device with a lens module in accordance with some embodiments.

[0010] FIG. **3** is a side view of an illustrative lens module in accordance with some embodiments.

[0011] FIGS. **4** and **5** are side views of an illustrative tunable lens in different tuning states in accordance with some embodiments.

[0012] FIG. **6** is a top view of an illustrative tunable lens with a lens shaping structure in accordance with some embodiments.

[0013] FIG. **7** is a side view of an illustrative actuator having a brake assembly with wedge-shaped brake calipers in accordance with some embodiments.

[0014] FIG. **8** is a side view of an illustrative actuator having a brake assembly with wedge-shaped brake calipers joined with a pivoting component in accordance with some embodiments.

[0015] FIG. **9** is a side view of an illustrative actuator having a brake assembly with a single wedge-shaped brake caliper in accordance with some embodiments.

[0016] FIG. **10**A is a side view of an illustrative actuator having a brake assembly with brake cams in accordance with some embodiments.

[0017] FIG. **10**B is a side view of an illustrative actuator having a brake assembly with a single brake cam in accordance with some embodiments.

[0018] FIG. **10**C is a side view of an illustrative actuator having a brake assembly with an L-shaped brake structure in accordance with some embodiments.

[0019] FIG. **11** is a side view of an illustrative actuator having a brake assembly with wedge-shaped brake calipers that engage wedges in a pivoting structure in accordance with some embodiments.

[0020] FIGS. **12**A-**12**D are side views of illustrative actuators having brake assemblies with flexures coupled to brake pads in accordance with some embodiments.

[0021] FIGS. **13**A and **13**B are side views of illustrative actuators having brake assemblies with bistable flexures coupled to brake pads in accordance with some embodiments.

[0022] FIG. **14** is a side view of an illustrative actuator having a brake assembly that includes flexure springs and piezoelectric members in accordance with some embodiments.

DETAILED DESCRIPTION

[0023] An electronic device, such as a head-mounted device, may include a tunable lens. The tunable lens may have adjustable optical properties. For example, actuators may move a periphery of the tunable lens to adjust the optical properties. In some embodiments, the actuators may include structures that are coupled to the tunable lens and that rotate about pivot axes.

[0024] When the tunable lens is not being adjusted, it may be desirable to fix the location of the actuators and therefore the periphery of the tunable lens to avoid adjustments to the tunable lens. Therefore, the actuators may include brake assemblies that include brakes, such as brake calipers, to prevent rotation of the structures. The brakes may apply a force to the structures in directions parallel to the pivot axes. In this way, the brake assemblies may prevent the rotation of the structures, and therefore the adjustment of the tunable lens, without applying undue stress to the structures.

[0025] A schematic diagram of an illustrative electronic device that may include tunable lenses is shown in FIG. **1**. As shown in FIG. **1**, electronic device **10** (sometimes referred to as head-mounted device **10**, system **10**, head-mounted display **10**, etc.) may have control circuitry **14**. In addition to being a head-mounted device, electronic device **10** may be other types of electronic devices such as a cellular telephone, laptop computer, speaker, computer monitor, electronic watch, tablet computer, etc. Control circuitry **14** may be configured to perform operations in head-mounted device **10** using hardware (e.g., dedicated hardware or circuitry), firmware and/or software. Software code for performing operations in head-mounted device **10** and other data is stored on non-transitory computer readable storage media (e.g., tangible computer readable storage media) in control circuitry **14**. The software code may sometimes be referred to as software, data, program instructions, instructions, or code. The non-transitory computer readable storage media (sometimes referred to generally as memory) may include non-volatile memory such as non-volatile random-access memory (NVRAM), one or more hard drives (e.g., magnetic drives or solid-state drives), one or more removable flash drives or other removable media, or the like. Software stored on the non-transitory computer readable storage media may be executed on the processing circuitry of control circuitry **14**. The processing circuitry may include application-specific integrated circuits with processing circuitry, one or more microprocessors, digital signal processors, graphics processing units, a central processing unit (CPU) or other processing circuitry.

[0026] Head-mounted device **10** may include input-output circuitry **16**. Input-output circuitry **16** may be used to allow a user to provide head-mounted device **10** with user input. Input-output circuitry **16** may also be used to gather information on the environment in which head-mounted device **10** is operating. Output components in circuitry **16** may allow head-mounted device **10** to provide a user with output.

[0027] As shown in FIG. **1**, input-output circuitry **16** may include a display such as display **18**. Display **18** may be used to display images for a user of head-mounted device **10**. Display **18** may be a transparent or translucent display so that a user may observe physical objects through the display while computer-generated content is overlaid on top of the physical objects by presenting computer-generated images on the display. A transparent or translucent display may be formed from a transparent or translucent pixel array (e.g., a transparent organic light-emitting diode display panel) or may be formed by a display device that provides images to a user through a transparent structure such as a beam splitter, holographic coupler, or other optical coupler (e.g., a display device such as a liquid crystal on silicon display). Alternatively, display **18** may be an opaque display that blocks light from physical objects when a user operates head-mounted device **10**. In this type of arrangement, a pass-through camera may be used to display physical objects to the user. The pass-through camera may capture images of the physical environment and the physical environment images may be displayed on the display for viewing by the user. Additional computer-generated content (e.g., text, game-content, other visual content, etc.) may optionally be overlaid over the physical environment images to provide an extended reality environment for the user. When display **18** is opaque, the display may also optionally display entirely computer-generated content (e.g., without displaying images of the physical environment).

[0028] Display **18** may include one or more optical systems (e.g., lenses) (sometimes referred to as optical assemblies) that allow a viewer to view images on display(s) **18**. A single display **18** may produce images for both eyes, or a pair of displays **18** may be used to display images. In configurations with multiple displays (e.g., left and right eye displays), the focal length and positions of the lenses may be selected so that any gap present between the displays will not be visible to a user (e.g., so that the images of the left and right displays overlap or merge seamlessly). Display modules (sometimes referred to as display assemblies) that generate different images for the left and right eyes of the user may be referred to as stereoscopic displays. The stereoscopic displays may be capable of presenting two-dimensional content (e.g., a user notification with text) and three-dimensional content (e.g., a simulation of a physical object such as a cube).

[0029] The example of device **10** including a display is merely illustrative and display(s) **18** may be omitted from device **10** if desired. Device **10** may include an optical pass-through area where real-world content is viewable to the user either directly or through a tunable lens.

[0030] Input-output circuitry **16** may include various other input-output devices. For example, input-output circuitry **16** may include one or more speakers **20** that are configured to play audio and one or more microphones **26** that are configured to capture audio data from the user and/or from the physical environment around the user.

[0031] Input-output circuitry **16** may also include one or more cameras such as an inward-facing camera **22** (e.g., that face the user's face when the head-mounted device is

mounted on the user's head) and an outward-facing camera **24** (that face the physical environment around the user when the head-mounted device is mounted on the user's head). Cameras **22** and **24** may capture visible light images, infrared images, or images of any other desired type. The cameras may be stereo cameras if desired. Inward-facing camera **22** may capture images that are used for gaze-detection operations, in one possible arrangement. Outward-facing camera **24** may capture pass-through video for head-mounted device **10**.

[0032] As shown in FIG. **1**, input-output circuitry **16** may include position and motion sensors **28** (e.g., compasses, gyroscopes, accelerometers, and/or other devices for monitoring the location, orientation, and movement of head-mounted device **10**, satellite navigation system circuitry such as Global Positioning System circuitry for monitoring user location, etc.). Using sensors **28**, for example, control circuitry **14** can monitor the current direction in which a user's head is oriented relative to the surrounding environment (e.g., a user's head pose). One or more of cameras **22** and **24** may also be considered part of position and motion sensors **28**. The cameras may be used for face tracking (e.g., by capturing images of the user's jaw, mouth, etc. while the device is worn on the head of the user), body tracking (e.g., by capturing images of the user's torso, arms, hands, legs, etc. while the device is worn on the head of user), and/or for localization (e.g., using visual odometry, visual inertial odometry, or other simultaneous localization and mapping (SLAM) technique).

[0033] Input-output circuitry **16** may also include other sensors and input-output components if desired. As shown in FIG. **1**, input-output circuitry **16** may include an ambient light sensor **30**. The ambient light sensor may be used to measure ambient light levels around head-mounted device **10**. The ambient light sensor may measure light at one or more wavelengths (e.g., different colors of visible light and/or infrared light).

[0034] Input-output circuitry **16** may include a magnetometer **32**. The magnetometer may be used to measure the strength and/or direction of magnetic fields around head-mounted device **10**.

[0035] Input-output circuitry **16** may include a heart rate monitor **34**. The heart rate monitor may be used to measure the heart rate of a user wearing head-mounted device **10** using any desired techniques.

[0036] Input-output circuitry **16** may include a depth sensor **36**. The depth sensor may be a pixelated depth sensor (e.g., that is configured to measure multiple depths across the physical environment) or a point sensor (that is configured to measure a single depth in the physical environment). The depth sensor (whether a pixelated depth sensor or a point sensor) may use phase detection (e.g., phase detection autofocus pixel(s)) or light detection and ranging (LIDAR) to measure depth. Any combination of depth sensors may be used to determine the depth of physical objects in the physical environment.

[0037] Input-output circuitry **16** may include a temperature sensor **38**. The temperature sensor may be used to measure the temperature of a user of head-mounted device **10**, the temperature of head-mounted device **10** itself, or an ambient temperature of the physical environment around head-mounted device **10**.

[0038] Input-output circuitry **16** may include a touch sensor **40**. The touch sensor may be, for example, a capacitive touch sensor that is configured to detect touch from a user of the head-mounted device.

[0039] Input-output circuitry **16** may include a moisture sensor **42**. The moisture sensor may be used to detect the presence of moisture (e.g., water) on, in, or around the head-mounted device.

[0040] Input-output circuitry **16** may include a gas sensor **44**. The gas sensor may be used to detect the presence of one or more gases (e.g., smoke, carbon monoxide, etc.) in or around the head-mounted device.

[0041] Input-output circuitry **16** may include a barometer **46**. The barometer may be used to measure atmospheric pressure, which may be used to determine the elevation above sea level of the head-mounted device.

[0042] Input-output circuitry **16** may include a gaze-tracking sensor **48** (sometimes referred to as gaze-tracker **48** and gaze-tracking system **48**). The gaze-tracking sensor **48** may include a camera (e.g., inward-facing camera **22**) and/or other gaze-tracking sensor components (e.g., light sources that emit beams of light so that reflections of the beams from a user's eyes may be detected) to monitor the user's eyes. Gaze-tracker **48** may face a user's eyes and may track a user's gaze. A camera in the gaze-tracking system may determine the location of a user's eyes (e.g., the centers of the user's pupils), may determine the direction in which the user's eyes are oriented (the direction of the user's gaze), may determine the user's pupil size (e.g., so that light modulation and/or other optical parameters and/or the amount of gradualness with which one or more of these parameters is spatially adjusted and/or the area in which one or more of these optical parameters is adjusted is adjusted based on the pupil size), may be used in monitoring the current focus of the lenses in the user's eyes (e.g., whether the user is focusing in the near field or far field, which may be used to assess whether a user is day dreaming or is thinking strategically or tactically), and/or other gaze information. Cameras in the gaze-tracking system may sometimes be referred to as inward-facing cameras, gaze-detection cameras, eye-tracking cameras, gaze-tracking cameras, or eye-monitoring cameras. If desired, other types of image sensors (e.g., infrared and/or visible light-emitting diodes and light detectors, etc.) may also be used in monitoring a user's gaze. The use of a gaze-detection camera in gaze-tracker **48** is merely illustrative.

[0043] Input-output circuitry **16** may include a button **50**. The button may include a mechanical switch that detects a user press during operation of the head-mounted device.

[0044] Input-output circuitry **16** may include a light-based proximity sensor **52**. The light-based proximity sensor may include a light source (e.g., an infrared light source) and an image sensor (e.g., an infrared image sensor) configured to detect reflections of the emitted light to determine proximity to nearby objects.

[0045] Input-output circuitry **16** may include a global positioning system (GPS) sensor **54**. The GPS sensor may determine location information for the head-mounted

device. The GPS sensor may include one or more antennas used to receive GPS signals. The GPS sensor may be considered a part of position and motion sensors **28**.

[0046] Input-output circuitry **16** may include any other desired components (e.g., capacitive proximity sensors, other proximity sensors, strain gauges, pressure sensors, audio components, haptic output devices such as vibration motors, light-emitting diodes, other light sources, etc.).

[0047] Head-mounted device **10** may also include communication circuitry **56** to allow the head-mounted device to communicate with external equipment (e.g., a tethered computer, a portable device such as a handheld device or laptop computer, one or more external servers, or other electrical equipment). Communication circuitry 56 may be used for both wired and wireless communication with external equipment.

[0048] Communication circuitry **56** may include radio-frequency (RF) transceiver circuitry formed from one or more integrated circuits, power amplifier circuitry, low-noise input amplifiers, passive RF components, one or more antennas, transmission lines, and other circuitry for handling RF wireless signals. Wireless signals can also be sent using light (e.g., using infrared communications).

[0049] The radio-frequency transceiver circuitry in wireless communications circuitry **56** may handle wireless local area network (WLAN) communications bands such as the 2.4 GHz and 5 GHz Wi-Fi® (IEEE 802.11) bands, wireless personal area network (WPAN) communications bands such as the 2.4 GHz Bluetooth® communications band, cellular telephone communications bands such as a cellular low band (LB) (e.g., 600 to 960 MHz), a cellular low-mid-band (LMB) (e.g., 1400 to 1550 MHz), a cellular midband (MB) (e.g., from 1700 to 2200 MHz), a cellular high band (HB) (e.g., from 2300 to 2700 MHz), a cellular ultra-high band (UHB) (e.g., from 3300 to 5000 MHz, or other cellular communications bands between about 600 MHz and about 5000 MHz (e.g., 3G bands, 4G LTE bands, 5G New Radio Frequency Range **1** (FR1) bands below 10 GHz, etc.), a near-field communications (NFC) band (e.g., at 13.56 MHz), satellite navigations bands (e.g., an L**1** global positioning system (GPS) band at 1575 MHz, an L**5** GPS band at 1176 MHz, a Global Navigation Satellite System (GLONASS) band, a BeiDou Navigation Satellite System (BDS) band, etc.), ultra-wideband (UWB) communications band(s) supported by the IEEE 802.15.4 protocol and/or other UWB communications protocols (e.g., a first UWB communications band at 6.5 GHz and/or a second UWB communications band at 8.0 GHz), and/or any other desired communications bands.

[0050] The radio-frequency transceiver circuitry may include millimeter/centimeter wave transceiver circuitry that supports communications at frequencies between about 10 GHz and 300 GHz. For example, the millimeter/centimeter wave transceiver circuitry may support communications in Extremely High Frequency (EHF) or millimeter wave communications bands between about 30 GHz and 300 GHz and/or in centimeter wave communications bands between about 10 GHz and 30 GHz (sometimes referred to as Super High Frequency (SHF) bands). As examples, the millimeter/centimeter wave transceiver circuitry may support communications in an IEEE K communications band between about 18 GHz and 27 GHz, a K_a communications band between about 26.5 GHz and 40 GHz, a K_u communications band between about 12 GHz and 18 GHz, a V communications band between about 40 GHz and 75 GHz, a W communications band between about 75 GHz and 110 GHz, or any other desired frequency band between approximately 10 GHz and 300 GHz. If desired, the millimeter/centimeter wave transceiver circuitry may support IEEE 802.11ad communications at 60 GHz (e.g., WiGig or 60 GHz Wi-Fi bands around 57-61 GHz), and/or 5^{th} generation mobile networks or 5^{th} generation wireless systems (**5**G) New Radio (NR) Frequency Range 2 (FR2) communications bands between about 24 GHz and 90 GHz.

[0051] Antennas in wireless communications circuitry **56** may include antennas with resonating elements that are formed from loop antenna structures, patch antenna structures, inverted-F antenna structures, slot antenna structures, planar inverted-F antenna structures, helical antenna structures, dipole antenna structures, monopole antenna structures, hybrids of these designs, etc. Different types of antennas may be used for different bands and combinations of bands. For example, one type of antenna may be used in forming a local wireless link and another type of antenna may be used in forming a remote wireless link antenna.

[0052] During operation, head-mounted device **10** may use communication circuitry **56** to communicate with external equipment **60**. External equipment **60** may include one or more external servers, an electronic device that is paired with head-mounted device **10** (such as a cellular telephone, a laptop computer, a speaker, a computer monitor, an electronic watch, a tablet computer, earbuds, etc.), a vehicle, an internet of things (IoT) device (e.g., remote control, light switch, doorbell, lock, smoke alarm, light, thermostat, oven, refrigerator, stove, grill, coffee maker, toaster, microwave, etc.), etc.

[0053] Electronic device **10** may have housing structures (e.g., housing walls, straps, etc.), as shown by illustrative support structures **62** of FIG. **1**. In configurations in which electronic device **10** is a head-mounted device (e.g., a pair of glasses, goggles, a helmet, a hat, etc.), support structures **62** may include head-mounted support structures (e.g., a helmet housing, head straps, temples in a pair of eyeglasses, goggle housing structures, and/or other head-mounted structures). The head-mounted support structures may be configured to be worn on a head of a user during operation of device **10** and may support control circuitry **14**, input-output circuitry **16**, and/or communication circuitry **56**.

[0054] FIG. **2** is a top view of electronic device **10** in an illustrative configuration in which electronic device **10** is a head-mounted device. As shown in FIG. **2**, electronic device **10** may include support structures (see, e.g., support structures **62** of FIG. **1**) that are used in housing the components of device **10** and mounting device **10** onto a user's head. These support structures may include, for example, structures that form housing walls and other structures for main unit **62-2** (e.g., exterior housing walls, lens module structures, etc.) and eyeglass temples or other supplemental support structures such as structures **62-1** that help to hold

main unit **62-2** on a user's face.

[0055] The electronic device may include optical modules such as optical module **70**. The electronic device may include left and right optical modules that correspond respectively to a user's left eye and right eye. An optical module corresponding to the user's left eye is shown in FIG. **2**.

[0056] Each optical module **70** includes a corresponding lens module **72** (sometimes referred to as lens stack-up **72**, lens **72**, or adjustable lens **72**). Lens **72** may include one or more lens elements arranged along a common axis. Each lens element may have any desired shape and may be formed from any desired material (e.g., with any desired refractive index). The lens elements may have unique shapes and refractive indices that, in combination, focus light (e.g., from a display and/or from the physical environment) in a desired manner. Each lens element of lens module **72** may be formed from any desired material (e.g., glass, a polymer material such as polycarbonate or acrylic, a crystal such as sapphire, etc.).

[0057] Modules **70** may optionally be individually positioned relative to the user's eyes and relative to some of the housing wall structures of main unit **26-2** using positioning circuitry such as positioner **58**. Positioner **58** may include stepper motors, piezoelectric actuators, motors, linear electromagnetic actuators, shape memory alloys (SMAs), and/or other electronic components for adjusting the position of displays, the optical modules **70**, and/or lens modules **72**. Positioners **58** may be controlled by control circuitry **14** (FIG. **1**) during operation of device **10**. For example, positioners **58** may be used to adjust the spacing between modules **70** (and therefore the lens-to-lens spacing between the left and right lenses of modules **70**) to match the interpupillary distance IPD of a user's eyes. In another example, the lens module may include an adjustable lens element (also referred to as a tunable lens element herein). The curvature of the adjustable lens element may be adjusted in real time by positioner(s) **58** to compensate for a user's eyesight and/or viewing conditions.

[0058] Each optical module may optionally include a display such as display **18** in FIG. **2**. As previously mentioned, the displays may be omitted from device **10** if desired. In this type of arrangement, the device may still include one or more lens modules **72** (e.g., through which the user views the real world). In this type of arrangement, real-world content may be selectively focused for a user.

[0059] FIG. **3** is a cross-sectional side view of an illustrative lens module with multiple lens elements. As shown, lens module **72** includes a first lens element **72-1** and a second lens element **72-2**. Each surface of the lens elements may have any desired curvature. For example, each surface may be a convex surface (e.g., a spherically convex surface, a cylindrically convex surface, or an aspherically convex surface), a concave surface (e.g., a spherically concave surface, a cylindrically concave surface, or an aspherically concave surface), a combination of convex and concave surfaces, or a freeform surface. A spherically curved surface (e.g., a spherically convex or spherically concave surface) may have a constant radius of curvature across the surface. In contrast, an aspherically curved surface (e.g., an aspheric concave surface or an aspheric convex surface) may have a varying radius of curvature across the surface. A cylindrical surface may only be curved about one axis instead of about multiple axes as with the spherical surface. In some cases, one of the lens surfaces may have an aspheric surface that changes from being convex (e.g., at the center) to concave (e.g., at the edges) at different positions on the surface. This type of surface may be referred to as an aspheric surface, a primarily convex (e.g., the majority of the surface is convex and/or the surface is convex at its center) aspheric surface, a freeform surface, and/or a primarily convex (e.g., the majority of the surface is convex and/or the surface is convex at its center) freeform surface. A freeform surface may include both convex and concave portions and/or curvatures defined by polynomial series and expansions. Alternatively, a freeform surface may have varying convex curvatures or varying concave curvatures (e.g., different portions with different radii of curvature, portions with curvature in one direction and different portions with curvature in two directions, etc.). Herein, a freeform surface that is primarily convex (e.g., the majority of the surface is convex and/or the surface is convex at its center) may sometimes still be referred to as a convex surface and a freeform surface that is primarily concave (e.g., the majority of the surface is concave and/or the surface is concave at its center) may sometimes still be referred to as a concave surface. In one example, shown in FIG. **3**, lens element **72-1** has a convex surface that faces display **18** and an opposing concave surface. Lens element **72-2** has a convex surface that faces lens element **72-1** and an opposing concave surface.

[0060] One or both of lens elements **72-1** and **72-2** may be adjustable (also referred to as tunable herein). In one example, lens element **72-1** is a non-adjustable lens element whereas lens element **72-2** is an adjustable lens element. The adjustable lens element **72**-2 may be used to accommodate a user's eyeglass prescription, for example. The shape of lens element **72-2** may be adjusted if a user's eyeglass prescription changes (without needing to replace any of the other components within device **10**). As another possible use case, a first user with a first eyeglass prescription (or no eyeglass prescription) may use device **10** with lens element **72-2** having a first shape and a second, different user with a second eyeglass prescription may use device **10** with lens element **72-2** having a second shape that is different than the first shape. Lens element **72-2** may have varying lens power and/or may provide varying amounts and orientations of astigmatism correction to provide prescription correction for the user.

[0061] The example of lens module **72** including two lens elements is merely illustrative. In general, lens module **72** may include any desired number of lens elements (e.g., one, two, three, four, more than four, etc.). Any subset or all of the lens elements may optionally be adjustable. Any of the adjustable lens elements in the lens module may optionally be fluid-filled adjustable lenses. Lens module **72** may also include any desired additional optical layers (e.g., partially reflective mirrors that reflect 50% of incident light, linear polarizers, retarders such as quarter wave plates, reflective polarizers, circular polarizers, reflective

circular polarizers, etc.) to manipulate light that passes through lens module.

[0062] In one possible arrangement, lens element **72-1** may be a removable lens element. In other words, a user may be able to easily remove and replace lens element **72-1** within optical module **70**. This may allow lens element **72-1** to be customizable. If lens element **72-1** is permanently affixed to the lens assembly, the lens power provided by lens element **72-1** cannot be easily changed. However, by making lens element **72-1** customizable, a user may select a lens element **72-1** that best suits their eyes and place the appropriate lens element **72-1** in the lens assembly. The lens element **72-1** may be used to accommodate a user's eyeglass prescription, for example. A user may replace lens element **72-1** with an updated lens element if their eyeglass prescription changes (without needing to replace any of the other components within electronic device **10**). Lens element **72-1** may have varying lens power and/or may provide varying amount of astigmatism correction to provide prescription correction for the user. Lens element **72-1** may include one or more attachment structures that are configured to attach to corresponding attachment structures included in optical module **70**, lens element **72-2**, support structures **62**, or another structure in electronic device **10**.

[0063] In contrast with lens element **72-1**, lens element **72-2** may not be a removable lens element. Lens element **72-2** may therefore sometimes be referred to as a permanent lens element, non-removable lens element, etc. The example of lens element **72-2** being a non-removable lens element is merely illustrative. In another possible arrangement, lens element **72-2** may also be a removable lens element (similar to lens element **72-1**).

[0064] As previously mentioned, one or more of the adjustable lens elements may be a fluid-filled lens element. An example is described herein where lens element **72-2** from FIG. **3** is a fluid-filled lens element. When lens element **72-2** is a fluid-filled lens element, the lens element may include one or more components that define the surfaces of lens element **72-2**. These components may also be referred to as lens elements. In other words, adjustable lens element **72-2** (sometimes referred to as adjustable lens module **72-2**, adjustable lens **72-2**, tunable lens **72-2**, etc.) may be formed by multiple respective lens elements.

[0065] FIG. **4** is a cross-sectional side view of illustrative adjustable fluid-filled lens element **72-2**. As shown, fluid-filled chamber **82** (sometimes referred to as chamber **82**, fluid chamber **82**, primary chamber **82**, etc.) that includes fluid 92 is interposed between lens elements **84** and **86**. Lens elements **84** and **86** may sometimes be referred to as part of chamber **82** or may sometimes be referred to as separate from chamber **82**. Fluid **92** may be a liquid, gel, or gas with a pre-determined index of refraction (and may therefore sometimes be referred to as liquid **92**, gel **92**, or gas **92**). The fluid may sometimes be referred to as an index-matching oil, an optical oil, an optical fluid, an index-matching material, an index-matching liquid, etc. Lens elements **84** and **86** may have the same index of refraction or may have different indices of refraction. Fluid **92** that fills chamber **82** between lens elements **84** and **86** may have an index of refraction that is the same as the index of refraction of lens element **84** but different from the index of refraction of lens element **86**, may have an index of refraction that is the same as the index of refraction of lens element **86** but different from the index of refraction of lens element **84**, may have an index of refraction that is the same as the index of refraction of lens element **84** and lens element **86**, or may have an index of refraction that is different from the index of refraction of lens element **84** and lens element **86**. Lens elements **84** and **86** may have a circular footprint, may have an elliptical footprint, or may have a footprint any another desired shape (e.g., an irregular footprint).

[0066] The amount of fluid **92** in chamber **82** may have a constant volume or an adjustable volume. If the amount of fluid is adjustable, the lens module may also include a fluid reservoir and a fluid controlling component (e.g., a pump, stepper motor, piezoelectric actuator, shape memory alloy (SMA), motor, linear electromagnetic actuator, and/or other electronic component that applies a force to the fluid in the fluid reservoir) for selectively transferring fluid between the fluid reservoir and the chamber.

[0067] Lens elements **84** and **86** may be transparent lens elements formed from any desired material (e.g., glass, a polymer material such as polycarbonate or acrylic, a crystal such as sapphire, etc.). Each one of lens elements **84** and **86** may be elastomeric, semi-rigid, or rigid. In one example, lens element **84** is an elastomeric lens element whereas lens element **86** is a rigid lens element.

[0068] Elastomeric lens elements (e.g., lens element **84** in FIGS. **4** and **5**) may be formed from a natural or synthetic polymer that has a low Young's modulus for high flexibility. For example the elastomeric membrane may be formed from a material having a Young's modulus of less than 1 GPa, less than 0.5 GPa, less than 0.1 GPa, etc.

[0069] Semi-rigid lens elements may be formed from a semi-rigid material that is stiff and solid, but not inflexible. A semi-rigid lens element may, for example, be formed from a thin layer of polymer or glass. Semi-rigid lens elements may be formed from a material having a Young's modulus that is greater than 1 Gpa, greater than 2 GPa, greater than 3 GPa, greater than 10 GPa, greater than 25 GPa, etc. Semi-rigid lens elements may be formed from polycarbonate, polyethylene terephthalate (PET), polymethylmethacrylate (PMMA), acrylic, glass, or any other desired material. The properties of semi-rigid lens elements may result in the lens element becoming rigid along a first axis when the lens element is curved along a second axis perpendicular to the first axis or, more generally, for the product of the curvature along its two principal axes of curvature to remain roughly constant as it flexes. This is in contrast to an elastomeric lens element, which remains flexible along a first axis even when the lens element is curved along a second axis perpendicular to the first axis. The properties of semi-rigid lens elements may allow the semi-rigid lens elements to form a cylindrical lens with tunable lens power and a tunable axis.

[0070] Rigid lens elements (e.g., lens element **86** in FIGS. **4** and **5**) may be formed from glass, a polymer material such as polycarbonate or acrylic, a crystal such as sapphire,

etc. In general, the rigid lens elements may not deform when pressure is applied to the lens elements within the lens module. In other words, the shape and position of the rigid lens elements may be fixed. Each surface of a rigid lens element may be planar, concave (e.g., spherically, aspherically, or cylindrically concave), or convex (e.g., spherically, aspherically, or cylindrically convex). Rigid lens elements may be formed from a material having a Young's modulus that is greater than greater than 25 GP*a*, greater than **30** GP*a*, greater than **40** GPa, greater than **50** GP*a*, etc.

[0071] In addition to lens elements **84** and **86** and fluid-filled chamber **82**, lens module **72-2** also includes a lens shaping element **88**. Lens shaping element **88** may be coupled to one or more actuators **90** (e.g., positioned around the circumference of the lens module). The lens shaping element **88** may also be coupled to lens element **84**. Actuators **90** may be adjusted to adjust the position of lens shaping element **88** (sometimes referred to as lens shaper **88**, deformable lens shaper **88**, lens shaping structure **88**, lens shaping member **88**, annular member **88**, ring-shaped structure **88**, etc.). The lens shaping element **88** in turn manipulates the positioning/shape of lens element **84**. In this way, the curvature of the lens element **84** (and accordingly, the lens power and/or other optical properties of lens module **72-2**) may be adjusted. An example of actuators **90** and lens shaper **88** being used to change the curvature of lens element **84** in FIG. **5**. As shown, lens shaper **88** is moved in direction **94** by actuators **90**. This results in lens element **84** having more curvature in FIGS. **5** than in **4**.

[0072] The example of tunable lens element **72-2** being a fluid-filled lens element is merely illustrative. In general, tunable lens element **72-2** may be any desired type of tunable lens element with adjustable optical power.

[0073] The shape (and corresponding optical power) of tunable lens element **72-2** may be adjusted in response to information from any of the components in input-output circuitry **16** (FIG. **1**).

[0074] FIG. **6** is a top view of an illustrative lens shaping element **88**. As shown, lens shaping element **88** may have an annular or ring shape with the lens shaping element surrounding a central opening. The lens shaping element may have any desired shape. For example, the lens shaping element may be circular, elliptical, or have an irregular shape. In the example of FIG. **6**, the lens shaping element has an elliptical shape (e.g., a non-uniform radius around the ring shape). For example, a first distance **96** (e.g., a minimum distance) from the center of the central opening to the edge of the lens shaping element may be smaller than a second distance **98** (e.g., a maximum distance) from the center of the central opening to the edge of the lens shaping element. Distance **96** and **98** may be less than 100 millimeters, less than 60 millimeters, less than 40 millimeters, less than 30 millimeters, greater than 10 millimeters, greater than 20 millimeters, between 10 and 50 millimeters, etc.

[0075] Lens shaping element **88** has a plurality of tabs **88**E that extend from the main portion of the lens shaping element. The tabs **88**E (sometimes referred to as extensions **88**E, actuator points **88**E, etc.) may each be coupled to a respective actuator **90**. Each actuator may selectively move its respective extension **88**E up and down (e.g., in the Z-direction) to control the position of tab **88**E in the Z-direction.

[0076] FIG. **6** shows how a plurality of tabs **88**E (and corresponding actuators) may be distributed around the perimeter of lens shaping element **88**. Tabs **88**E may be distributed around lens shaping element **88** in a uniform manner (e.g., with equal spacing between each pair of adjacent tabs **88**E) or in a non-uniform manner (e.g., with unequal spacing between at least two of the adjacent tabs **88**E).

[0077] Between each pair of adjacent tabs **88**E, there is a lens shaper segment **88**S. In the example of FIG. **6**, there are **8** tabs **88**E and **8** actuators **90** around the perimeter of lens shaping element **88**. This example is merely illustrative. In general, more tabs (and corresponding actuators) may allow for greater control of the shape of the lens element (e.g., lens element **84**) to which lens shaping element **88** is coupled. Any desired number of tabs and actuators (e.g., one, two, three, four, more than four, more than six, more than eight, more than ten, more than twelve, more than twenty, less than twenty, less than ten, between four and twelve, etc.) may be used depending upon the specific target shapes for the lens element, the target cost/complexity of the lens module, etc.

[0078] Lens shaping element **88** may be elastomeric (e.g., a natural or synthetic polymer that has a low Young's modulus for high flexibility, as discussed above in greater detail) or semi-rigid (e.g., formed from a semi-rigid material that is stiff and solid, but not inflexible, as discussed above in greater detail). A semi-rigid lens shaping element may, for example, be formed from a thin layer of polymer, glass, metal, etc. Because lens shaping element **88** is formed in a ring around the lens module, lens shaping element **88** does not need to be transparent (and therefore may be formed from an opaque material such as metal). The rigidity of lens shaping element **88** may be selected such that the lens shaping element assumes desired target shapes when manipulated by the actuators around its perimeter.

[0079] One or more structures such as a lens housing **102** (sometimes referred to as housing **102**, lens chassis **102**, chassis **102**, support structure **102**, bezel **102**, ring-shaped housing **102**, ring-shaped chassis **102**, etc.) may also be included in tunable lens element **72-2**. Actuators **90** may be positioned within lens housing **102**. Lens housing **102** may optionally define a portion of the fluid-filled chamber **82**. Lens housing **102** may extend in a ring around the periphery of the tunable lens.

[0080] FIG. **7** is a cross-sectional side view of an illustrative actuator **90** that may be used to adjust a tunable lens element. Actuator **90** may include structure **110** (sometimes referred to as rotating structure **110**, movable structure **110**, or main structure **110** herein) and brake assembly **114**. Structure **110** may be moved by actuating component **119** that is coupled to structure **110**, such as one or more shape memory alloy (SMA) wires, motors, magnets, hydraulic actuators, and/or any other suitable actuators. For example, SMA wires may run from one end of structure **110** to another end of structure **110** and may be expanded/contracted to rotate structure **110** about pivot axis **117**. However,

this is merely illustrative. In general, any suitable actuating component may be coupled to structure **110** and may be used to move structure **110**. For example, structure **110** may be rotated about pivot axis **117** by actuating component **119**. In the illustrative example of FIG. **7**, structure **110** may move into and out of the page (e.g., by being rotated by actuating component **119**) in the +Z and -Z directions. Structure **110** may be coupled to a portion of lens shaping element **88** of FIG. **6**, such as extension **88**E. Therefore, by moving structure **110** using an actuator, lens shaping element **88** may be adjusted.

[0081] Structure **110**, the associated actuator(s), and brake assembly **114** may be formed in actuator housing **112** (also referred to as housing **112** herein). Actuator housing **112** may be formed from polymer, metal, or another suitable material.

[0082] When structure **110** (and therefore lens shaping element **88**) is not being adjusted, it may be desirable to fix the position of structure **110** using brake assembly **114**. Brake assembly **114** may include one or more brakes. In the example of FIG. **7**, brake assembly **114** includes two brakes: brake caliper **116**A (also referred to as caliper **116**A herein) and brake caliper **116**B (also referred to as caliper **116**B herein). Brake caliper **116**A may apply a first force (e.g., in the -Y direction) to surface **113** of main structure **110**, and brake caliper **116**B may apply a second force (e.g., in the +Y direction) to surface **111** of main structure **110**.

[0083] Brake calipers **116** may be attached to one another using component **118**. Component **118** may have a curved shape and may be formed from an insert molded component, a metal component that is bent into a curved shape, or another suitable component. Each of brake calipers **116** may have a wedge-shaped surface. For example, brake caliper **116**A may have wedge-shaped surface **130**A and brake caliper **116**B may have wedge-shaped surface **130**B. Housing **112** may have wedges that engage the wedge-shaped surfaces **130** of brake calipers **116**.

[0084] The wedges of housing **112** (that engage wedge-shaped surfaces **130**) may extend at angle **132** relative to the Y-axis. Angle **132** may be selected based on a desired/suitable gearing between the force of spring mechanism **124** and the force of brake calipers **116** on structure **110**. For example, if the wedge angle is increased, then the gearing between the force of spring mechanism **124** and the force of brake calipers **116** on structure **110** is increased. Therefore, angles of wedges of housing **112** may be adjusted to adjust the force applied to structure **110** using brake calipers **116**.

[0085] Component **118** may be coupled to portion **120**, which in turn may be coupled to spring mechanism **124**. Spring mechanism **124** may include shuttle **122**. Shuttle **122** may be biased in the position shown in FIG. **7** using a spring or another suitable biasing mechanism, such as spring **121** that extends between shuttle **122** and housing **112** (or another fixed structure).

[0086] Shuttle **122** may be coupled to one or more spring actuation components, such as one or more SMA wires, one or more motors, one or more magnets, and/or one or more hydraulic components. In the example of FIG. **7**, shuttle **122** may be coupled to SMA wire **128** via anchor **127**. Anchor **126** of SMA wire **128** may be coupled to a portion of actuator **90** outside of spring mechanism **124**, such as to a portion of housing **112**.

[0087] Anchors **126** and **127** may sometimes be referred to as connectors **126** and **127**, mechanical connectors **126** and **127**, electrical connectors **126** and **127**, and mechanical and electrical connectors **126** and **127** herein. In particular, anchors **126** and **127** may be both mechanically and electrically connected to SMA wire **128**. Mechanically, anchor **126** may be attached to housing **112** (or another suitable fixed structure) and anchor **127** may be coupled to shuttle **122**. Anchors **126** and **127** may also provide electrical connections to SMA wire **128**. Control circuitry **14** (FIG. **1**) may control voltages applied to anchors **126** and **127** to control a current through SMA wire **128**. The current through SMA wire **128** may be adjusted to selectively contract SMA wire **128**.

[0088] In operation, because shuttle **122** is maintained in the position of FIG. **7** by a biasing member, such as spring **121**, brake calipers **116** may engage structure **110** in a resting state. In this way, brake calipers **116** may prevent structure **110** from moving and adjusting the associated lens.

[0089] When it is desired to adjust the lens, SMA wire **128** may be contracted (e.g., by adjusting the current through SMA wire **128**), which may move shuttle **122** (and therefore portion **120** to which shuttle **122** is coupled) in the -X direction. Component **118** may similarly be moved in the -X direction, which may move brake calipers **116** away from main structure **110** along the wedges of housing **112**. When brake calipers **116** are disengaged/moved away from main structure **110**, the one or more actuators (e.g., additional SMA wires or motors) may be used to move main structure **110** and adjust the lens.

[0090] After adjustment, SMA wire **128** may be extended to its original position (e.g., the position shown in FIG. **7**), and the biasing mechanism (e.g., a spring) may move shuttle **122**, portion **120**, and component **118**, in the +X direction. Therefore, brake calipers **116** may move along the wedges of housing **112** toward and into contact with structure **110**. In other words, brake calipers **116** may engage structure **110** to prevent further movement of structure **110** and adjustment of the lens. In this way, brake calipers **116** may apply a force to structure **110** to selectively fix a position of structure **110**.

[0091] In particular, brake calipers **116** may apply the force to structure **110** in a direction parallel to the pivot axis of structure **110**. In the example of FIG. **7**, structure **110** is configured to rotate in the +Z and -Z directions, placing the pivot axis along the Y-axis. By using brake calipers **116** to apply the force to structure **110** parallel to the Y-axis (e.g., in the +Y and -Y directions), the position structure **110** may be fixed without applying undue stress to structure **110**.

[0092] Brake assembly **114**, main structure **110**, and actuator **119** may all fit within actuator housing **112**. In particular, actuator housing **112** may have outer surface **115**, with a radius of curvature of 30 mm or less, of 25 mm or less, of between 20 mm and 30 mm, or another suitable radius of curvature.

[0093] Although shuttle **122** is shown as being actuated by SMA wire **128**, this is merely illustrative. In general, spring mechanism **124** may include any suitable actuator(s), such as motors.

[0094] The example of FIG. **7** in which an insert molded component is used for component **118**, is merely illustrative. In some embodiments, other components may be used to close brake calipers **116**. An illustrative example of a flexible component that pivots to close brake calipers **116** is shown in FIG. **8**.

[0095] As shown in FIG. **8**, brake calipers **116**A and **116**B may be coupled using component **134** of brake assembly **114**. Component **134** may include portions **134**A and **134**B that are joined at pivot **136**. Pivot **136** may be a fastener, such as a pin, that attaches portions **134**A and **134**B together.

[0096] Portions **134**A and **134**B may expand and contract relative to one another about pivot **136**. Additionally, a biasing member, such as expansion spring **138**, may extend between portions **134**A and **134**B to bias portions **134**A and **134**B away from one another.

[0097] In operation, when SMA wire **128** (or other actuator) pulls shuttle **122** and portion **120** in the -X direction, component **134** may move in the -X direction, and portions **134**A and **134**B may be pushed away from each other (e.g., by expansion spring **138**). Therefore, brake calipers **116** may be moved along the wedges of housing **12** away from structure **110**.

[0098] Instead of, or in addition to, using SMA wire or another actuator in spring mechanism **124** to move component **134**, a piezoelectric element may be incorporated between calipers **116** and pivot **136**. The piezoelectric element may push portions **134**A and **134**B away from each other when it is desired to disengage brake calipers **116** from structure **110**. In these embodiments, spring mechanism **124** (including SMA wire **128**) may be omitted from actuator **90**, if desired.

[0099] In some embodiments, instead of having brake calipers **116** on both sides of structure **110**, a single brake caliper may apply a force to a single surface of structure **110**. An illustrative example is shown in FIG. **9**.

[0100] As shown in FIG. **9**, brake assembly **114** may include a single caliper **116**. In operation, caliper **116** may be pulled in the -X direction along a wedge of housing **112** by portion **120** (and shuttle **122**) in response to contraction by SMA wire **128** (or the actuation of another actuator) to disengage structure **110**.

[0101] When caliper **116** is engaging structure **110**, caliper **116** may apply a force against surface **111** of structure **110**. Surface **113** may be pushed against a portion of housing **112**, such as portion **140**, or against another suitable fixed structure (such as a pad affixed to housing **112**). In this way, a single caliper may fix the position of structure **110**.

[0102] Regardless of whether one or two calipers **116** are used in brake assembly **114**, the wedge-shaped surfaces of caliper(s) **116** and/or the wedge(s) of housing **112** may be coated to reduce friction when caliper(s) **116** move along the wedge(s) of housing **112**. Alternatively or additionally, ball bearings or other suitable friction-reducing components may be included between caliper(s) **116** and the wedge(s) of housing **112**.

[0103] Although FIGS. **7-9** have shown brake assembly **114** including brake calipers **116** having wedge-shaped surfaces that move along a wedge of a housing, this is merely illustrative. In general, brake assembly **114** may include any suitable brakes. For example, in some embodiments, brake assembly **114** may include brake calipers with wedge-shaped surfaces that slope in the opposite direction as shown in FIGS. **7-9**, and housing **112** may have wedges with matching slope. In other embodiments, brake assembly **114** may include brake cams and/or other brake structures. Illustrative examples are shown in FIGS. **10**A-**10**C.

[0104] As shown in FIG. **10**A, brake assembly **114** of actuator **90** may include brake cams **142**A and **142**B (also referred to as cams **142**A and **142**B herein). Cam **142**A may be biased against surface **113** of structure **110** by rotary spring **144**A, and cam **142**B may be biased against surface **111** of structure **110** by rotary spring **144**B. To release cams **142**A and **142**B from structure **110**, an actuator may be used to rotate cams **142**A and **142**B about pivots **146**A and **146**B, respectively. In the illustrative example of FIG. **10**A, SMA wire **148**A may be contracted to pull cam **142**A in direction **150**A, and SMA wire **148**B may be contracted to pull cam **142**B in direction **150**B. In this way, cams **142** may be disengaged from structure **110**, allowing structure **110** to be moved.

[0105] When structure **110** has been adjusted, SMA wires **148** may be expanded, and rotary springs **144** may place cams **142** back into contact with structure **110**.

[0106] Instead of using two brake cams in brake assembly **114**, a single brake cam may be used. An illustrative example is shown in FIG. **10**B.

[0107] As shown in FIG. **10**B, brake assembly **114** may include a single cam **142**. Single cam **142** may apply a force to surface **113** (or surface **111**) of structure **110**, and the opposite surface (surface **111** in the example of FIG. **10**B) may be pushed into contact with fixed member **152**. Fixed member **152** may be, for example, a portion of actuator housing **112** (FIGS. **7-9**). In this way, a single cam **142** may be used to maintain the position of structure of **110**.

[0108] The cam structures of FIGS. **10**A and **10**B are merely illustrative of brakes that may be used to fix the position of structure **110**. In some embodiments, one or more L-shaped brake structures may be used. An illustrative example is shown in FIG. **10**C.

[0109] As shown in FIG. **10**C, brake assembly **114** may include L-shaped brake structure **154** that is biased (e.g., by a rotary spring or other biasing component) in direction **158** about pivot **156**. Therefore, L-shaped brake structure **154** will apply a force to surface **113** (or surface **111**) of structure **110**, and the opposite surface (surface **111** in the example of FIG. **10**C) may be pushed into contact with fixed member **152**. In this way, L-shaped structure brake **154** may form a brake in brake assembly **114** to fix a position of structure **110**. When it is desired to adjust structure **110**, L-shaped brake structure **154** may be pulled in direction **160** (e.g., using an SMA wire) to disengage L-shaped brake structure **154** from structure **110**.

[0110] Although FIG. **10**C has shown brake assembly **114** including a single L-shaped brake structure **154** applying a force to one of the surfaces of structure **110**, this is merely illustrative. Brake assembly **114** may include multiple L-shaped brake structures **154**, such as L-shaped brake structures **154** to apply forces to both sides of structure **110**, if desired.

[0111] Although FIGS. **10**A-**10**C have shown and described adjusting brake cams and/or L-shaped structures using one or more SMA wires, this is merely illustrative. In general, any suitable actuator, such as motors, hydraulic actuators, or magnetic actuators, as examples, may be used to adjust brake cams and/or L-shaped structures in brake assembly **114**.

[0112] In the examples of FIGS. **7**-**9**, housing **112** is shown as having wedges, and calipers **116** are shown as having wedge-shaped surfaces that move along the wedges of the housing. However, this arrangement is merely illustrative. In some embodiments, brake assembly **114** may include brake calipers with wedge-shaped surfaces that engage with wedges of structure **110**. An illustrative example is shown in FIG. **11**.

[0113] As shown in FIG. **11**, structure **110** may include wedge **166**A on surface **113** and wedge **166**B on surface **111**. Brake caliper **162**A may have wedge-shaped surface **164**A that engages with wedge **166**A, and brake caliper **162**B may have wedge-shaped surface **164**B that engages with wedge **166**B. In this way, brake calipers **162** may move along wedges **166** to engage structure **110** and fix the position of structure **110**. When it desired to adjust structure **110**, brake calipers **162** may be moved in the -X direction, away from wedges **166**.

[0114] In the example of FIG. **11**, brake calipers **162** may move not move along housing **112**, instead being guided into contact with structure **110** by wedges **166** of structure **110**.

[0115] Instead of, or in addition to, using brake calipers (e.g., brake calipers **116** of FIGS. **7**-**9** or brake calipers **162** of FIG. **11**), brake cams (e.g., cams **142** of FIGS. **10**A and **10**B), or L-shaped brakes (e.g., L-shaped brake structures **154** of FIG. **10**C), flexures may support brakes and be used to move the brakes into and out of contact with structure **110**. Illustrative examples of flexures that may be used are shown in FIGS. **12**A-**12**D.

[0116] As shown in FIG. **12**A, brake assembly **114** may include flexure **168**. Flexure **168** may include flexure arms **170**A and **170**B that are respectively attached to fixed components **172**A and **172**B. Fixed components **172**A and **172**B may be, for example, a portion of actuator housing **112** or attached to housing **112** (FIGS. **7**-**9**). Flexure arms **170**A and **170**B may be coupled to central flexure portion **174**, which in turn may be attached to flexure brake pad carriers **176**A and **176**B. Brake pads **178**A and **178**B may be coupled to flexure brake pad carriers **176**A and **176**B, respectively.

[0117] Central flexure portion **174** may be at least partially flexible. For example, central flexure portion **174** may be able to bend/flex in directions **182**A and **182**B. In some embodiments, central flexure portion **174** may be formed from elastomeric material. However, this is merely illustrative. Central flexure portion **174** may be formed from any suitable flexible or partially flexible material.

[0118] In general, flexure **168** may bias brake pad **178**A against surface **113** of structure **110** and brake pad **178**B against surface **111** of structure **110**, which may prevent movement of structure **110**. When it is desired to adjust the position of structure **110**, central flexure portion **174** may be bent in directions **182**A and **182**B. For example, central flexure portion **174** may be moved in directions **182**A and **182**B using one or more flexure actuation components such as one or more SMA wires (e.g., by contracting the SMA wires), one or more motors, one or more magnets, and/or one or more hydraulic actuators. The bending of central flexure portion **174** in directions **182**A and **182**B may move flexure brake pad carriers **176**A and 176B and therefore brake pads **178**A and **178**B in directions **182**A and **182**B. In this way, brake pads **178** may be moved away/disengaged from structure **110**, allowing structure **110** to be moved. Releasing central flexure portion **174** (e.g., by relaxing the SMA wires) will return brake pads **178** into contact with structure **110**.

[0119] Another illustrative example of a flexure that may be used in brake assembly **114** is shown in FIG. **12**B. As shown in FIG. **12**B, flexure **184** may include flexure arms **186**A and **186**B coupled by bar **188**. Bar **188** may be a stiff bar attached to a fixed portion (e.g., housing **112**) while allowing flexure arms **186**A and **186**B rotate in directions **191**A and **191**B, respectively. Brake pads **178**A and **178**B may be coupled to flexure arms **186**A and **186**B, respectively.

[0120] Biasing component **190** (e.g., an expansion spring) may bias flexure arms **186**A and **186**B in the directions opposite directions **191**A and **191**B. Therefore, absent any external force, brake pad **178**A may be biased against surface **113** of structure **110**, and brake pad **178**B may be biased against surface **111** of structure **110**. In this way, structure **110** may be fixed in place by brake pads **178**.

[0121] When it is desired to adjust structure **110**, portions of flexure arms **186**A and **186**B may be moved in common direction **192**. For example, the portions of flexure arms **186**A and **186**B may be moved in direction **192** using one or more flexure actuation components such as one or more SMA wires (e.g., by contracting the SMA wires), one or more motors, one or more magnets, and/or one or more hydraulic actuators. The movement of the portions of flexure arms **186**A and **186**B in common direction **192** may rotate flexure arms **186**A and **186**B about the flexible portions of bar **188** (e.g., in directions **191**A and **191**B, respectively). The rotation of flexure arms **186**A and **186**B may move brake pad **178**A away from surface **113** in direction **191**A and may move brake pad **178**B away from surface **111** in direction **191**B, which may allow structure **110** to be moved. Releasing flexure arms **186**A and **186**B (e.g., by relaxing the SMA wires) will return brake pads **178** into contact with structure **110**.

[0122] Another illustrative example of a flexure that may be used in brake assembly **114** is shown in FIG. **12**C. As shown in FIG. **12**C, flexure **194** may include flexure arms **196**A and **196**B coupled by bar **198** and by flexures **200**A and **200**B. Bar **198** may be a stiff bar attached to a fixed

portion (e.g., housing **112**) while allowing flexure arms **196**A and **196**B to move in common direction **205**. Brake pads **178**A and **178**B may be coupled to flexure brake pad carriers **202**A and **202**B, respectively. Flexure brake pad carrier **202**A may be coupled between flexure arm **196**A and fixed portion **204**A (e.g., a portion of housing **112**), and flexure brake pad carrier **202**B may be coupled between flexure arm **196**B and fixed portion **204**B (e.g., a portion of housing **112**).

[0123] Due to flexure brake pad carrier **202** being coupled between flexure arms **196** and fixed portions **204**, brake pad **178**A may be biased against surface **113** of structure **110**, and brake pad **178**B may be biased against surface **111** of structure **110**. In this way, structure **110** may be fixed in place by brake pads **178**.

[0124] When it is desired to adjust structure **110**, flexure arms **196**A and **196**B may be moved in common direction **205**. For example, flexure arms **196**A and **196**B may be moved using one or more flexure actuation components such as one or more SMA wires (e.g., by contracting the SMA wires), one or more motors, one or more magnets, and/or one or more hydraulic actuators. The movement of flexure arms **196**A and **196**B in common direction **205** may move flexure arms **196** in common direction **205**, which may move flexure brake pad carrier **202**A upward and flexure brake pad carrier **202**B downward. This movement may move brake pad **178**A away from surface **113** and brake pad **178**B away from surface **111**, allowing structure **110** to be moved. Releasing flexure arms **196**A and **196**B (e.g., by relaxing the SMA wires) will return brake pads **178** into contact with structure **110**.

[0125] Another illustrative example of a flexure that may be used in brake assembly **114** is shown in FIG. **12**D. As shown in FIG. **12**D, flexure **195** may include brake calipers **197**A and **197**B. Brake caliper **197**A may be coupled to flexures **199**A and **199**B, and brake caliper **197**A may be coupled to brake caliper **197**B via spring **201**. Flexures **199**A and **199**B may be compliant flexures but may be stiff in a direction out of the page. Spring **201** may be a pre-loaded spring that is coupled to rotation point (e.g., pivot **203**). Although two flexures **199**A and **199**Bare shown in the example of FIG. **12**D, any suitable number of flexures, such as a single flexure, may be coupled to brake caliper **197**A.

[0126] Due to brake caliper **197**A being coupled to flexures **199**A and **199**B, and brake caliper **197**B being coupled to brake caliper **197**A, brake calipers **197**A and **197**B may be biased toward structure **110**. Therefore, in the absence of force on flexure **195**, structure **110** may be fixed in place by brake calipers **197**.

[0127] When it is desired to adjust structure **110**, an upper portion of brake caliper **197**B (e.g., near surface **209**) may be moved in direction **207**. For example, the upper portion of brake caliper **197**B may be moved using one or more flexure actuation components such as one or more SMA wires (e.g., by contracting the SMA wires), one or more motors, one or more magnets, and/or one or more hydraulic actuators. The movement of the upper portion of brake caliper **197**B in direction **207** may rotate the bottom portion of brake caliper **197**B away from structure **110** and may disengage brake caliper **197**B from structure **110**. At the same time, the movement of the upper portion of brake caliper **197**B in direction **207** may rotate spring **201** about pivot **203** in direction **209**, thereby moving brake caliper **197**A away from structure **110**. Therefore, the movement of the upper portion of brake caliper **197**B in direction **207** may move brake calipers **197** away from structure **110**, allowing structure **110** to be moved. Releasing the upper portion of brake caliper **197**B (e.g., by relaxing the SMA wires) will return brake calipers **197** into contact with structure **110**.

[0128] Although not shown in FIG. **12**D, brake pads may be coupled between brake calipers **197** and structure **110**, if desired. Moreover, although the illustrative example of FIG. **12**D shows rotation being provided by flexure **195**, brake calipers **197** may instead by rotated by a sliding or rolling bearing instead of a flexure, and the spring (e.g., spring **201**) may be provided by an external component (e.g., a component outside of brake assembly **114**).

[0129] In the examples of FIGS. **12**A-**12**D, the flexures are biased for the brake pads to engage structure **110** unless one or more forces are being applied to the flexures. In other words, the brake pads are biased toward structure **110**. However, in some embodiments, it may be desirable for the brake pads to be stable when engaging structure **110** and when disengaged from structure **110**. Therefore, bistable flexures may be used in brake assembly **114**. Illustrative examples of bistable flexures are shown in FIGS. **13**A and **13**B.

[0130] As shown in FIG. **13**A, brake assembly **114** may include bistable flexure **208**. Bistable flexure 208 may include fixed portions **210**A and **210**B (e.g., portions of housing **112**). Flexure arms **212**A and **212**B may be coupled to fixed portion **210**A, and flexure arms **214**A and **214**B may be coupled to fixed portion **210**B. Flexure arm **216**A may be coupled between flexure arms **212**A and **214**A, and flexure arm **216**B may be coupled between flexure arms **212**B and **214**B. Brake pad **178**A may be coupled to flexure arm **216**A, and brake pad **178**B may be coupled to flexure arm **216**B.

[0131] In operation, flexure **208** may be stable in a first state with brake pad **178**A applying a force against surface **113** of structure **110** and brake pad **178**B applying a force against surface **111** of structure **110**. When it is desired to move brake pads 178 away from structure **110**, flexure actuation components **218** (e.g., magnets) may be activated to move flexure arms **212**, **214**, and **216**, and therefore brake pads **178**, away from structure **110**. When flexure arms **212**, **214**, and **216**, and brake pads **178** have been moved away from structure **110**, flexure **208** may be in a second state. Flexure **208** may be stable in both the first state in the second state. In other words, flexure actuation components **218** may need to be activated again (e.g., with an opposite polarity) to move flexure **208** back to the first state after it has been moved into the second state. In this way, flexure **208** may be a bistable flexure that may be used to move brake pads **178** into and out of contact with structure **110**.

[0132] Another illustrative bistable flexure is shown in FIG. **13**B. As shown in FIG. **13**B, brake assembly **114** may include bistable flexure **219**. Bistable flexure **219** may

include fixed portions **220**A and **220**B (e.g., portions of housing **112**). Flexure arm **222**A may be coupled to fixed portion **220**A via flexible portion **224**A and spring **226**A, and flexure arm **222**B may be coupled to fixed portion **220**B via flexible portion **224**B and spring **226**B. Brake pad **178**A may be coupled to flexure arm **222**A, and brake pad **178**B may be coupled to flexure arm **222**B.

[0133] In operation, flexure **219** may be stable in a first state with brake pad **178**A applying a force against surface **113** of structure **110** and brake pad **178**B applying a force against surface **111** of structure **110**. When it is desired to move brake pads 178 away from structure **110**, flexure actuation components (e.g., SMA wires, magnets, motors, etc.) may be activated to move flexure arms **222**, and therefore brake pads **178**, away from structure **110**. When flexure arms **222** and brake pads **178** have been moved away from structure **110**, flexure **219** may be in a second state. Due to the presence of springs **226**A and **226**B, flexure **219** may be stable in both the first state in the second state. In other words, the flexure actuation components (e.g., SMA wires, magnets, motors, etc.) to move flexure **219** back to the first state after it has been moved into the second state. In this way, flexure **219** may be a bistable flexure that may be used to move brake pads **178** into and out of contact with structure **110**.

[0134] In some embodiments, flexure springs may be coupled to piezoelectric elements to support brakes and to move the brakes into and out of contact with structure **110**. An illustrative example is shown in FIG. **14**.

[0135] As shown in FIG. **14**, brake assembly **114** may include flexure springs **230**A and **230**B. Flexure springs **230**A and **230**B may be, for example, pre-formed flexure springs formed from metal, polymer, and/or other suitable material(s). In some embodiments, flexure springs **230**A and **230**B may be parallel arms (e.g., parallel flexure spring arms) of a single flexure spring (e.g., a pre-formed flexure spring). In other words, flexure springs **230**A and **230**B may be flexure spring arms **230**A and **230**B. However, this is merely illustrative. In general, one or more spring structures may be used to form flexure springs **230**A and **230**B. For example, flexure springs **230**A and **230**B may be formed from coil springs.

[0136] Flexure springs **230**A and **230**B may be grounded mechanically within brake assembly **114**, or may be assembled in structure (e.g., flexure springs **230**A and **230**B may be separately attached to one another and/or to other portions of brake assembly **114**).

[0137] Piezoelectric member **232**A may be coupled to flexure spring **230**A, and brake pad **178**A may be coupled to piezoelectric member **232**A. Similarly, piezoelectric member **232**B may be coupled to flexure spring **230**B, and brake pad **178**B may be coupled to piezoelectric member **232**B.

[0138] Piezoelectric members **232** may each include one or more multi-layer piezoelectric elements (e.g., stacked piezoelectric elements), or may include one or more single layer piezoelectric elements. Piezoelectric members **232** may be electrically coupled to circuitry in the electronic device, such as control circuitry **14** (FIG. **1**) using flexure springs **230**A and **230**B (e.g., if flexure springs **230**A and **230**B are formed from conductive material) and/or other suitable electrical connectors.

[0139] Overall, brake assembly **114** may be stiff in the arrangement of FIG. **14**. In particular, flexure springs **230**, piezoelectric members **232**, and brake pads **178** may combine to have a high resonant quality factor.

[0140] In operation, flexure springs **230** may bias piezoelectric members **232** and brake pads **178** toward structure **110**. Piezoelectric members **232** may vibrate brake pads **178**, pushing brake pads **178** against the upper and lower surfaces of structure **110** with a periodic normal force. In particular, piezoelectric members **232** may be adjusted between applying a high normal force against the surfaces of structure **110** and applying a low normal force against the surfaces of structure **110** (e.g., by adjusting the voltage on piezoelectric members **232**). When piezoelectric members **232** apply the high normal force, the friction between brake pads **178** and structure **110** may be sufficient to prevent structure **110** from moving. When piezoelectric members apply the low normal force, the friction between brake pads **178** and structure **110** may be low enough to allow structure **110** to be adjusted. In this way, flexure springs **230**, piezoelectric members **232**, and brake pads **178** may apply an adjustable periodic normal force to structure **110** to brake structure **110**.

[0141] The examples of FIGS. **7-14** where actuator **90** is configured to move structure **110** Z-direction about a Y-axis pivot axis and where brake assembly **114** is configured to apply brake force(s) in a direction parallel to the Y-axis pivot axis is merely illustrative. In general, the actuators of FIGS. **7-14** may be used in any desired application and may move any desired component in any suitable direction. In other words, actuator **90** may be oriented in any suitable direction, and brake assembly **114** is configured to apply brake force(s) in a direction parallel to the pivot axis

[0142] The foregoing is merely illustrative, and various modifications can be made to the described embodiments. The foregoing embodiments may be implemented individually or in any combination.

What is claimed is:

1. An actuator comprising:

a main structure;

an actuating component that is coupled to the main structure and is configured to selectively rotate the main structure about a pivot axis; and

a brake assembly that is configured to selectively fix a position of the main structure, wherein the brake assembly comprises a brake that is configured to apply a force to the main structure in a direction parallel to the pivot axis.

2. The actuator of claim **1**, wherein the actuating component comprises a shape memory alloy wire.

3. The actuator of claim **1**, wherein the main structure has opposing first and second surfaces, the actuator further comprising:

a housing in which the main structure, the actuating component, and the brake assembly are formed, wherein the housing has a wedge, and the brake is a brake caliper that is configured to move along the wedge of the housing to apply the force to the first

surface of the main structure.

4. The actuator of claim **3**, wherein the brake assembly further comprises a spring that is configured to pull on the brake caliper to maintain the force of the brake caliper on the main structure and a spring actuation component configured to selectively engage the spring to move the brake caliper along the wedge and away from the main structure.

5. The actuator of claim **4**, wherein the spring actuation component comprises a shape memory alloy wire.

6. The actuator of claim **4**, wherein the brake caliper is configured to push the second surface of the main structure into contact with a portion of the housing.

7. The actuator of claim **4**, wherein the housing comprises an additional wedge, the main structure is interposed between the wedge and the additional wedge, and the brake assembly further comprises an additional brake caliper that is configured to move along the additional wedge of the housing to apply an additional force to the second surface of the structure.

8. The actuator of claim **7**, wherein the brake caliper and the additional brake caliper are coupled to the spring with an insert molded component.

9. The actuator of claim **7**, wherein the brake caliper and the additional brake caliper are coupled to the spring using a component having first and second portions coupled at a pivot.

10. The actuator of claim **2**, wherein the main structure comprises a wedge and the brake comprises a caliper with a wedge-shaped surface that is configured to engage with the wedge of the main structure to apply the force to the main structure.

11. The actuator of claim **2**, wherein the brake comprises a brake cam that is configured to rotate to apply the force to the main structure.

12. The actuator of claim **11**, wherein the brake cam is configured to apply the force to a first surface of the main structure, and the brake assembly further comprises an additional brake cam configured to apply an additional force to a second surface of the main structure opposite the first surface.

13. The actuator of claim **2**, wherein the brake comprises an L-shaped brake structure that is configured to rotate to apply the force to the main structure.

14. The actuator of claim **2**, wherein the brake is a first brake pad that applies the force to a first surface of the main structure, the brake assembly further comprises a second brake pad that applies an additional force to a second surface of the structure opposite the first surface, and the first and second brake pads are coupled to a flexure.

15. The actuator of claim **14**, wherein the flexure comprises first and second flexure arms and a central flexure portion coupled to the first and second flexure arms, wherein the central flexure portion is configured to be bent to move the first and second brake pads away from the main structure.

16. The actuator of claim **14**, wherein the flexure comprises first and second flexure arms, and wherein at least a portion of each of the first and second flexure arms are configured to be moved in a common direction to move the first and second brake pads away from the main structure.

17. The actuator of claim **14**, wherein the flexure is a bistable flexure that is stable at a first position in which the first and second brake pads apply the force and the additional force to the main structure and a second position in which the brake pads are disengaged from the main structure.

18. The actuator of claim **17**, wherein the brake assembly further comprises a magnet that is configured to move the flexure between the first position and the second position.

19. The actuator of claim **2**, wherein the brake is a first brake caliper that applies the force to a first surface of the main structure, the brake assembly further comprises a second brake caliper that applies an additional force to a second surface of the structure opposite the first surface, the first brake caliper is coupled to at least one flexure, the first brake caliper is coupled to the second brake caliper with a spring coupled to a rotation point, and an upper portion of the second brake caliper is configured to be moved in a given direction to rotate the first and second brake calipers away from the first and second surfaces.

20. The actuator of claim **2**, wherein the brake is a first brake pad that applies the force to a first surface of the main structure, the brake assembly further comprises a second brake pad that applies an additional force to a second surface of the structure opposite the first surface, the first and second brake pads are respectively coupled to first and second piezoelectric members which in turn are respectively coupled to first and second flexure springs, and the piezoelectric members are configured to vibrate to push the first and second brake pads against the main structure with an adjustable periodic normal force.

21. An actuator comprising:

a housing comprising first and second wedges;

a main structure in the housing, wherein the main structure comprises opposing first and second surfaces;

an actuating component in the housing that is configured to selectively rotate the main structure about a pivot axis; and

a brake assembly in the housing that is configured to selectively fix a position of the main structure, wherein the brake assembly comprises:

a first brake caliper that is configured to move along the first wedge of the housing to apply a first force to the first surface of the main structure in a first direction parallel to the pivot axis,

a second brake caliper that is configured to move along the second wedge of the housing to apply a second force to the second surface of the main structure in a second direction parallel to the pivot axis,

a spring that is configured to bias the first and second brake calipers toward the main structure to maintain the first and second forces on the main structure, and

a spring actuation component configured to selectively engage the spring to move the first and second brake calipers along the first and second wedges and away from the main structure.

22. An actuator comprising:

a housing;

a structure in the housing, wherein the structure comprises opposing first and second surfaces;

an actuating component in the housing is configured to selectively rotate the structure about a pivot axis; and

a brake assembly in the housing that is configured to selectively fix a position of the structure, wherein the brake assembly comprises:

a first brake pad that is configured to apply a first force to the first surface of the structure in a first direction parallel to the pivot axis,

a second brake pad that is configured to apply a second force to the second surface of the structure in a second direction parallel to the pivot axis,

a flexure to which the first and second brake pads are coupled, and

a flexure actuation component that is configured to move at least a portion of the flexure to move the first and second brake pads away from the structure.

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