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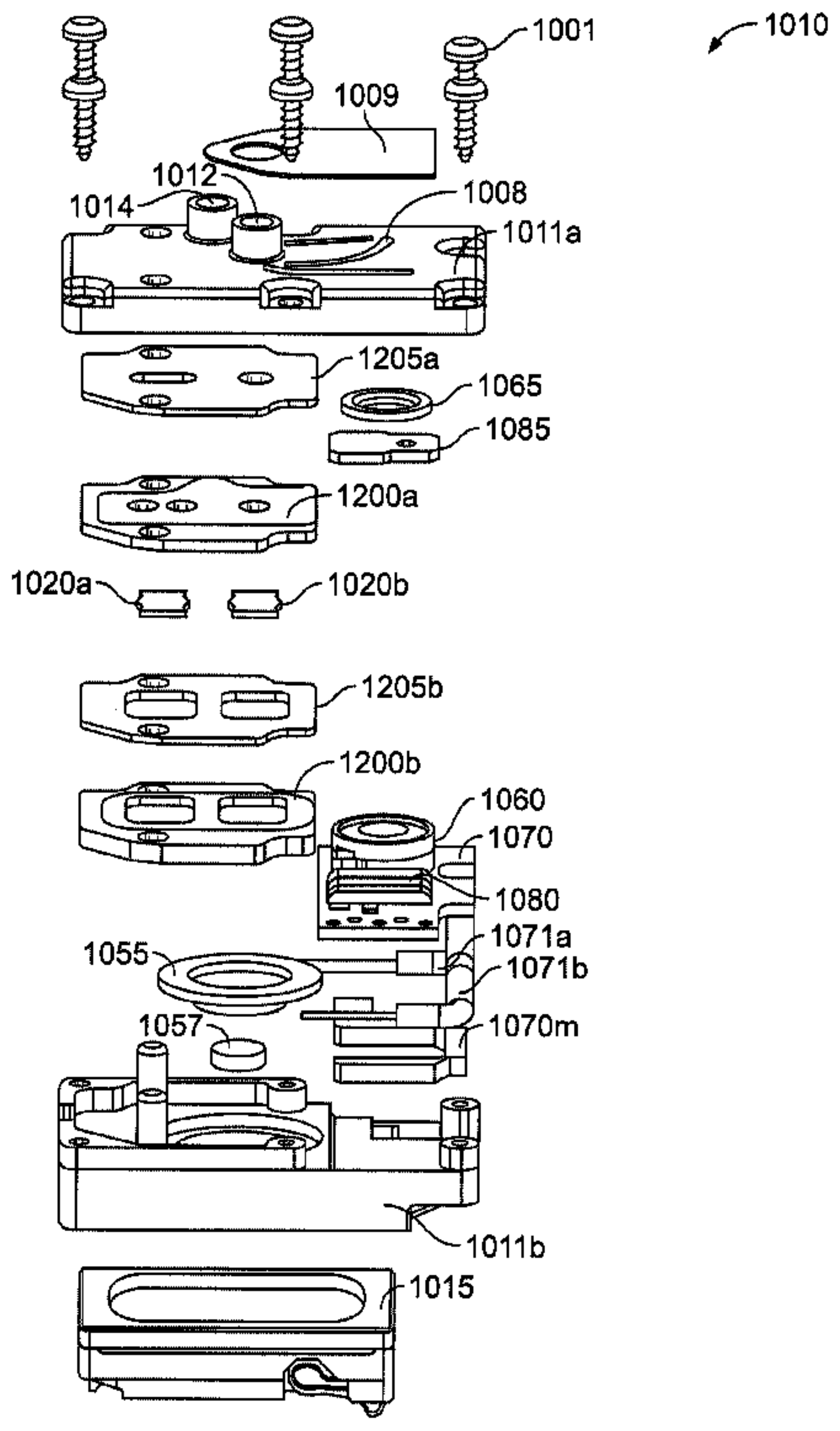
(54) **Title**: PUMPS, ACTUATORS AND RELATED DEVICES AND METHODS FOR MAKING



(57) **Abrégé/Abstract**:

A miniature diaphragm pump. The diaphragm is loaded with energy during the exhaust stroke and the loaded energy is released during the pump stroke, which improves the efficiency of the miniature pump. Energy is loaded via a permanent magnet fixed to the diaphragm. The pump includes a processor for dynamically controlling the position of the diaphragm and the performance of the pump.

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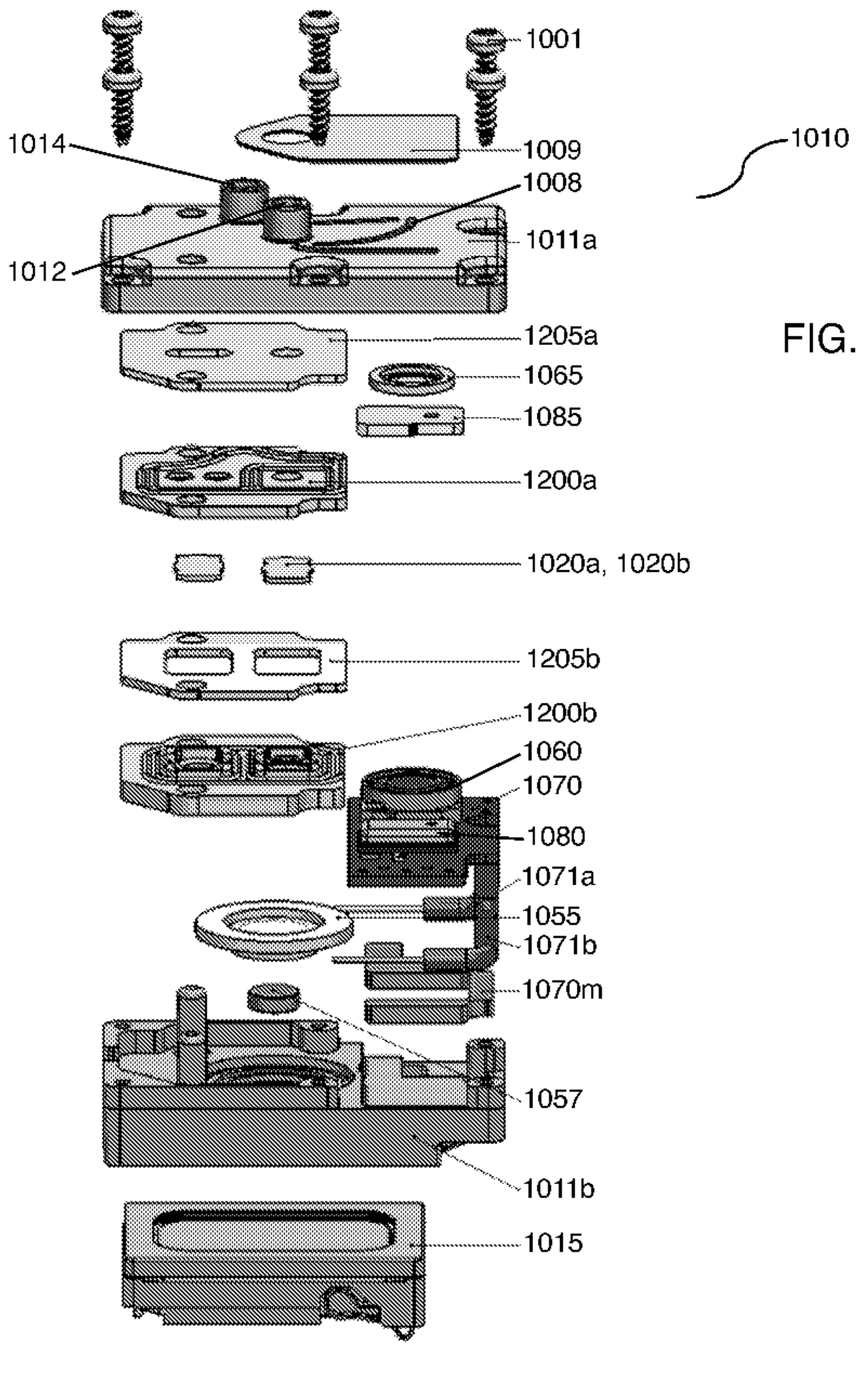

FIG. 10

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Pumps, actuators and related devices and methods for making

BACKGROUND OF THE INVENTION

[001] Miniature pumps have been made for applications in microfluidics for fields such as chemical analysis and other “lab-on-a-chip” applications. Many of these miniature pumps are diaphragm pumps driven by an electromagnetic mechanism. The interaction between a permanent magnet and an electromagnetic coil (capable of having its polarity reversed) causes the diaphragm to reciprocate and drive the pump. The diaphragm is typically fixed to either the coil or to the permanent magnet and other element of the electromagnetic pairing is held fixed with respect to the diaphragm.

[002] Such arrangements can operate efficiently when pumping fluid or in conditions where there is not a large pressure differential. However, if there is a large pressure differential across the diaphragm of such a pump, more power is needed to drive the pump. In the context of miniature pumps, it can be difficult to send more power to the electromagnetic mechanism without creating undesirable problem such as heat build-up.

[003] Larger scale pumps deal with large pressure differentials across a diaphragm by using mechanical energy to help propel the diaphragm during the pump stroke. For example, while electromagnetic forces alone may drive the diaphragm during the exhaust stroke, a mechanical spring can help drive the diaphragm during the pump stroke. That is, during the exhaust stroke a mechanical spring is compressed and when the electromagnetic field is reversed the mechanical spring unloads its loaded energy to return the diaphragm. However, such an arrangement has its highest energy at the beginning of the pump stroke and loses energy at the same time the diaphragm is encountering high resistance. Further, such mechanical loading is not practical in a miniature pump.

[004] These challenges and others can be addressed by the embodiments disclosed herein.

BRIEF SUMMARY OF THE INVENTION

[005] Certain embodiments of the present invention are related to devices and methods for improving the efficiency of miniature diaphragm pumps and in particular miniature diaphragm pumps driven by electromagnetic actuators.

[006] In some embodiments, the miniature diaphragm pump is loaded with energy during the exhaust stroke and the loaded energy is released during the pump stroke, which improves the efficiency of the miniature pump.

[007] In some embodiments, a supplemental permanent magnet is fixed to a diaphragm of a miniature electromagnetically driven diaphragm pump. The supplemental permanent magnet is separated from a fixed pole magnet during the exhaust stroke of the pump and is magnetically attracted to the fixed pole magnet during the pump stroke. Separating the permanent magnet from the pole magnet loads energy during the exhaust stroke.

[008] Certain embodiments of the present invention include a control system for operating a miniature diaphragm pump. The control system can include control, storage, sensing, and I/O components.

[009] Certain embodiments of the present invention include a processor for dynamically controlling the position and/or performance of the diaphragm in the miniature diaphragm pump. In some embodiments, the offset and/or the gain is dynamically controlled in response to measured operational parameters in order to achieve desired operational characteristics.

BRIEF DESCRIPTION OF SEVERAL VIEWS OF THE DRAWINGS

[010] Figure 1 illustrates a perspective view of a miniature pump according to an embodiment of the invention.

[011] Figure 2 illustrates a cross-section of the perspective view of Figure 1.

[012] Figure 3 illustrates an exploded perspective view of a miniature pump according to an embodiment of the invention.

[013] Figure 4 illustrates a close up view of the cross-sectional view of Figure 2.

[014] Figures 5A and 5B illustrate a perspective view and a plan view, respectively, of a cross-section of a portion of a miniature pump according to certain embodiments.

[015] Figures 6A and 6B illustrate schematics of the mechanism of interaction between the actuator and the diaphragm of a miniature pump according to certain embodiments.

[016] Figure 7 is a graphical depiction of an efficiency comparison between a miniature electromagnetic diaphragm pump using an additional loading magnet according to an embodiment of the invention and an electromagnetic diaphragm pump without a loading magnet.

[017] Figures 8A and 8B illustrate a perspective view and a plan view, respectively, of a cross-section of a portion of a miniature pump body according to certain embodiments.

[018] Figure 9A illustrates a control and I/O subsystem including a number of control, storage and I/O components according to some embodiments of the present invention.

[019] Figure 9B shows a flowchart illustrating a number of steps performed by a processor to dynamically control a diaphragm according to pressure values measured by a sensor according to some embodiments of the present invention.

[020] Figure 9C illustrates an exemplary evolution over a number of pump cycles of several parameters described above, according to some embodiments of the present invention.

[021] Figure 9D shows an exemplary sequence of steps performed by a control system to implement an autostart mode.

[022] Figure 10 illustrates an exploded perspective view of an embodiment of a miniature pump.

[023] Figures 11A and 11B illustrate different views of a cross-section of a portion of one embodiment of a blow-off valve.

[024] Figures 12A and 12B illustrate exterior views of a blow-off valve according to some embodiments of the present invention.

[025] Figures 13A and 13B illustrate different views of a lower pump body according to some embodiments of the present invention.

[026] Figures 14A, 14B, and 14C illustrate different views of an upper pump body according to some embodiments of the present invention.

[027] Figures 15A, 15B, and 15C illustrate different views of a lower valve assembly body according to some embodiments of the present invention.

[028] Figures 16A and 16B illustrate different views of an upper valve assembly body according to some embodiments of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[029] Before the present devices and methods are described, it is to be understood that this invention is not limited to particular embodiments described. It is also to be understood that the terminology used herein is for the purpose of describing particular embodiments only, and is not intended to be limiting, since the scope of the present invention will be limited only by the appended claims.

[030] Unless defined otherwise, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. Although any methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present invention, the preferred methods and materials are now described.

[031] Short summaries of certain terms are presented in the description of the invention. Each term is further explained and exemplified throughout the description, figures, and examples. Any interpretation of the terms in this description should take into account the full description, figures, and examples presented herein.

[032] The singular terms “a,” “an,” and “the” include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to an object can include multiple objects unless the context clearly dictates otherwise. Similarly,

references to multiple objects can include a single object unless the context clearly dictates otherwise.

[033] The terms “substantially,” “substantial,” and the like refer to a considerable degree or extent. When used in conjunction with an event or circumstance, the terms can refer to instances in which the event or circumstance occurs precisely as well as instances in which the event or circumstance occurs to a close approximation, such as accounting for typical tolerance levels or variability of the embodiments described herein.

[034] The term “about” refers to a value, amount, or degree that is approximate or near the reference value. The extent of variation from the reference value encompassed by the term “about” is that which is typical for the tolerance levels or measurement conditions.

[035] All recited connections may be direct connections and/or indirect operative connections through intermediary structure.

[036] A set of elements includes one or more elements.

[037] Unless otherwise stated, performing a comparison between two elements encompasses performing a direct comparison to determine whether one element is larger (or larger than equal to) the other, as well as an indirect comparison, for example by comparing a ratio or a difference of the two elements to a threshold

[038] Figure 1 illustrates a perspective view of a miniature pump 10, which includes inlet port 12 and outlet port 14. The miniature pump 10 includes pump body 11, which can be a single piece or can be formed from multiple pieces. In Figure 1, the pump body 11 includes upper body 11a and lower body 11b. The miniature pump 10 also includes actuator 15. Preferably, the actuator 15 is an electromagnetic voice-coil type actuator such as those commonly used in mobile phones and other electronic devices.

[039] Figure 2 illustrates a cross-section of the perspective view of Figure 1 of the miniature pump 10. Figure 2 illustrates the diaphragm assembly 50, which includes diaphragm 55. Figure 2 also illustrates the actuator membrane 5 on the upper surface of the actuator 15. The actuator membrane 5 is coupled to the diaphragm assembly 50 and drives the motion for the miniature pump to function.

[040] Figure 3 illustrates an exploded perspective view of the miniature pump 10. Figure 3 illustrates the diaphragm assembly 50 as including upper spacer 53, diaphragm 55, magnet 57, and housing 59. The upper spacer 53 helps define the upper portion of the pumping chamber in which the diaphragm 55 reciprocates. The upper spacer 53 may alternately be a component, such as a molded component, of the lower pump body 11b. The magnet 57 is attached to the lower surface of diaphragm 55 and also attached to the upper surface of the actuator membrane 5. The housing 59 is attached to the lower surface of the lower pump body 11b. The spacer 53 is configured to fit within the inner circumference of the upper section of housing 59. The outer edges of the diaphragm 55 are sandwiched between the lower surface of the spacer 53 and the upper surface of the inner ring of housing 59 such that the spacer 53 and the housing 59 cooperate to keep the outer edges of the diaphragm 55 fixed. The edges of the diaphragm 55 are held fixed while the inner portion of the diaphragm 55 is able to reciprocate up and down, and the diaphragm 55 thereby acts as the volume displacement mechanism of the miniature pump 10. The components that make up diaphragm assembly 50 should be joined in a fluid-tight and/or air-tight manner.

[041] Figure 3 illustrates the lower pump body 11b, which can be a molded part that incorporates many of the flow-paths and flow-control features of the miniature pump 10. For example, the inlet valve recess 21a is configured to accept the inlet valve 20a and the outlet valve recess 21b is configured to accept the outlet valve 20b. Also within lower pump body 11b are openings and ports configured to complement the valve and diaphragm arrangement and allow for controlled flow of gas or liquid through the lower pump body 11b.

[042] Figure 3 illustrates a control board 70, a blow-off valve 60, and a sensor 80, all of which can be housed in recessed areas within the pump body. In Figure 3, both the upper pump body 11a and the lower pump body 11b include features configured to house the control board 70, the blow-off valve 60, and the sensor 80.

[043] Generally speaking, the operation of the inlet valve 20a and the outlet valve 20b is similar to a positive displacement diaphragm pumps. That is, when

the diaphragm is withdrawn away from the inlet port 12, the inlet valve 20a is also drawn away by negative pressure from upper inlet chamber port 202a and engages against inlet port offset 201a. This movement creates a flowpath down through the inlet port 12, through the upper inlet chamber port 203a (see Figure 8B), across the inlet valve 20a, and down through the lower inlet chamber port 202a. The negative pressure also draws the outlet valve 20b into sealing engagement with the lower outlet chamber port 202b, which seals the outlet chamber and prevents flow through to the outlet 14.

[044] When the diaphragm 55 begins its return stroke towards the inlet port 12, positive pressure forces the inlet valve 20a away from the inlet port offset 201a and into sealing engagement with the upper inlet chamber port 203a. The positive pressure also forces the outlet valve 20b away from the lower outlet chamber port 202b and into engagement with the outlet port offset 201b. This movement creates a flowpath from the diaphragm chamber, through the lower outlet chamber port 202b, across outlet valve 20b, through upper outlet chamber port 203b (see Figure 8B) and out through outlet 14.

[045] Figure 4 illustrates a close up view of the cross-sectional view of Figure 2. In Figure 4, the inlet valve 20a is depicted in its closed position such that its upper surface is sealingly engaged against upper inlet chamber port 202a and the outlet valve 20b is depicted as engaged against the outlet port offset 201b. Further, outlet valve 20b is depicted as disengaged from lower outlet chamber port 202b.

[046] The valves are sized and configured to be movable by the range of pressure expected from the use environment of the miniature pump 10. For example, the valves should have a weight to surface area ratio such that they are movable by the flow of liquid or gas when the miniature pump is in use. Further, the valves are made of a material that enables the valves to sealingly engage against their respective ports when moved into such as sealing position by liquid or gas flow. Rubber is one example of a suitable material for making valves in such a miniature pump.

[047] Figures 5A and 5B illustrate a perspective view and a plan view, respectively, of a cross-section of a portion of a miniature pump 10 according to

certain embodiments. Figures 5A and 5B illustrate the housing 59 engaged with a section of lower pump body 11b. A portion of the diaphragm is shown as engaged to housing 59 and labeled with the reference 55a. Actually, the diaphragm 55 spans the housing 59 and in this perspective view would obscure the magnet 57 from view. For the purposes of these views, only a portion of the diaphragm 55 is shown. The magnet 57 is attached to the actuator membrane 5.

[048] When known diaphragm displacement pumps are connected to a closed chamber in order to pull vacuum on such a chamber, each pump stroke requires successively more energy than the last stroke as the pressure difference across the diaphragm increases. That is, the greater the vacuum in the closed chamber, the more difficult it is for the diaphragm to travel a full stroke. Generally, pumps are driven with more power in order to generate longer pump strokes under higher vacuum conditions.

[049] In contrast, pumps according to certain embodiments do not require as much of an increase in power to generate longer pump strokes under higher vacuum conditions because these miniature pumps are loaded on the exhaust stroke. In contrast to previously known positive displacement diaphragm pumps, the miniature pump 10 includes the magnet 57, which functions to load the pump stroke of the miniature displacement pump during the exhaust stroke. The actuator membrane 5 can be driven using a sinusoidal signal such that the actuator membrane 5 reciprocates between an upper position and a lower position. Since the actuator membrane 5 is attached to the diaphragm 55, the reciprocation of the actuator membrane 5 causes a similar reciprocation of the diaphragm 55. When the actuator membrane 5 and diaphragm 55 reciprocate away from the pump body 11, the diaphragm motion is expanding the size of the diaphragm chamber and drawing gas or liquid within the chamber in a pump stroke. When the actuator membrane 5 and diaphragm 55 reciprocate toward the pump body 11, the diaphragm motion is contracting the size of the diaphragm chamber 54 in an exhaust stroke. The inlet valve 20a and the outlet valve 20b are, of course, moving in concert with such pump strokes and exhaust strokes to allow gas or liquid to flow one way through the miniature pump from the inlet to the outlet.

[050] The actuator 15 can be an electromagnetic voice coil, which includes an electromagnetic drive element coupled to the actuator membrane 5. Such a voice coil actuator performs essentially like a loudspeaker, such that waveform signals sent to the electromagnetic drive element drive the actuator membrane in a pattern generated by the waveform.

[051] Figures 6A and 6B illustrate schematics of the mechanism of interaction between the actuator and the diaphragm. The actuator 15 includes an actuator base 15b, an actuator membrane 5, an actuator pole magnet 7, and actuator coil 3. The actuator pole magnet 7 is fixed to the actuator base 15b. The actuator coil 3 is fixed to the underside of the actuator membrane 5. The magnet 57 is a permanent magnet and is fixed to the upper surface of the actuator membrane 5 and to the underside of the diaphragm 55. In some cases, the position of the magnet 57 is adjustable up and down with respect to the actuator membrane 5, but in Figures 6A and 6B it is depicted as fixed to the actuator membrane 5.

[052] During the pump stroke, electric current is applied to the actuator coil 3 to create an electromagnetic field that attracts the actuator coil 3 to the actuator pole magnet 7. The actuator coil 3 is fixed to the actuator membrane 5, which is connected to the diaphragm 55. Thus, the diaphragm 55 is pulled away from the diaphragm chamber 54, thereby increasing the volume of the chamber and drawing air or liquid through the inlet valve and into the diaphragm chamber in a pump stroke.

[053] Referring still to Figures 6A and 6B, the magnet 57 is oriented to be magnetically attracted to the actuator pole magnet 7. During the pump stroke when the diaphragm 55 is pulled away from the diaphragm chamber 54, the magnetic attraction between the magnet 57 and the actuator pole magnet 7 helps pull the diaphragm 55 and the actuator membrane 5 more fully back towards the actuator pole magnet 7 than if the magnet 57 was not present in this position. This is especially helpful at high suction where the diaphragm 55 would not ordinarily be able to travel as far downward because of the pressure drop across the diaphragm 55. That is, at low levels of negative pressure in the diaphragm chamber 54, there is low resistance to pulling the diaphragm 55 away from the diaphragm chamber 54. Thus, the electromagnetic force generated by low power

in the actuator coil 3 is sufficient to drive the pump stroke. However, at higher levels of negative pressure in the diaphragm chamber 54, there is higher resistance to pulling the diaphragm 55 and therefore higher power would be required. The magnet 57 is helpful in this context because it adds magnetic force to pull the diaphragm 55 down without requiring additional power since the magnet 57 is a permanent magnet.

[054] Figure 6B depicts the exhaust stroke, in which electric current is applied to the actuator coil 3 to create an electromagnetic field that repels the actuator coil 3 from the actuator pole magnet 7. Repelling the actuator coil 3 forces the actuator membrane 5 and the diaphragm 55 towards the diaphragm chamber 54, which reduces the volume of the diaphragm and drives air or liquid through the outlet valve in an exhaust stroke. During this exhaust stroke, the magnet 57 is also pushed away from the actuator pole magnet 7. That is, the electromagnetic force is sufficient to repel the actuator coil 3, and all the components fixed to it (such as the actuator membrane 5, the magnet 57, and the diaphragm membrane 55) away from the actuator pole magnet 7.

[055] Advantageously, the magnet 57 is moved away from the actuator pole magnet 7 during the exhaust stroke. This is an advantage because the diaphragm 55 encounters comparatively low resistance during the exhaust stroke as gas or liquid is displaced from the diaphragm chamber 54. Thus, the exhaust stroke separates the magnet 57 from the actuator pole magnet 7 with relatively low additional power requirement than if the magnet 57 was not on the diaphragm 55. Then, during the pump stroke, the separation between the magnet 57 from the actuator pole magnet 7 provides additional magnetic force as described above. As a result, the miniature pump is able to operate more efficiently at low power than a conventional electromagnetic diaphragm pump.

[056] Figure 7 is a graphical depiction of an efficiency comparison between an miniature electromagnetic diaphragm pump using an additional “loading” magnet according to an embodiment of the invention and an electromagnetic diaphragm pump without a loading magnet. This graph plots the physical displacement, or stroke length, of the diaphragm as a function of the number of pump strokes as the electromagnetic pump is used to evacuate a closed chamber. Further, this

graph assumes that the pumps are driven at a generally constant power, although the benefit of the loading magnet is not limited to constant power applications. Because the pumps in the graph are evacuating a closed chamber, the pressure difference across the diaphragm increases with each pump stroke as the negative pressure increases inside the closed chamber. While the loaded and the unloaded diaphragm both travel at or near their full displacement during the initial pump strokes, the efficiency of the pumps diverges as negative pressure increases. The unloaded diaphragm (labeled as “no loading”) has a rapidly diminishing pump stroke such that it becomes comparatively inefficient at higher pump strokes. The loaded diaphragm, in contrast, is able to be physically displaced to a greater degree in this constant power application because of the passive magnetic loading force of the permanent magnet fixed to the diaphragm.

[057] The relative strength of the magnetic forces among the actuator components (i.e., the electromagnetic coil and the pole magnet) and the diaphragm magnet can be used to tune the efficiency of the miniature pump. For example, a stronger diaphragm magnet will provide more loaded energy to the pump stroke of the diaphragm when separated from the pole magnet, but will also require more power to be separated during the exhaust stroke.

[058] In some embodiments, the diaphragm magnet is fitted with an adjustment mechanism that allows the separation between the diaphragm magnet and the pole magnet to be varied. For example, the diaphragm magnet could be housed within a recess fixed to the upper surface of the actuator membrane. The diaphragm magnet could rest atop a tapered adjustment screw such that when the screw is turned one direction the magnet moves closer to the actuator membrane and when the screw is turned the opposite direction the magnet moves farther from the actuator membrane.

[059] Advantageously, magnetic fields are sensitive to distance. The strength of the magnetic field between the two permanent magnets (the actuator pole magnet and the diaphragm magnet) can decay following the inverse cube of the distance from the source. That is, if D is the distance between the magnets and F is the strength of the forces, then $F = 1/D^3$. This is advantageous for embodiments of the invention because the force is much higher when the

permanent magnets are closer, such as at the maximum displacement of the diaphragm during the pump stroke. And, the force is much lower at the minimum displacement of the diaphragm during the exhaust stroke. The loaded miniature pump designs of embodiments of the invention can operate with significantly more efficiency than unloaded pump designs because of this inverse relationship between force and distance.

[060] In accordance with some embodiments, the miniature pump preferably is about 12 to 20mm long, about 10 to 15mm wide and about 3 to 9mm high, more preferably about 18mm long, about 12mm wide and about 7mm high. The mass is preferably about 1 to 5 grams, more preferably about 3 grams. The miniature pump preferably operates with a voltage between about 3.5 to 5 volts, peak current when running of about 100 to 200 mA, and standby current of about 20 to 40 mA. The miniature pump is self-priming and preferably is less than about 90 dB two inches away, more preferably, less than about 70 dB two inches away. The miniature pump preferably has a peak suction of about -6 in Hg, more preferably about -8 in Hg. The suction rate is preferably about 0 to -6 in Hg in less than about 10 seconds with 10 mL volume of air, more preferably about 0 to -8 in Hg in less than about 10 seconds with 10 mL volume of air.

[061] Figures 8A and 8B illustrate a perspective view and a plan view, respectively, of a cross-section of a portion of the pump body 11 according to certain embodiments. In these views, upper channel 52a and lower channel 52b are in fluid connection from the diaphragm chamber to the blow-off valve 60 and the sensor 80. The valve channel 62 and the sensor channel 82 are in fluid connection with upper channel 52a. These channels allow for monitoring and control of the pressure in the diaphragm chamber via the sensor 80 and the blow-off valve 60. The channels can be designed as part of the molded pump body 11 sections, can be drilled into the pump body 11 after molding, or can be tubes or other conduits that are included in an overmolding step or during assembly of the pump body.

[062] The blow-off valve 60, the sensor 80, and the control board 70 work together in a closed loop control system for monitoring and adjusting the performance of the miniature pump. In one example, the closed loop control

systems can be programmed to maintain a level of negative pressure within the diaphragm chamber. That is, the sensor continuously monitors the pressure level in the diaphragm chamber and provides that data to the control board. The firmware (or software) on the control board can compare the data to the programmed pressure level and then send power to the actuator to drive the miniature pump to increase the pressure or send a signal to the blow-off valve to release negative pressure. In another example, a pre-programmed or user-selected suction profile can be generated using the closed loop control system. That is, rather than seeking a set level of negative pressure, the closed loop control system seeks a time-dependent pattern of pressure levels by continuously comparing the negative pressure level in the diaphragm chamber with the time-dependent level specified in the profile. The blow-off valve or the pump can then be activated as needed.

[063] In another example, the closed loop control system can help optimize the efficiency of operation and reduce noise levels. In this example, the firmware uses a look-up table to find optimal operating conditions for the miniature pump at a given level of negative pressure. At a given pressure the miniature pump may operate most efficiently at a certain power signal profile. That is, a particular shape of the signal waveform (e.g., the amplitude and frequency of a sinusoidal signal) may allow the miniature pump to operate more quietly than another similar shape at a given pressure. Generally, noise in the miniature pump is generated by the diaphragm hitting the walls of the diaphragm chamber and by the valves hitting the walls of their valve recesses and offsets. By calibrating the position of the diaphragm and valves at given power levels and pressure levels and cross-referencing those positions against power and pressure levels in a look-up table accessible to the firmware, the miniature pump can be operated in a way that reduces or eliminated valve and/or diaphragm noise. Further, reducing or minimizing diaphragm and valve noise increases the efficiency of the miniature pump since less energy is lost to the pump body through collisions between the valves and/or diaphragm and the pump body.

[064] Another advantage of the closed loop control system is that the blow-off valve can be activated under certain conditions. For example, if the negative

pressure exceeds a certain level, the firmware can activate the blow-off valve to allow air into the diaphragm chamber. As another example, if the valve temperature rises above a certain level (as detected by a temperature sensor integrated into the miniature pump and in communication with the control board), the firmware can activate the blow-off valve.

[065] Generally, the control and sensing components of the miniature pump can reside within the pump housing or can be remote from the pump. That is, a processor and sensor can be located away from the actual pump body and still be able to provide the sensing and control features described herein. Also, the blow-off valve maybe located remotely from the pump body provided it has the fluid connection necessary to provide the pressure relief performance. Thus, the closed loop feedback system can exist in a system of physically separate components that are functionally interconnected.

[066] Figure 9A illustrates a control and I/O subsystem 220 including a number of control, storage, and I/O components according to some embodiments of the present invention. Some of the components may be part of the control board 70, while others, such as a set of user input-output (I/O) devices 232, may be electrically connected to, but physically separated from, the control board 70. In some embodiments, the control board 70 includes a processor 224, a memory 226, a set of storage devices 234, and a set of external communications interface controller(s) 230, and analog-to-digital (A/D) converter 234, and a digital-to-analog (D/A) converter 236, all interconnected by a set of buses 250. Analog circuitry 238 is connected to A/D converter 234. Analog circuitry 238 includes components such as amplifiers and filters configured to perform analog processing such as amplification and filtering on analog signals received by the control board 70 from external sensors. Analog circuitry 240 is connected to D/A converter 236. Analog circuitry 240 includes components such as amplifiers configured to perform analog processing such as amplification on analog signals received from D/A converter 236. A/D converter 234 and D/A converter 236 connect the processor 224 to the blow-off valve 60, sensor 80 and diaphragm 55, as described below.

[067] In some embodiments, the processor 224 comprises a microcontroller integrated circuit or other microprocessor configured to execute computational and/or logical operations with a set of signals and/or data. Such logical operations are specified for the processor 224 in the form of a sequence of processor instructions (e.g. machine code or other type of software). A memory unit 226 may comprise random access memory (RAM, e.g. DRAM) storing data/signals read and/or generated by processor 224 in the course of carrying out instructions. The processor 224 may also include additional on-die RAM and/or other storage.

[068] Storage devices 228 include computer-readable media enabling the non-volatile storage, reading, and writing of software instructions and/or data, such as EEPROM/flash memory devices. Communications interface controller(s) 230 allow the subsystem 220 to connect to digital devices/computer systems outside the control board 70 through wired and/or wireless connections. For example, wired connections may be used for connections to components such as user I/O devices 232, while wireless connections such as Wi-Fi or Bluetooth connections may be used to connect to external components such as a smartphone, tablet, PC or other external controller. Buses 250 represent the plurality of system, peripheral, and/or other buses, and/or all other circuitry enabling communication between the processor 224 and devices 226, 228, 230, 234, and 236. Depending on hardware manufacturer, some or all of these components may be incorporated into a single integrated circuit, and/or may be integrated with the processor 224.

[069] User I/O devices 232 include user input devices providing one or more user interfaces allowing a user to introduce data and/or instructions to control the operation of subsystem 220, and user output devices providing sensory (e.g. visual, auditory, and/or haptic) output to a user. User input devices may include buttons, touch-screen interfaces, and microphones, among others. User output devices may include one or more display devices, speakers, and vibration devices, among others. Input and output devices may share a common piece of hardware, as in the case of touch-screen devices.

[070] In some embodiments, the processor 224 controls the positioning of the diaphragm 55 by using analog circuitry 240 to dynamically control a direct current (DC) offset and a gain of a diaphragm drive signal. The offset level controls the resting position of diaphragm 55, while the gain controls the amplitude of a sinusoidal or other periodic signal waveform which determines the amplitude of the excursion of the diaphragm 55 from its resting position. The offset and gain may be controlled dynamically in response to measured operational parameters in order to achieve desired operational characteristics, as described below. In particular, the offset and/or gain may be changed in response to variations in pressure measured using the sensor 80.

[071] As the pump operates over time in a given evacuation sequence, the pressure differential across the diaphragm 55 generally increases. Without changes in offset and gain, the increasing pressure differential would lead to a gradual change in the resting position of the diaphragm 55. The increase in pressure difference leads to changes in the optimal offset and gain values for achieving particular pump characteristics such as maximum rate of increase in pressure difference (pumping speed), minimum current consumption (or maximum energy efficiency), or minimal noise. In some embodiments, the offset is decreased (or increased) over time to compensate for the effect of the increased pressure differential across diaphragm 55 on the resting position of diaphragm 55. The offset and gain values may be varied according to a pressure lookup table, and/or according to dynamically measured changes in one or more parameters of interest, such as a pressure difference (delta) observed over one pump cycle.

[072] Figure 9B shows a flowchart illustrating a number of steps performed by processor 224 to dynamically control the diaphragm 55 according to pressure values measured by the sensor 80 according to some embodiments of the present invention. In a step 300, processor 224 receives an instantaneous pressure value measured by the sensor 80 for the current pump cycle. In a step 302, the pressure difference (delta) relative to a previously-measured pressure value (e.g. a pressure value measured for the immediately-prior pump cycle) is determined. In a step 304, the determined pressure delta is compared to

one or more reference values, in order to determine a magnitude and/or sign of offset and/or gain adjustments to be made for subsequent pump cycles. A reference value may be equal to or otherwise determined according to a pressure delta measured for an immediately-previous pump cycle, or an expected pressure delta for a given measured pump pressure as retrieved from a calibration table or other storage. Performing such a comparison may comprise subtracting a reference value from the measured pressure delta.

[073] In a step 306, it is determined whether the offset is to be updated for the next pump cycle. In some embodiments, the determination whether to update the offset may be performed independently of the pressure delta comparison described above. For example, offset updates may be performed during certain blocks of cycles while gain updates are performed during other blocks of cycles, in order to attempt to separate the measured effects on pressure delta of offset and gain changes. In another example, offset and gain updates may be performed on alternating pump cycles. In some embodiments, both offset and gain updates may be performed during at least some pump cycles. In some embodiments, a determination whether to update the offset may be performed according to the pressure delta comparison described above, if it is determined that an offset change is likely to improve pump performance.

[074] In a step 308, the offset is updated according to the pressure delta comparison performed in step 304. In some embodiments, updating the offset comprises incrementing or decrementing the offset by a fixed step (e.g. ±1) if it is determined that such incrementing/decrementing is likely to lead to improve pump performance on the next pump cycle.

[075] In a step 310, is it determined whether the gain is to be updated for the next pump cycle. Step 310 may be performed in a manner similar to that described above for step 306. Subsequently, in a step 312, the gain is updated according to the pressure delta comparison performed in step 304. In some embodiments, updating the gain comprises incrementing or decrementing the gain by a fixed step (e.g. ±1) if it is determined that such incrementing/decrementing is likely to lead to improve pump performance on the next pump cycle.

[076] Figure 9C illustrates an exemplary evolution over a number of pump cycles of several parameters described above, according to some embodiments of the present invention. The x-axis denotes time (or pump cycles), while the y-axis illustrates the various parameter values. An estimated offset 400 represents an offset chosen according to a predetermined calibration table, independently of dynamically-measured pressure values. A dynamically-determined offset 402 represents an offset chosen according to dynamically-determined pressure delta values as described above. A vacuum level (compression) 404 represents the measured vacuum level, or pressure differential across the diaphragm 55. A gain 408 represents a gain. A pressure delta 406 represents the pressured delta observed over each pump cycle, i.e. effectively the derivative of the vacuum level 404.

[077] As illustrated in Figure 9C, the vacuum level 404 increases over time as the pump operates, with the per-cycle pressure delta 406 generally decreasing over time as the pump works against an increasing diaphragm pressure differential. The gain 408 suitable for maintaining the pump in an optimal operating regime increases over time. At each time point, a low gain leads to a suboptimal displaced volume, while a high gain can lead to a loss of efficiency and/or noise if the diaphragm 55 collides with an external structure at the end of its excursion. At the same time, the offset corresponding to an optimal operating regime decreases over time, compensating for the effect of the pressure differential across the diaphragm 55 on the central position of diaphragm 55. The dynamically-determined offset 402 may differ from the previously-determined (calibrated) offset 400, for example due to differences between the individual characteristics of the pump (which determine the offset 402) and the general pump characteristics used to generate the calibration data determining the estimated offset 400. For example, while the general offset 400 decreases monotonically, the dynamically-determined offset 402 occasionally increased. Also, the dynamically-determined offset 402 at times decreased at a different rate than the general offset 400. Using dynamically-determined offset 402 facilitates the manufacture of pumps using less-stringent manufacturing tolerances, as optimal pump operation is less dependent on any mismatch between individual

pump characteristics and the general pump characteristics reflected in calibration data.

[078] In some embodiments, a pump and associated control system as described above may be used to generate pressure patterns other than a monotonically-increasing one such as the one illustrated in Figure 9C. For example, alternating pressure (suction) periods may be used by alternating periods of increased pumping (and/or decreased associated relief valve use) with periods of decreased or stopped pumping (and/or increased associated relief valve use).

[079] Figure 9D shows an exemplary sequence of steps performed by a control system to implement an autostart mode. In a step 500, processor 224 receives a current measured pressure value while the pump is off. In a step 502, processor 224 compares the measured pressure to a predetermined positive threshold. Detecting a high level of positive pressure indicates that the chamber to be evacuated has been engaged and somewhat sealed. If the measured pressure is not above the threshold, the process returns to step 500. If the measured pressure is above the threshold, processor 224 starts the pump autostart process by turning on the pump (step 504). A current pressure value for the present pump cycle is received in a step 506, and compared to a prior pressure value in a step 508. In a step 510, it is determined whether the measured pressure value(s) indicate that the chamber seal has been breached. For example, a sudden large drop in pressure or a return to atmospheric pressure may indicate that the chamber no longer sealed. If no major loss of seal is detected, the offset and/or gain are adjusted as described above (step 512), and the process returns to step 506 to receive a pressure value for the next pump cycle. If major loss of seal is detected, the pump is turned off (step 514), and the process returns to step 500 to allow detecting a new engagement of a chamber.

[080] In some embodiments, step 512 may include turning on and off the pump so as to maintain a certain level of negative pressure. Step 512 may include monitoring parameters such as the fraction of time that the pump is on or the pump pressure slow to determine whether to increase or decrease the pump's

activity. The pump then self-regulates to maintain a certain level of negative pressure.

[081] Figure 10 illustrates an exploded perspective view of an embodiment of a miniature pump 1010. The miniature pump 1010 includes an actuator 1015, which can be an electromagnetic voice-coil type actuator such as those commonly used in mobile phones and other electronic devices. Attached to the actuator 1015 is the lower body 1011b, which contains the diaphragm assembly as described previously herein. Figure 10 specifically depicts certain elements of the diaphragm assembly, including the magnet 1057 and the diaphragm 1055. The lower body 1011b and the lower valve assembly body 1200b together form the diaphragm chamber as described elsewhere herein. Figure 10 further illustrates lower body 1011b supporting the control board 1070 via the control board mount 1070m and control board wires 1071a, 1071b extending from the control board 1070, providing electrical connectivity to the electromagnetic features of the diaphragm assembly. Also present on the control board 1070 are the sensor 1080, which has the sensor gasket 1085 forming a seal between the sensor 1080 and the upper body 1011a, and the blow-off valve 1060. The blow-off valve diaphragm 1065 is illustrated in Figure 10, while the upper sections of the blow-off valve, including its exit port, are not specifically pictured.

[082] Still referring to Figure 10, lower valve assembly body 1200b is attached to the upper surface of the outer ring of diaphragm 1055 in the manner describer herein (see, for example, Figures 5A, 5B, 6A, and 6B and the related description). The lower valve assembly body 1200b can include the valve recesses, inlet ports, and sealing surfaces necessary to provide the valve action described herein. These features can be integrally formed into the lower valve assembly body 1200b, such as by injection molding a unitary part, they can be formed from multiple molding process, or they can be fabricated into the lower valve assembly body 1200b by cutting or machining or the like. The lower valve assembly gasket 1205b is placed between lower valve assembly body 1200b and upper valve assembly body 1200a and provides a fluid tight seal to the valve chambers. The inlet valve 1020a and outlet valve 1020b can float within the valve chambers and function as described elsewhere herein.

[083] Again still referring to Figure 10, upper valve assembly body 1200a is similar to lower valve assembly body 1200b in that it can include the valve recesses, inlet ports, and sealing surfaces necessary to provide the valve action described herein and such features can be formed in the same variety of ways described for lower valve assembly body 1200b. Further, the fluid flow paths necessary to provide connections among the valve chambers, pressure sensor, and blow-off valve can be formed in upper valve assembly body 1200a. The upper valve assembly gasket 1205a can form the upper boundary of some of these flow paths and provides a seal between the upper valve assembly body 1200a and the upper body 1011a. The upper body 1011a, in turn, can also have flow paths, which in Figure 10 are depicted as upper body channels 1008. The upper valve assembly gasket 1205a and the upper body seal 1009 for the lower and upper boundaries, respectively, for certain flow paths. Further, the cutouts in the upper valve assembly gasket 1205a provide a fluid connection to the inlet port 1012 and outlet port 1014 on the upper body 1011a. Screws 1001 are used in the final assembly of the miniature pump 1010, but of course other methods of securing the upper body 1011a to the lower body 1011b can be used.

[084] The flow paths in the upper body 1011a provide several connections, such as: (1) a connection between the blow-off valve and the inlet port of the miniature pump; (2) a connection between the blow-off valve and the outlet port of the miniature pump; and (3) a connection between the pressure sensor and the suction chamber.

[085] Figures 11A and 11B illustrate different views of a cross-section of a portion of one embodiment of a blow-off valve. The upper surface of the blow-off valve diaphragm 1065 engages a port on the outer case of the blow-off valve (which is not pictured). The underside of the blow-off valve diaphragm 1065 is secured to a blow-off valve attractor plate 1068, which is formed from a ferrous material. Below the blow-off valve attractor plate 1068 is the blow-off valve yoke 1067 and the blow-off valve coil 1069, which cooperate to provide electromagnetic forces that can attract the blow-off valve attractor plate 1068. The blow-off valve diaphragm 1065 is formed such that in its resting state it forms a seal against the port on the blow-off valve. When current is run through the

blow-off valve coil 1069, the blow-off valve attractor plate 1068 is pulled down, which in turn pulls the blow-off valve diaphragm 1065 away from its sealed position. The blow-off valve yoke 1067, blow-off valve coil 1069, and blow-off valve attractor plate 1068 are housed within the blow-off valve case 1061. Figures 12A and 12B illustrate exterior views of the blow-off valve 1060, including the blow-off valve port 1062 and blow-off valve case 1061.

[086] The blow-off valve diaphragm 1065 can be formed from materials such as silicone rubber or its equivalents. The blow-off valve attractor plate 1068 and the blow-off valve yoke 1067 can be formed from alloys with comparatively high magnetic permeability, such as a nickel-iron alloy. The blow-off valve coil 1069 can be formed from winding copper or other conductive wire. The blow-off valve case 1061 can be formed from a polymer-based material, such as a glass-filled polycarbonate.

[087] The blow-off valve functions by having a minimum preload that presses the diaphragm against the valve port to ensure that the valve is closed prior to initiating suction. The preload can be chosen by using a diaphragm material with sufficient elastic modulus such that the diaphragm remains engaged against valve port in the assembled state. In some embodiments, the blow-off valve can further include a non-magnetic compression spring within the electromagnet assembly that always pushes up on the attractor plate. In this scenario, the diaphragm would be designed to be as flexible as possible and preload could vary in accordance with the tolerances associated with the spring constant and the free length.

[088] Because this electromagnetic blow-off valve operates within a miniature pump that itself is driven by electromagnetic forces, it is necessary to take into account the overall magnetic fields experience by the attractor plate. The valve diaphragm should be stiff enough to not be affected by such peripheral magnetic forces. That is, the diaphragm should resist unwanted displacement via interaction between the attractor plate coupled to the diaphragm and the peripheral magnetic fields. Yet, a stiffer diaphragm requires a stronger local magnetic field to displace it and the attractor plate. One method to achieve a desirable local magnetic field is to optimize the number of coil turns in the blow-

off valve coil. A greater number of coil turns can be achieved by growing the overall electromagnet in height or diameter. While it is more space efficient to grow in height (resistance increases more slowly given lower total wire length which can prevent having to jump to a lower gauge wire), increases in the outer diameter can also provide space for more coils, which may utilize the available enclosure space more effectively.

[089] In some embodiments, the maximum current available to the electromagnet is assumed to be 300mA. This is based on limitations of the battery (1C max). If higher currents could be sourced, the resistance of the component (current 10-12 ohms) would also have to be reduced given the assumed minimum battery voltage of 3.0 V for a miniature pump. In general, the current draw of the blow-off valve should be monitored according to the application of the miniature pump.

[090] The term “blow-off” valve as used herein refers generally to a type of valve used to control or limit the pressure in a system or vessel. Such valves may also be known as relief valves, safety valves, and the like, and certain embodiments herein encompass such valves regardless of how they are named.

[091] Figures 13A and 13B illustrate different views of a lower pump body 1011b according to certain embodiments. The lower pump body 1011b includes a cutout that forms a diaphragm spacer 1053. The edge of the diaphragm contacts the edge of the diaphragm spacer 1053 and is thereby spaced away from the actuator membrane of the actuator that is attached to the underside of the lower pump body 1011b.

[092] Figures 14A, 14B, and 14C illustrate different views of an upper pump body 1011a according to certain embodiments. The upper pump body 1011a includes upper body channels 1008, which connect the ports 1012 and 1014 to the sensor area and the blow-off valve area of the upper pump body 1011a. The upper pump body 1011a includes a sealing feature 1206. A sealing feature 1206 generally circumscribes the areas of the upper pump body 1011a the areas of the upper pump body 1011a in which fluid is handled. The sealing feature 1206 can be a raised area, such as a ridge, that mechanically interacts with a gasket to form a reliable seal around the fluid handling area.

[093] Figures 15A, 15B, and 15C illustrate different views of an upper valve assembly body 1200a according to certain embodiments. The upper valve assembly body 1200a includes ports, recesses and offsets similar to those described elsewhere herein. Figure 15A depicts a semi-transparent perspective view of the lower surface of the upper valve assembly body 1200a and Figure 15B depicts a plan view of that same surface. The upper valve assembly body 1200a includes inlet valve recess 1021a and outlet valve recess 1021b, which provide a seating area for the inlet valve and outlet valve, respectively. The inlet and outlet valves interact with the upper inlet chamber port 1203a and upper outlet chamber port 1203b to provide the valved pumping action described herein. Further, the upper valve assembly body 1200a includes outlet port offset 1201b. A sealing feature 1206 is present on this lower surface of the upper valve assembly body 1200a to provide improved sealing to the lower valve assembly gasket 1205b and separation of the inlet and outlet areas. Figure 15C depicts the upper surface of the upper valve assembly body 1200a, having the upper inlet chamber port 1203a and upper outlet chamber port 1203b. A sealing feature 1206 is present on this upper surface of the upper valve assembly body 1200a to provide improved sealing to the upper valve assembly gasket 1205a and separation of the inlet and outlet areas.

[094] Figures 16A and 16B illustrate different views of a lower valve assembly body 1200b according to certain embodiments. Figure 16A depicts a semi-transparent perspective view of the upper surface of the lower valve assembly body 1200b and Figure 16B depicts a plan view of that same surface. The lower valve assembly body 1200b includes inlet valve recess 1021a and outlet valve recess 1021b, which provide a seating area for the inlet valve and outlet valve, respectively. The inlet and outlet valves interact with the lower inlet chamber port 1202a and lower outlet chamber port 1202b to provide the valved pumping action described herein. Further, the upper valve assembly body 1200a includes inlet port offset 1201a. A sealing feature 1206 is present on this upper surface of the lower valve assembly body 1200b to provide improved sealing to the lower valve assembly gasket 1205b and separation of the inlet and outlet areas.

[095] While the invention has been described with reference to certain embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from its scope. Therefore, it is intended that the invention not be limited to the particular embodiment disclosed, but that the invention will include all embodiments falling within the scope of the appended claims.

CLAIMS:

1. A miniature pump, comprising:

a voice coil actuator comprising a support member, an electromagnetic coil, and a pole magnet wherein the electromagnetic coil is coupled to the support member;

a diaphragm coupled to the support member, wherein motion of the support member drives motion in the diaphragm with respect to a chamber; and

a permanent magnet coupled to the diaphragm.

2. The miniature pump of claim 1 wherein the permanent magnet and the pole magnet are separated by a first distance, which increases to a second distance when the electromagnetic coil repels the pole magnet.

3. The miniature pump of claim 1 wherein the magnetic poles of each of the pole magnet and the permanent magnet are arranged such that the pole magnet and the permanent magnet are magnetically attracted to each other.

4. The miniature pump of claim 1 wherein the pole magnet and the permanent magnet are arranged with the electromagnetic coil in a space between them.

5. The miniature pump of claim 1 further comprising a processor for dynamically controlling the position of the diaphragm.

6. The miniature pump of claim 5 wherein the processor dynamically controls the diaphragm in response to measured data.

7. The miniature pump of claim 5 further comprising a sensor for measuring data.

8. The miniature pump of claim 6 or claim 7 wherein the data is pressure.

9. The miniature pump of claim 6 or claim 7 wherein the data is diaphragm position.

10. The miniature pump of claim 5 wherein the processor dynamically controls a direct current offset in an electrical signal.

11. The miniature pump of claim 5 wherein the processor dynamically controls a direct current gain in an electrical signal.

12. The miniature pump of claim 1 further comprising a processor for initiating an autostart process.

13. The miniature pump of claim 12 further comprising a sensor for measuring pressure.

14. The miniature pump of claim 13 wherein the processor initiates the autostart process in response to a pressure change measured by the sensor.

15. The miniature pump of claim 13 wherein the processor turns off the pump in response to a pressure change measured by the sensor.

16. The miniature pump of claim 1 or claim 15 further comprising a blow-off valve.

17. The miniature pump of claim 16 wherein the blow-off valve is opened in response to a measured change in temperature.

18. The miniature pump of claim 1 wherein the permanent magnet maintains a fixed distance from the electromagnetic coil during reciprocation of the diaphragm.

19. The miniature pump of claim 1 wherein the permanent magnet and the pole magnet are separated by a distance and that distance is adjustable via an adjusting member.

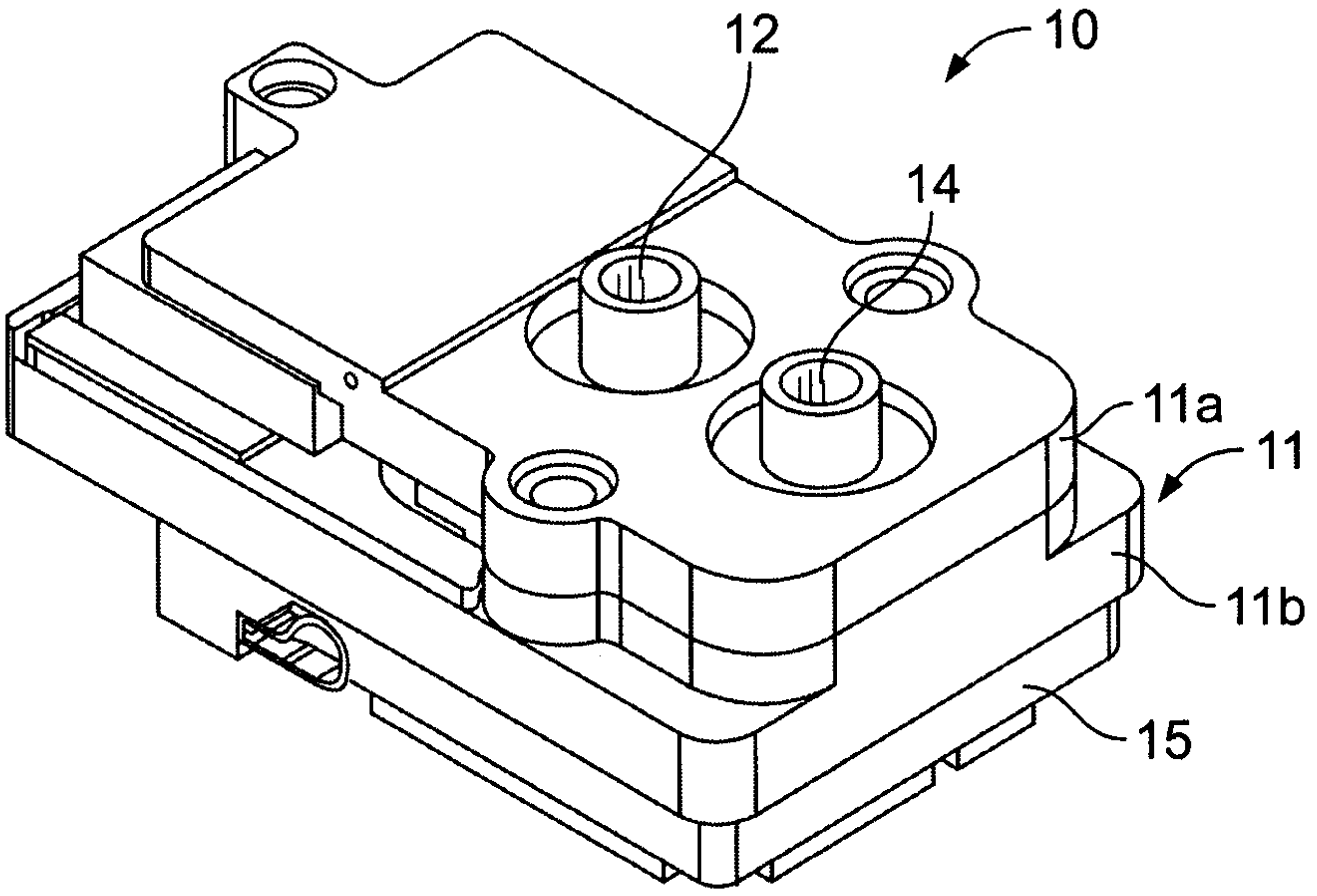


FIG. 1

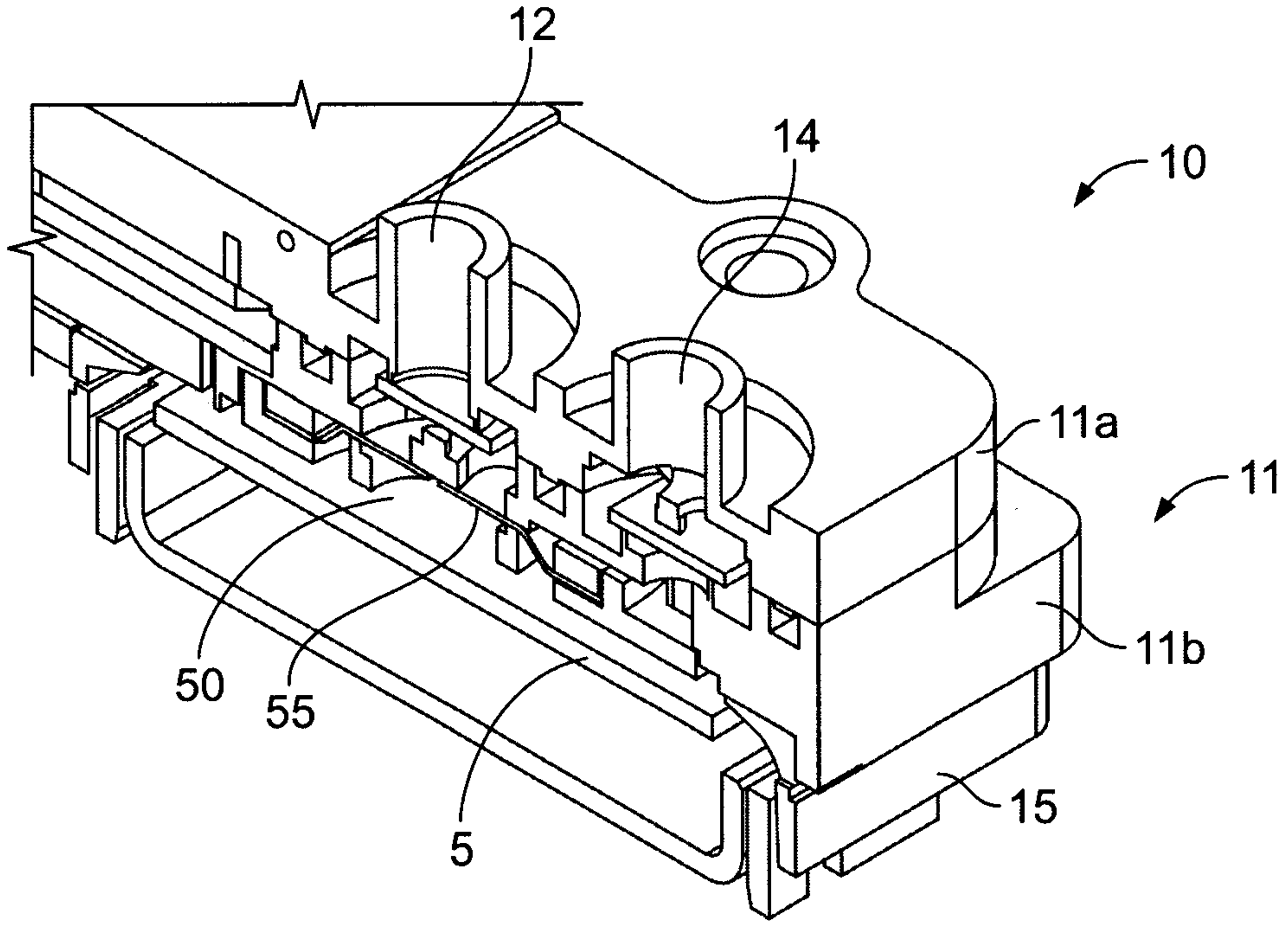


FIG. 2

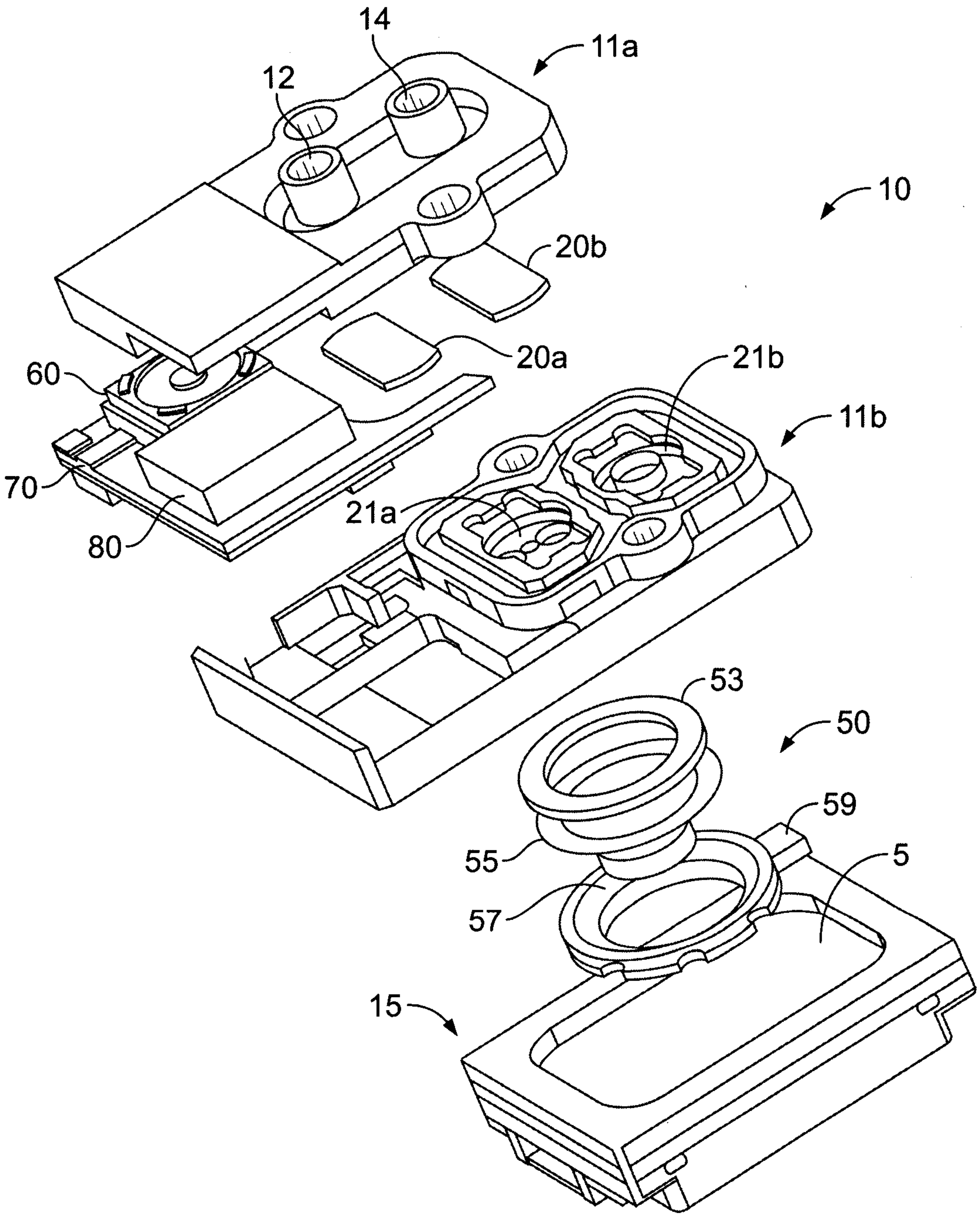


FIG. 3

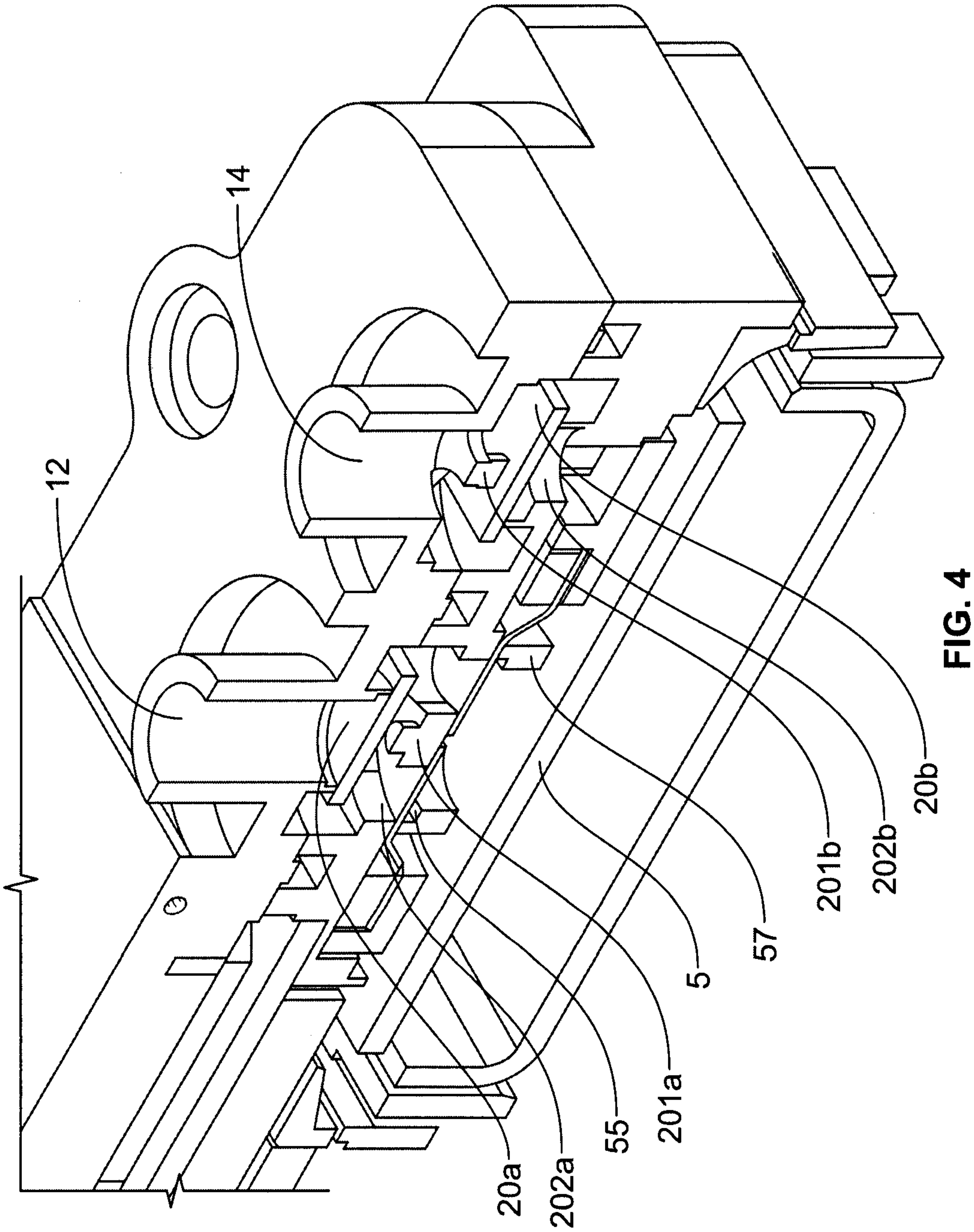


FIG. 4

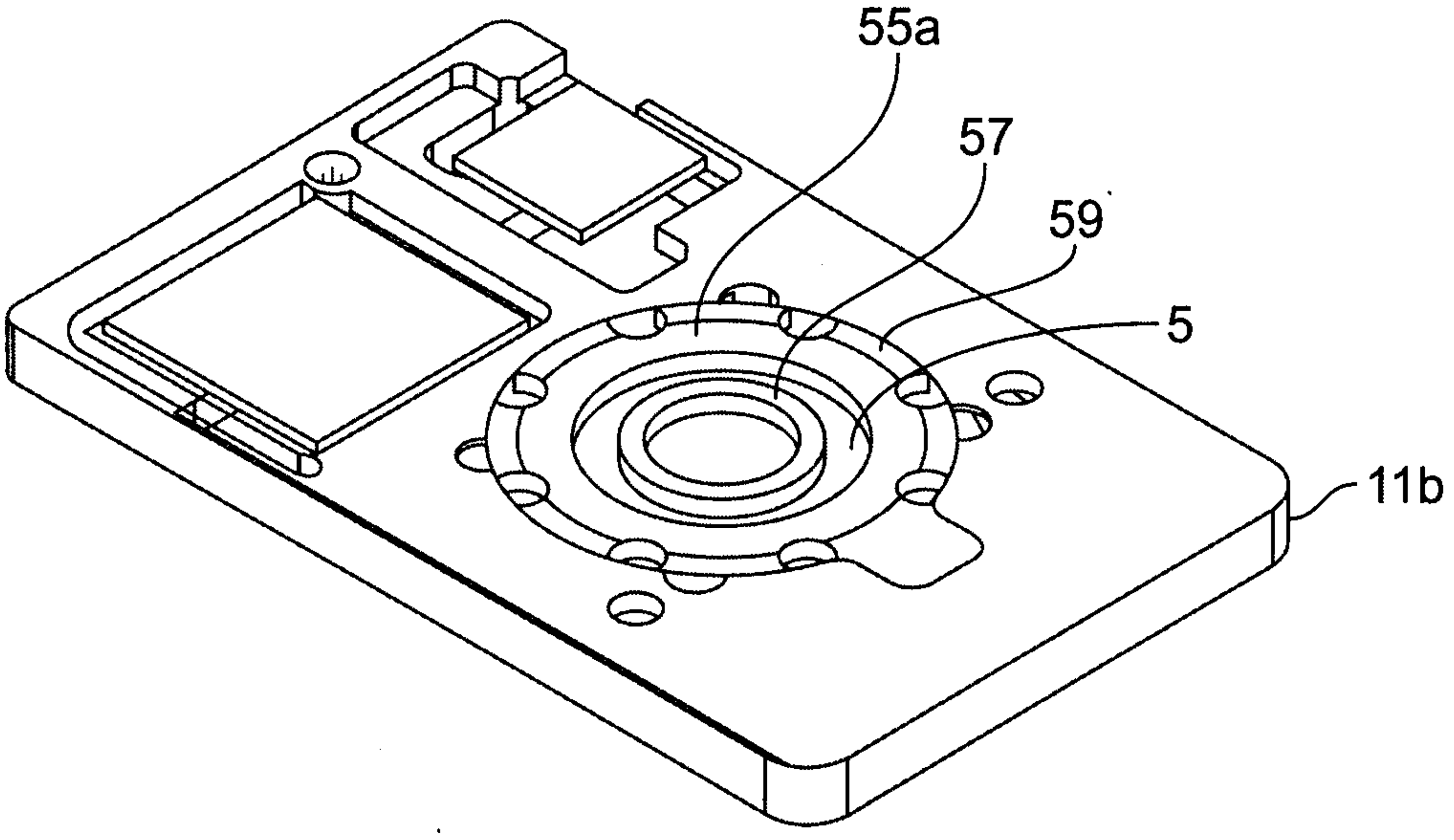


FIG. 5A

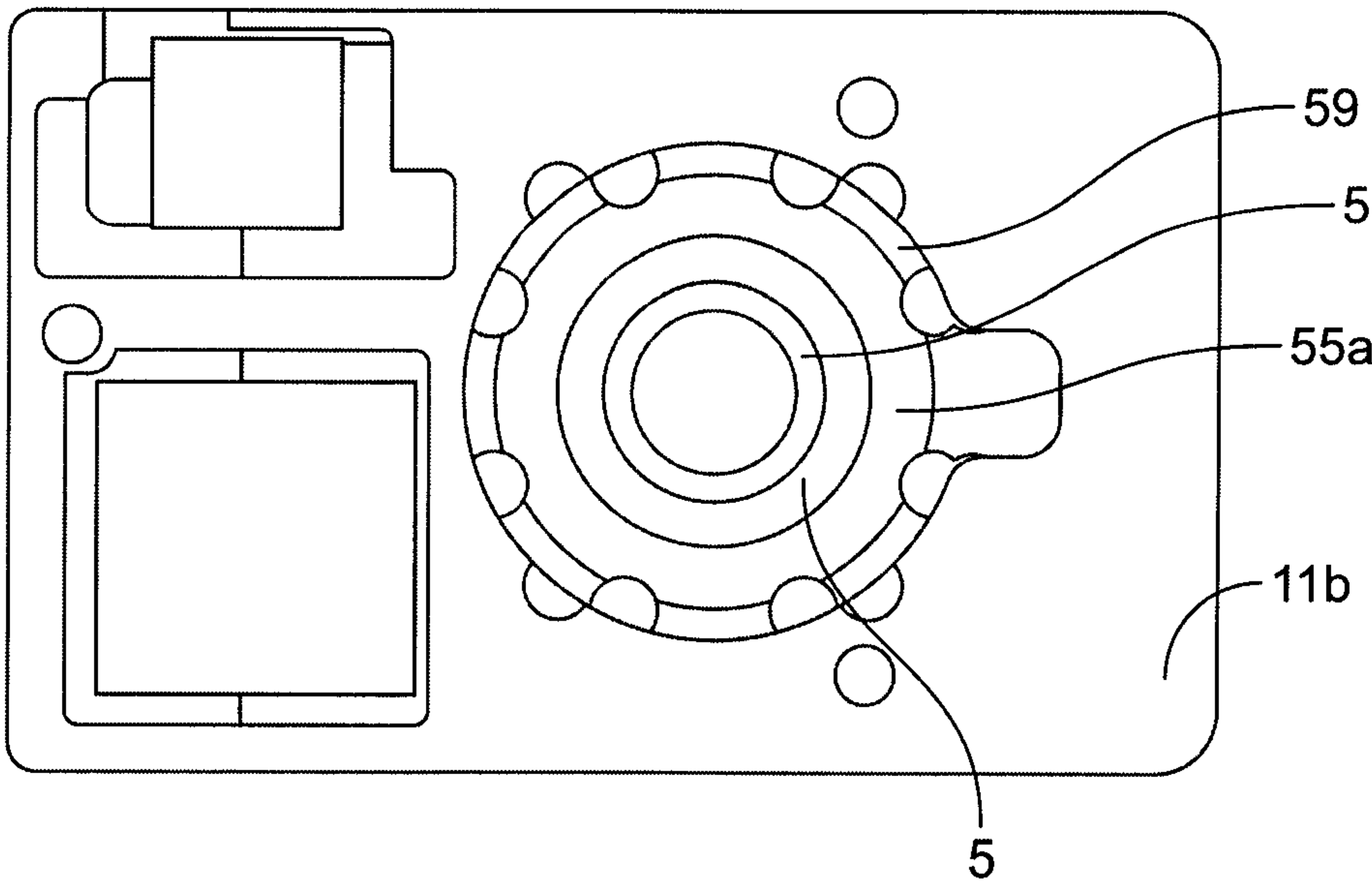


FIG. 5B

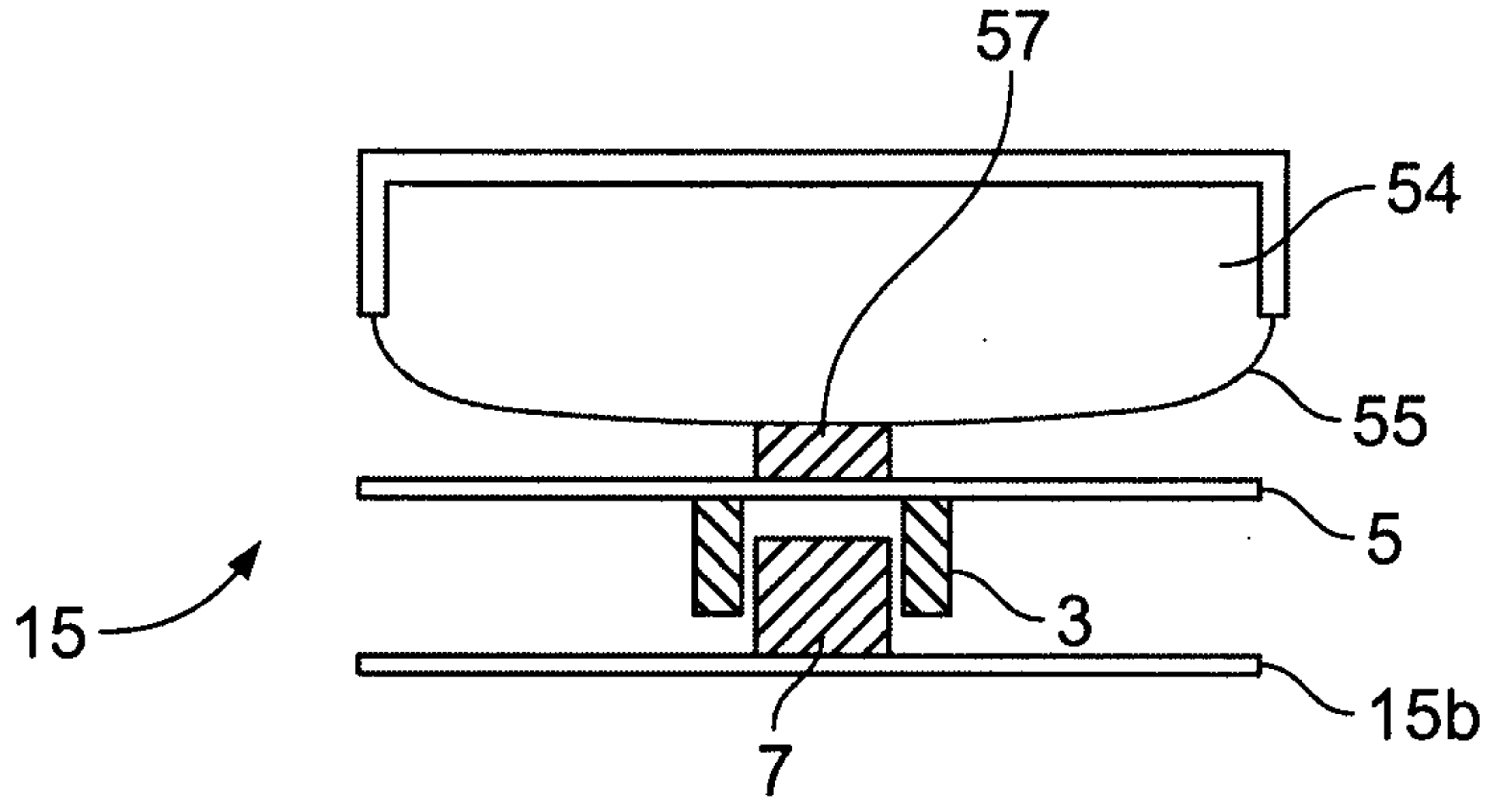


FIG. 6A

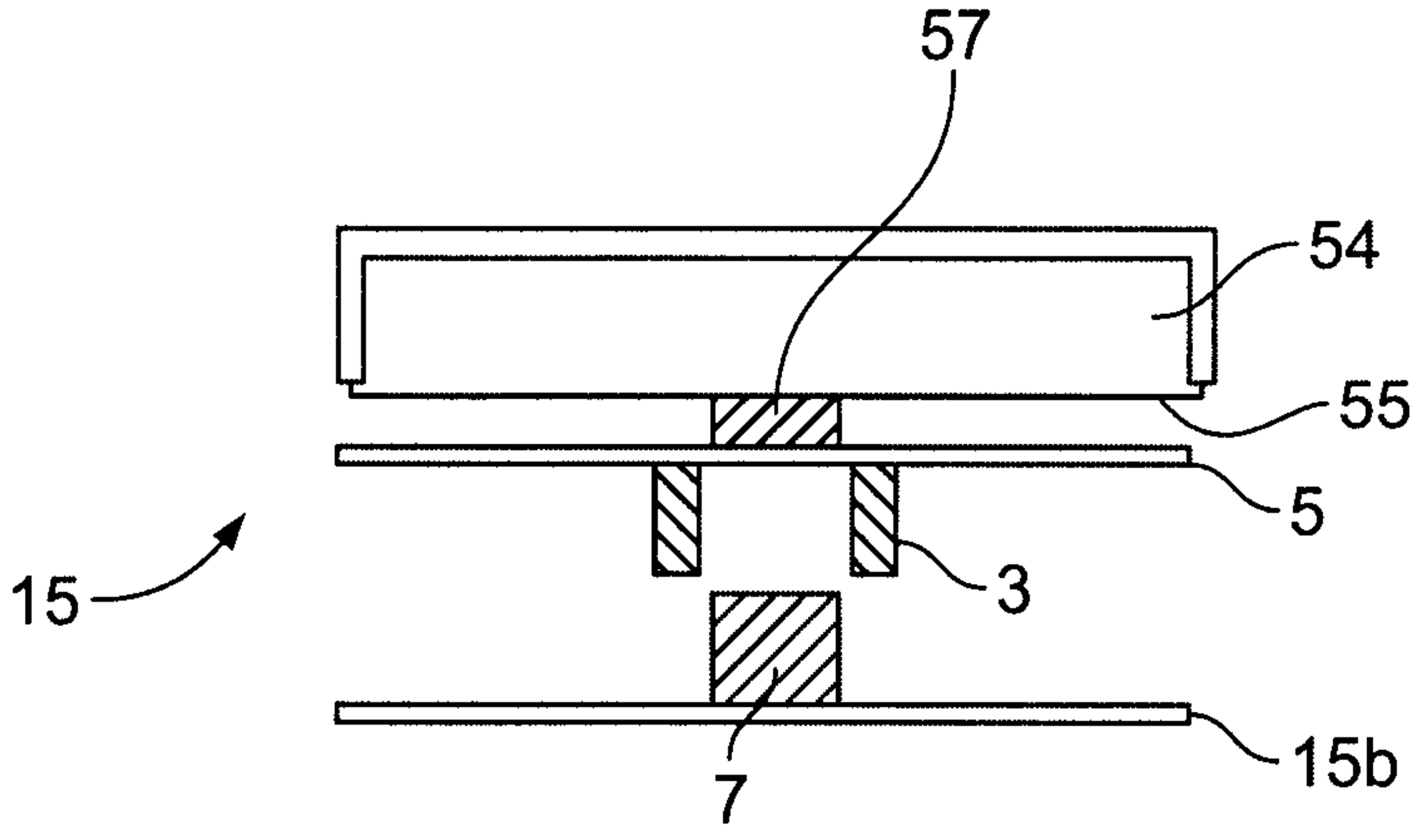


FIG. 6B

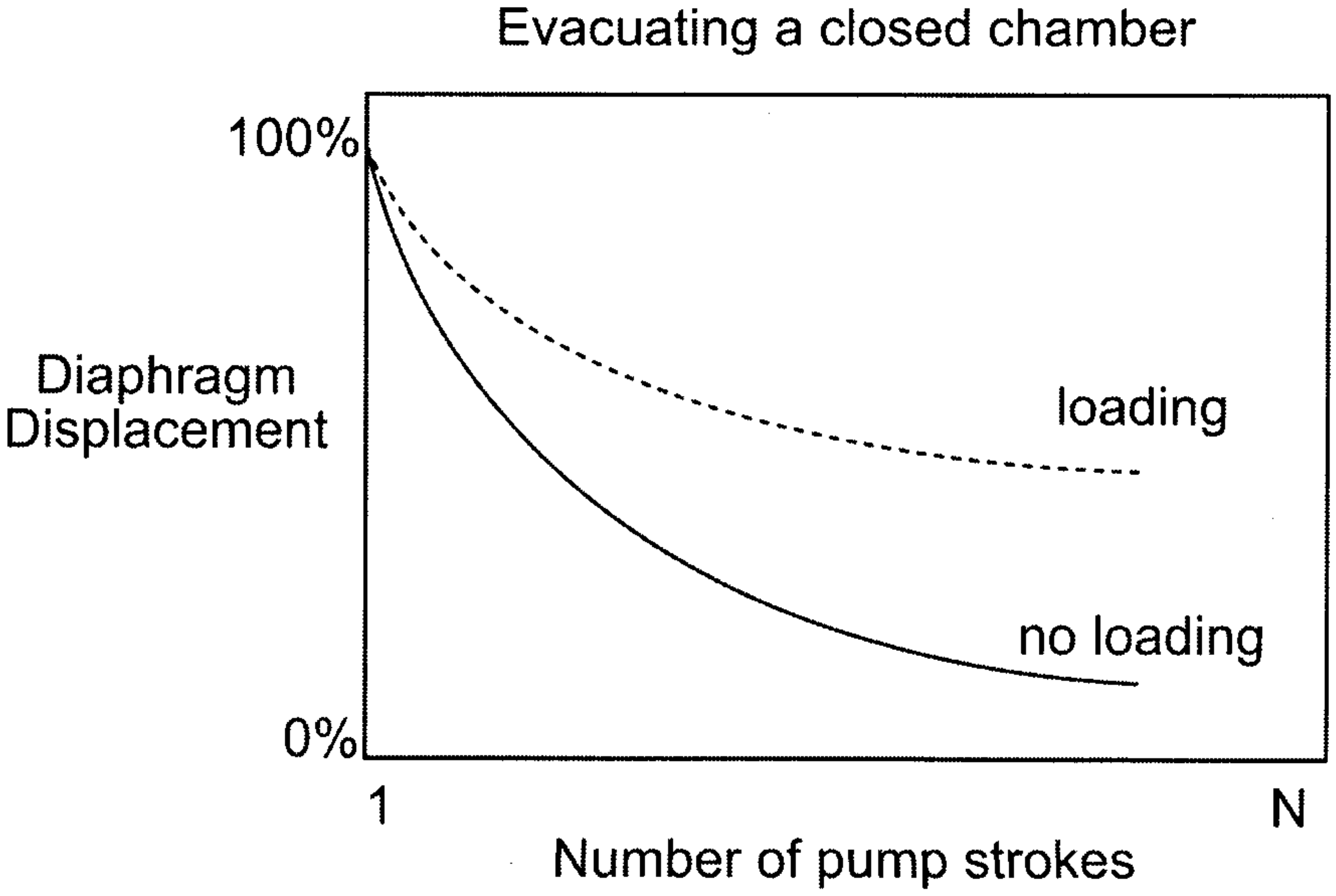


FIG. 7

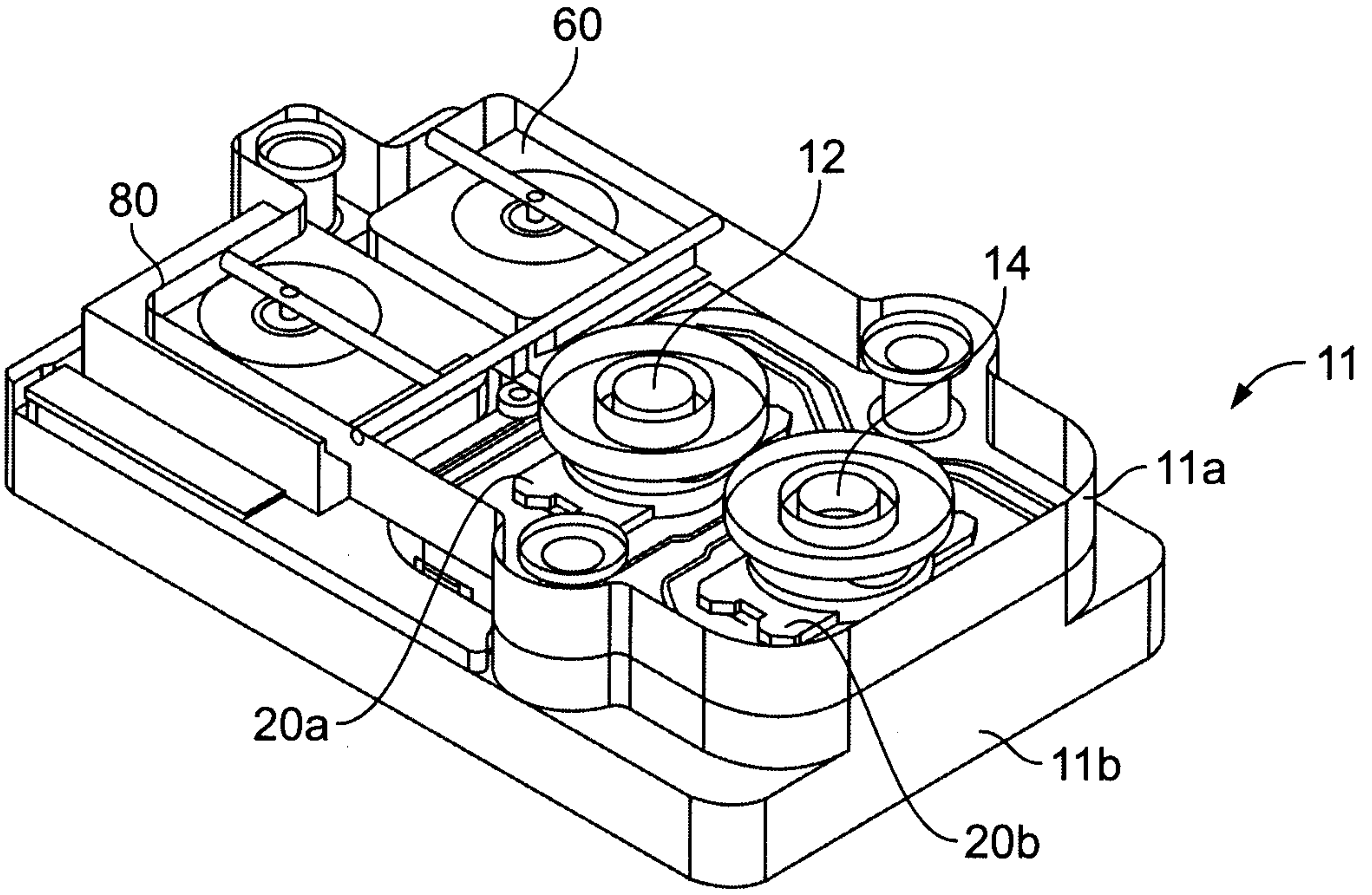

60
12
80
14
11
11a
20a
11b
20b

FIG. 8A

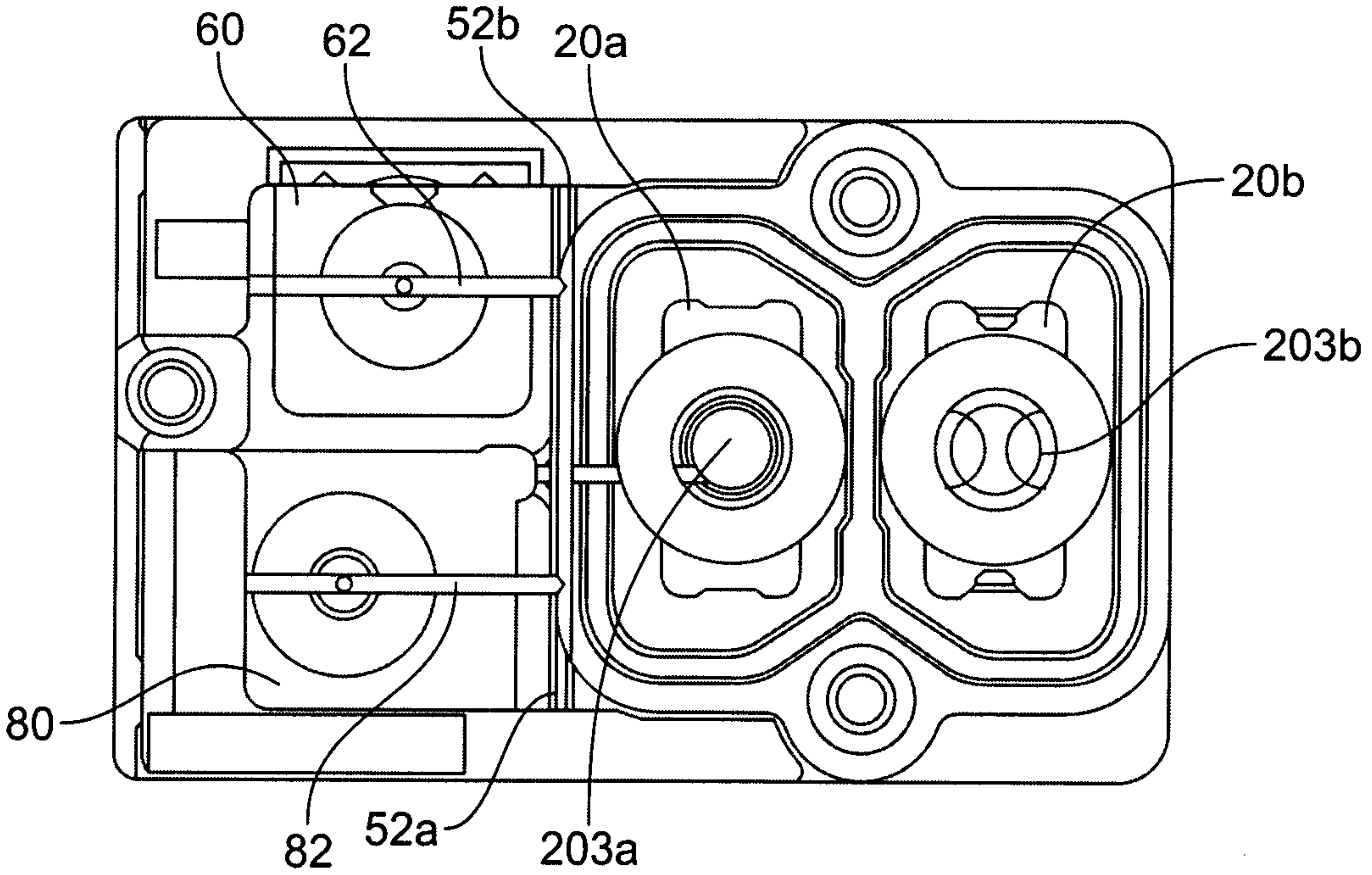

60
62
52b
20a
20b
203b
80
82
52a
203a

FIG. 8B

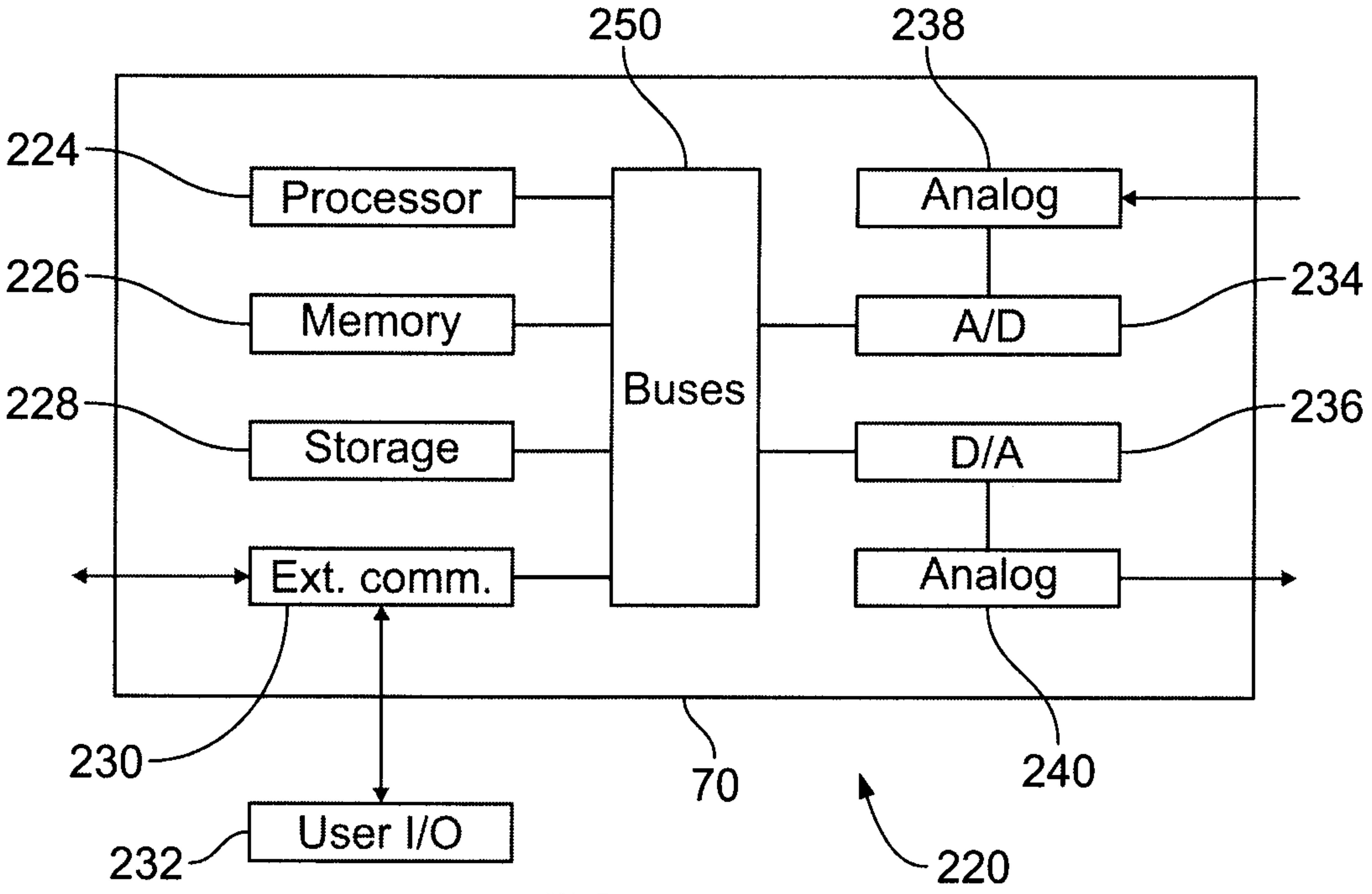


FIG. 9A

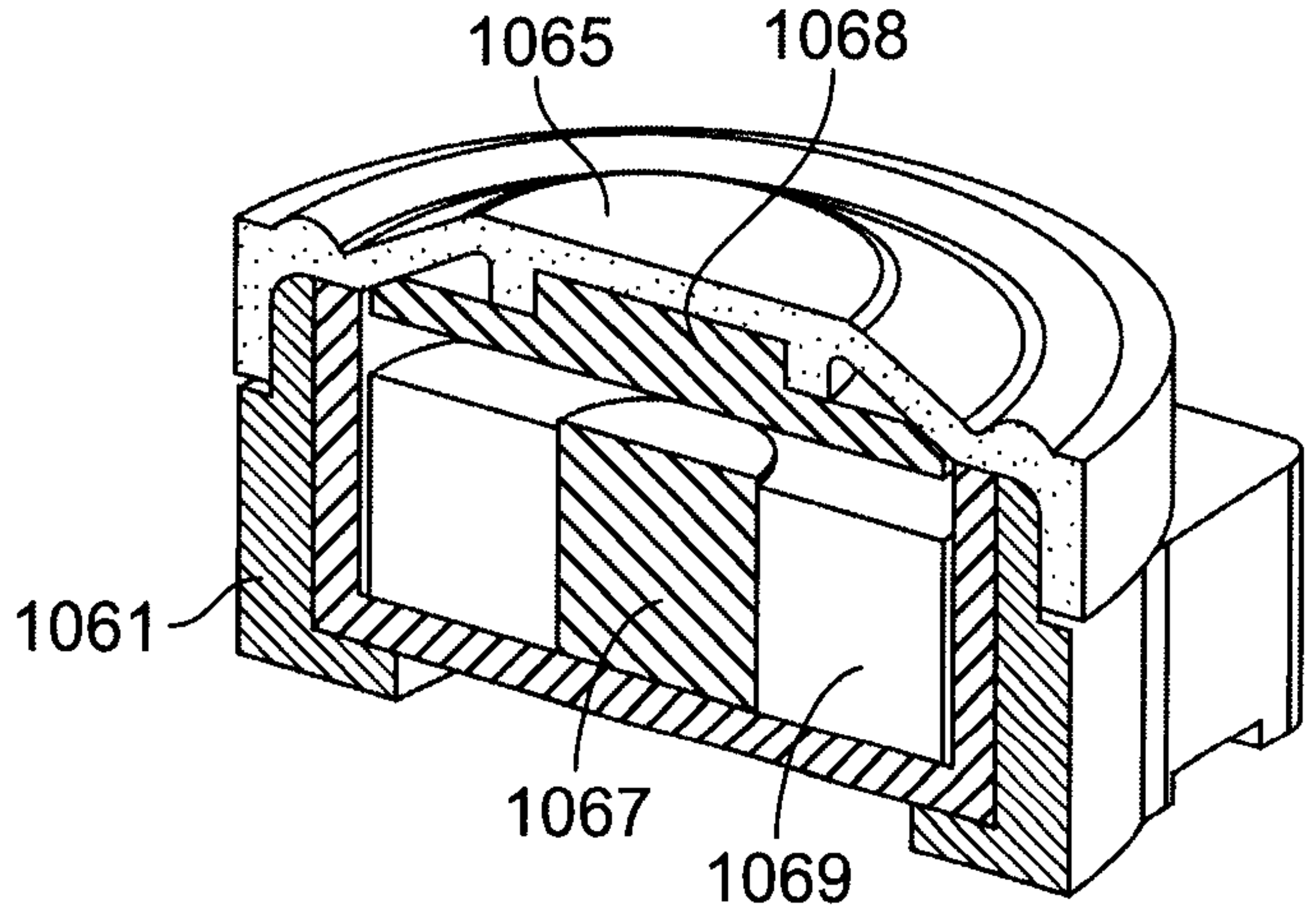


FIG. 11A

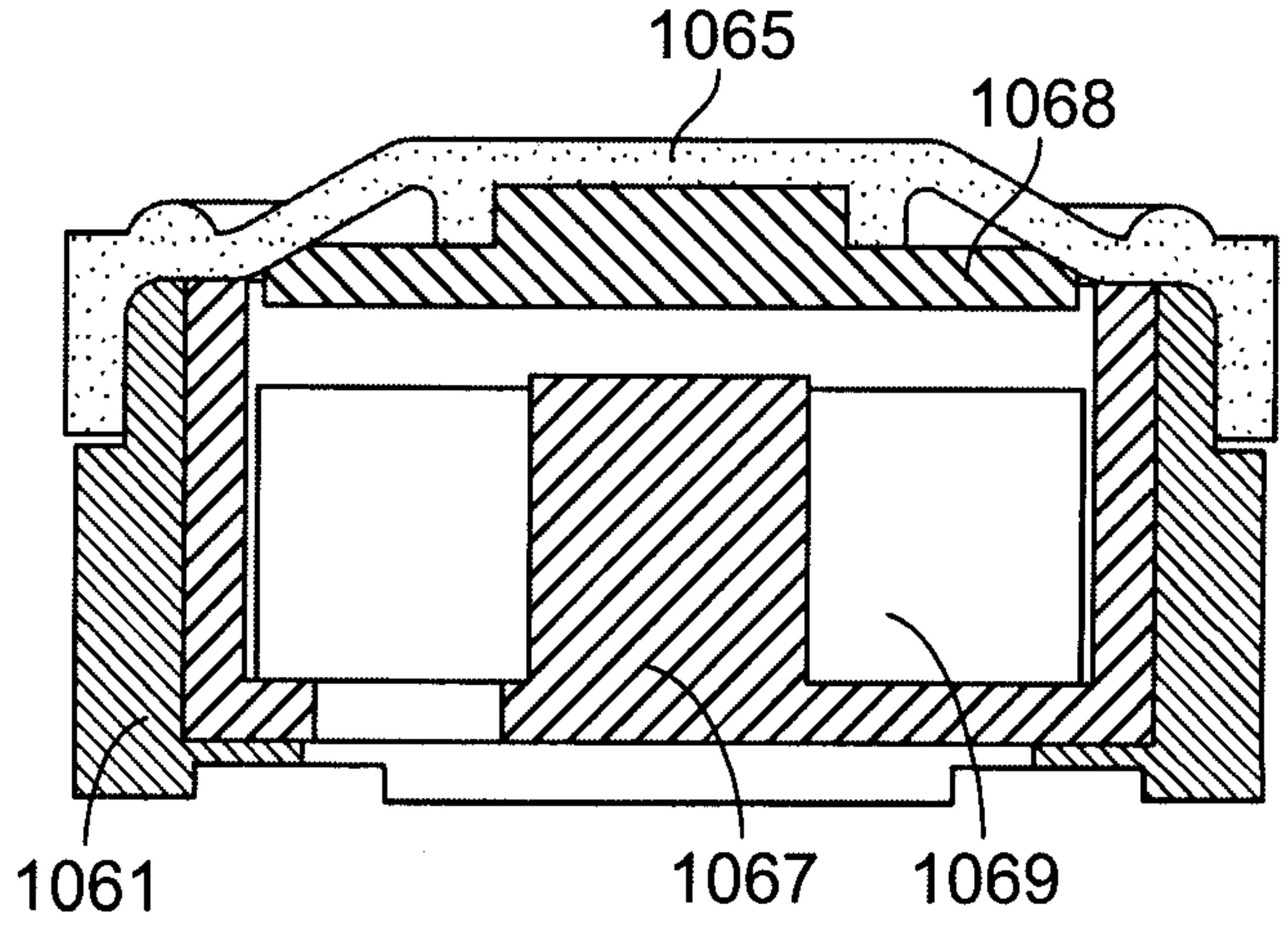


FIG. 11B

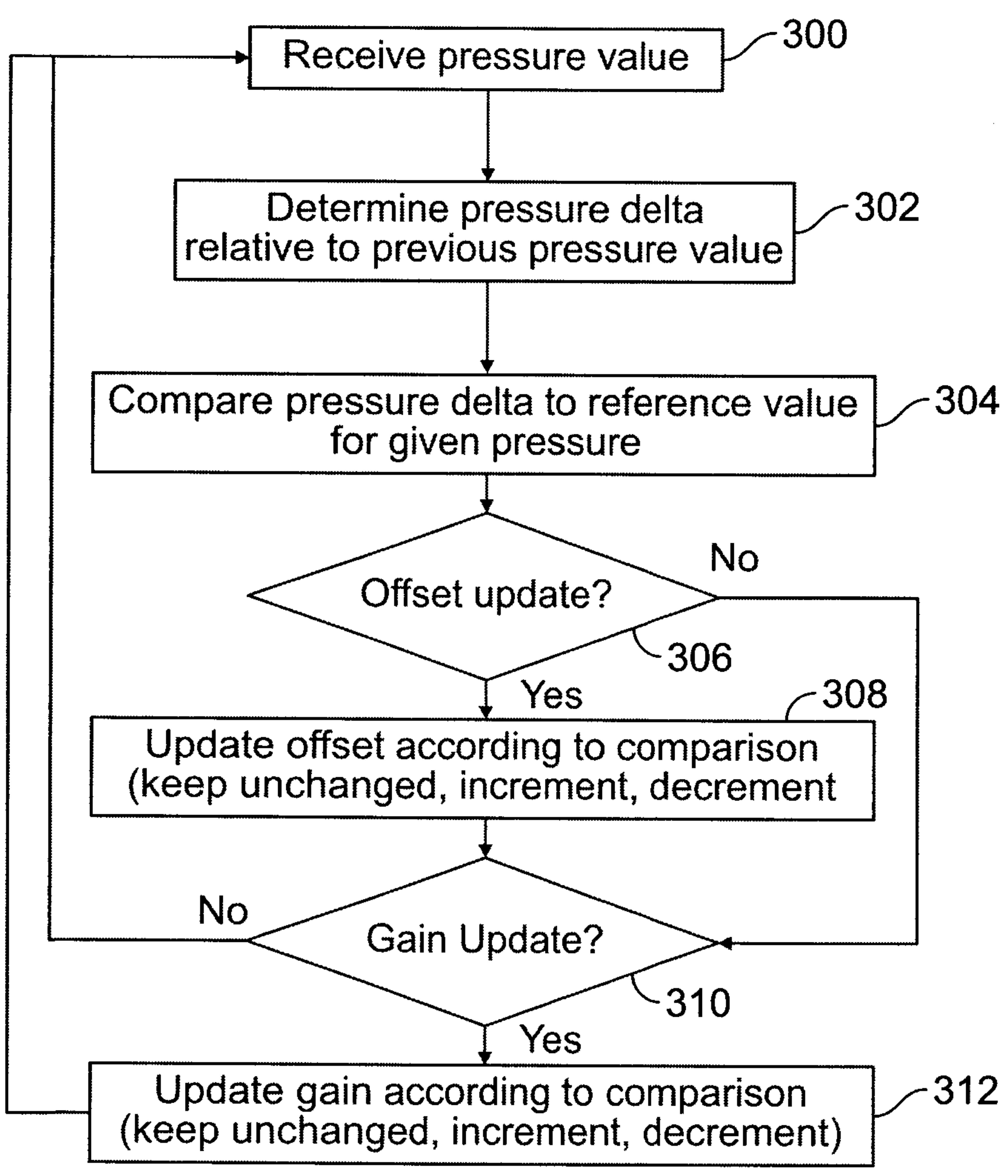

Receive pressure value
300
Determine pressure delta relative to previous pressure value
302
Compare pressure delta to reference value for given pressure
304
Offset update?
306
No
Yes
Update offset according to comparison (keep unchanged, increment, decrement
308
No
Gain Update?
310
Yes
Update gain according to comparison (keep unchanged, increment, decrement)
312

FIG. 9B

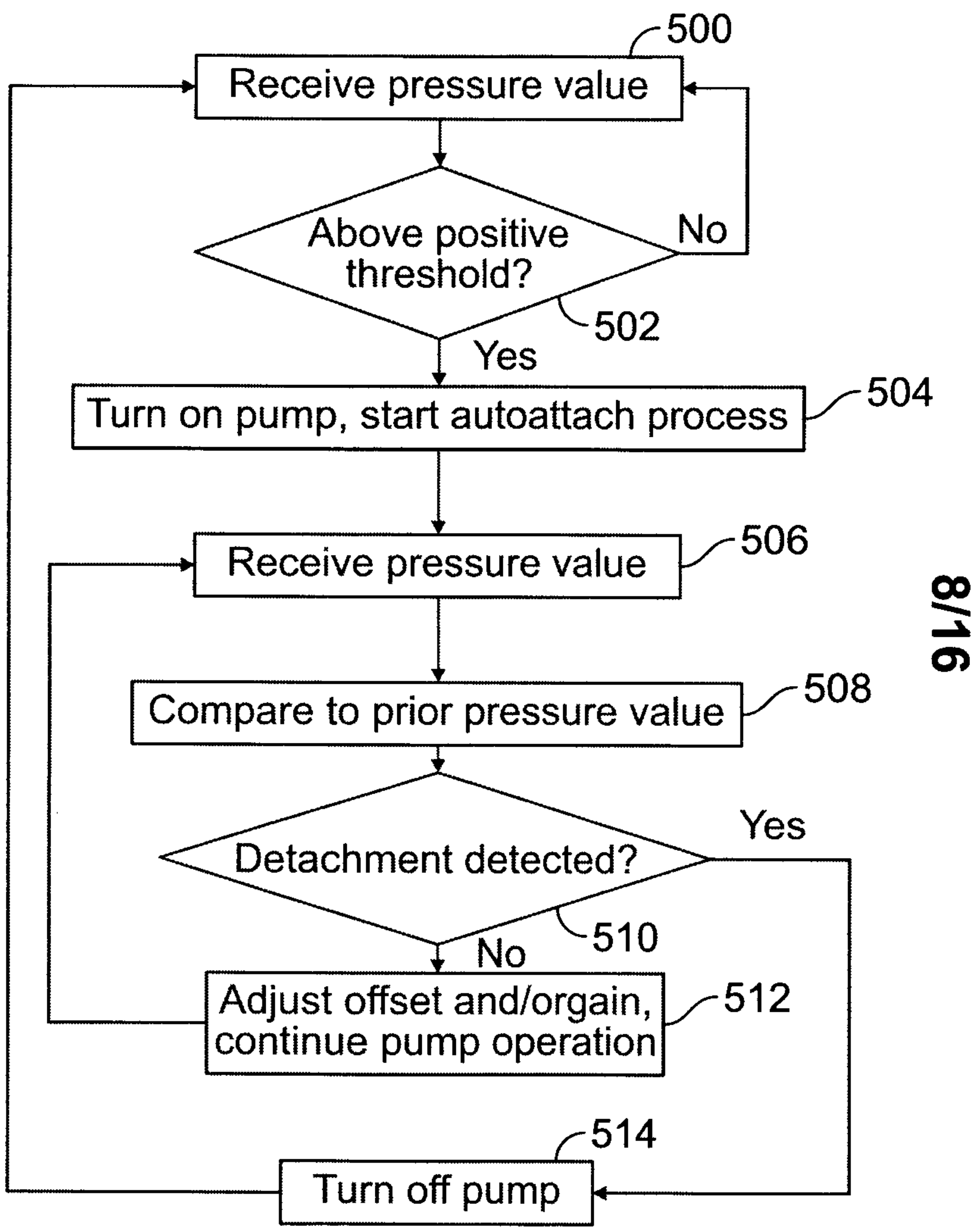

500
Receive pressure value
Above positive threshold?
No
502
Yes
Turn on pump, start autoattach process
504
Receive pressure value
506
Compare to prior pressure value
508
Detachment detected?
Yes
510
No
Adjust offset and/orgain, continue pump operation
512
514
Turn off pump

FIG. 9D

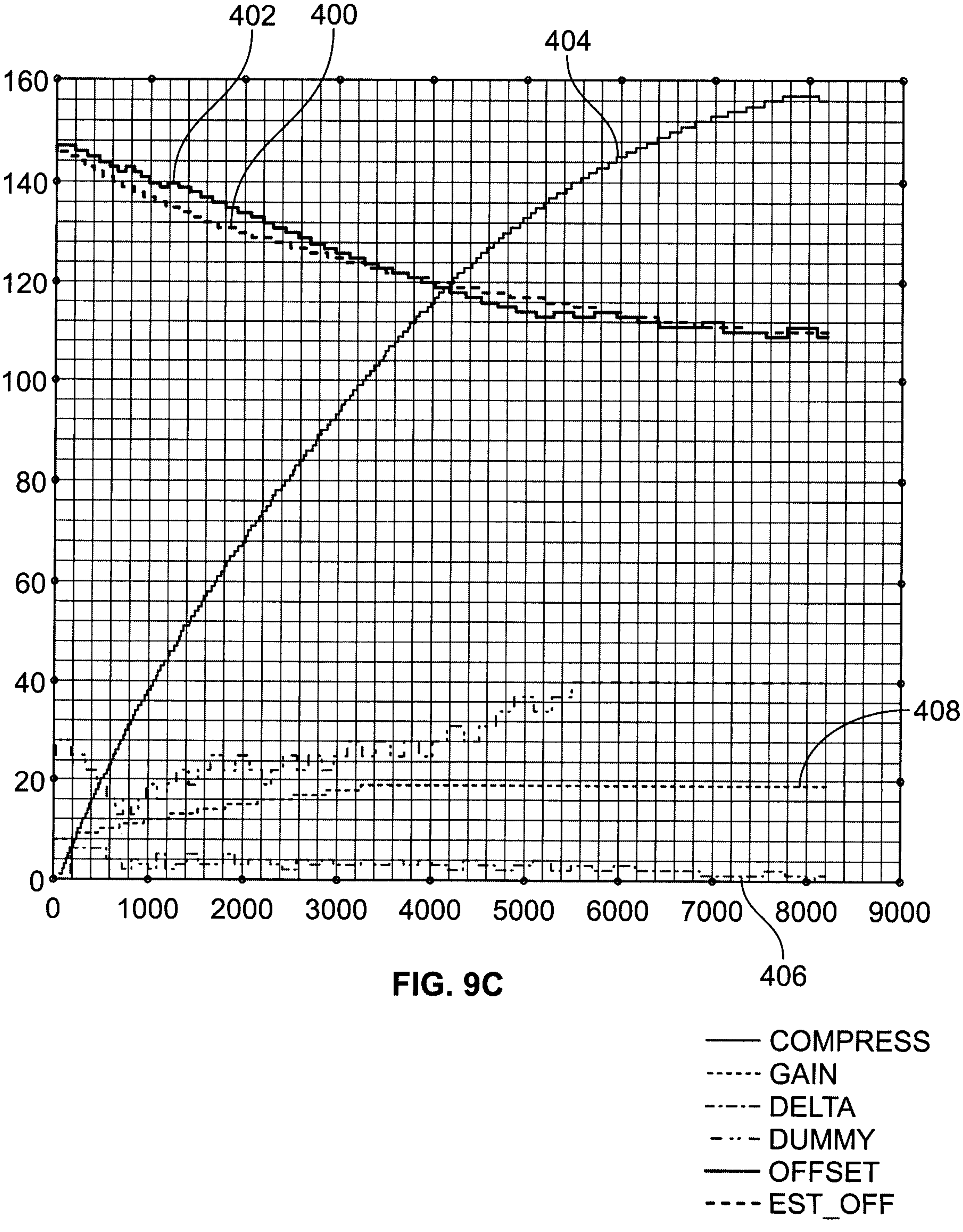

402
400
404
408
406
160
140
120
100
80
60
40
20
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
COMPRESS
GAIN
DELTA
DUMMY
OFFSET
EST_OFF

FIG. 9C

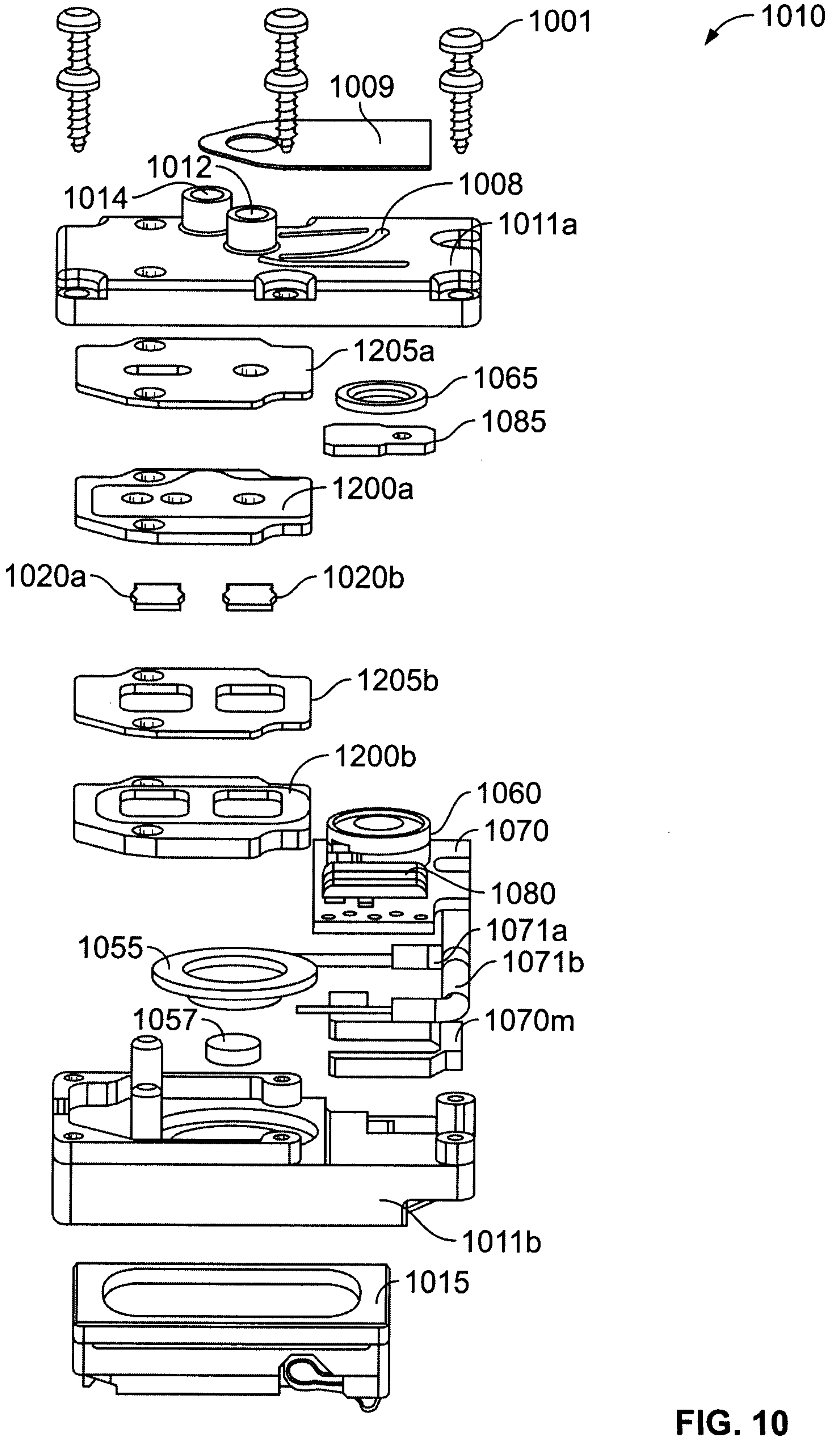

1010
1001
1009
1012
1014
1008
1011a
1205a
1065
1085
1200a
1020a
1020b
1205b
1200b
1060
1070
1080
1055
1071a
1071b
1057
1070m
1011b
1015

FIG. 10

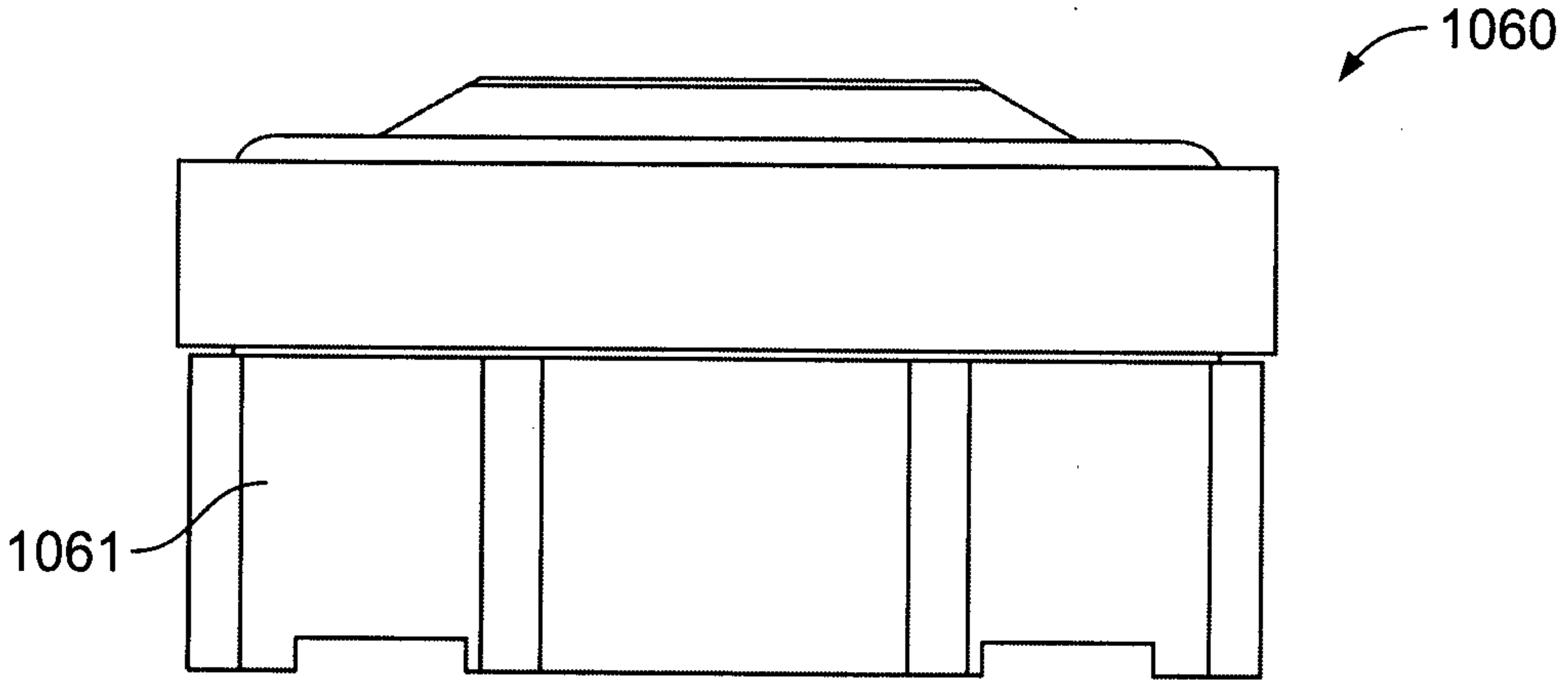


FIG. 12A

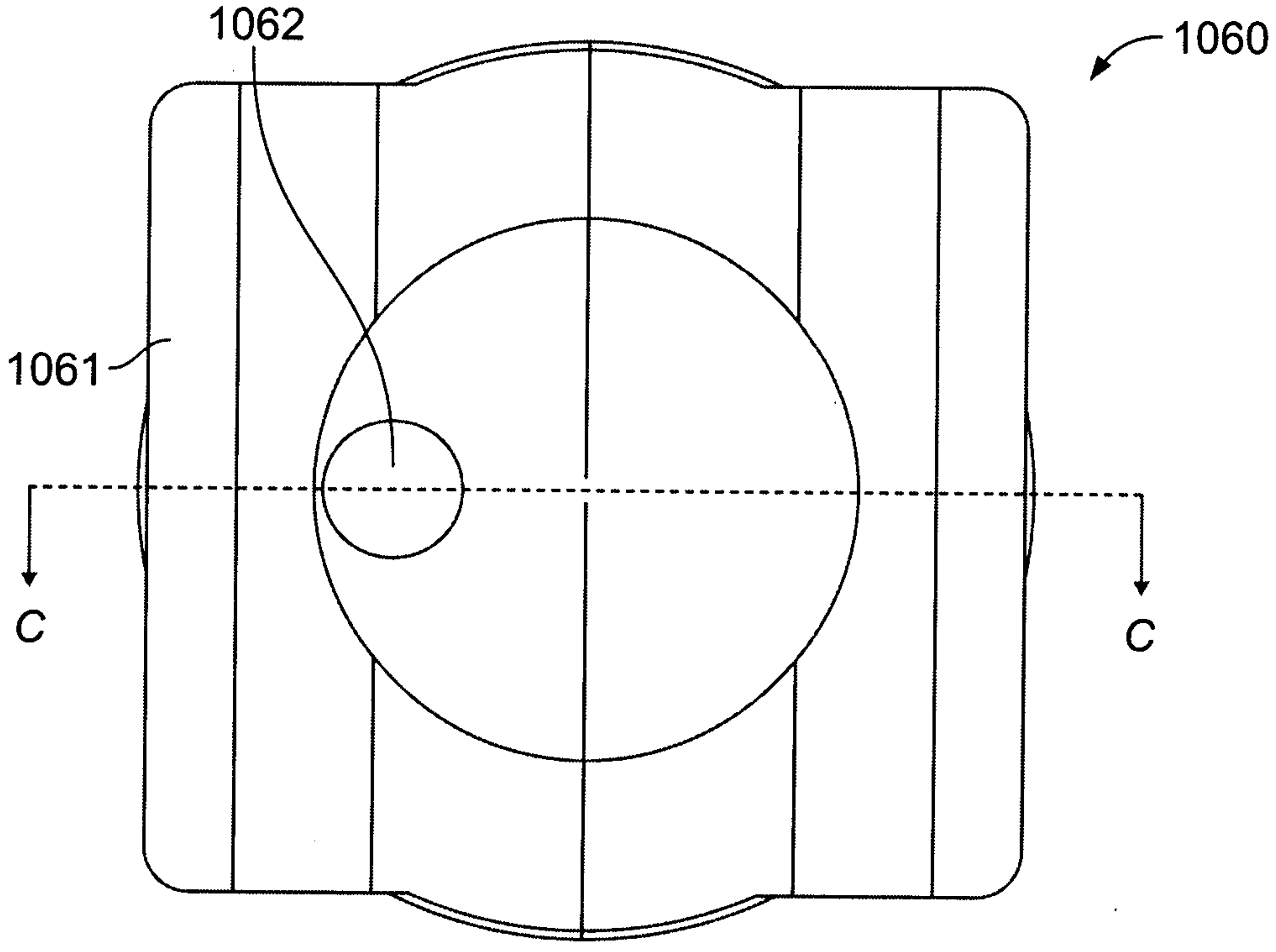


FIG. 12B

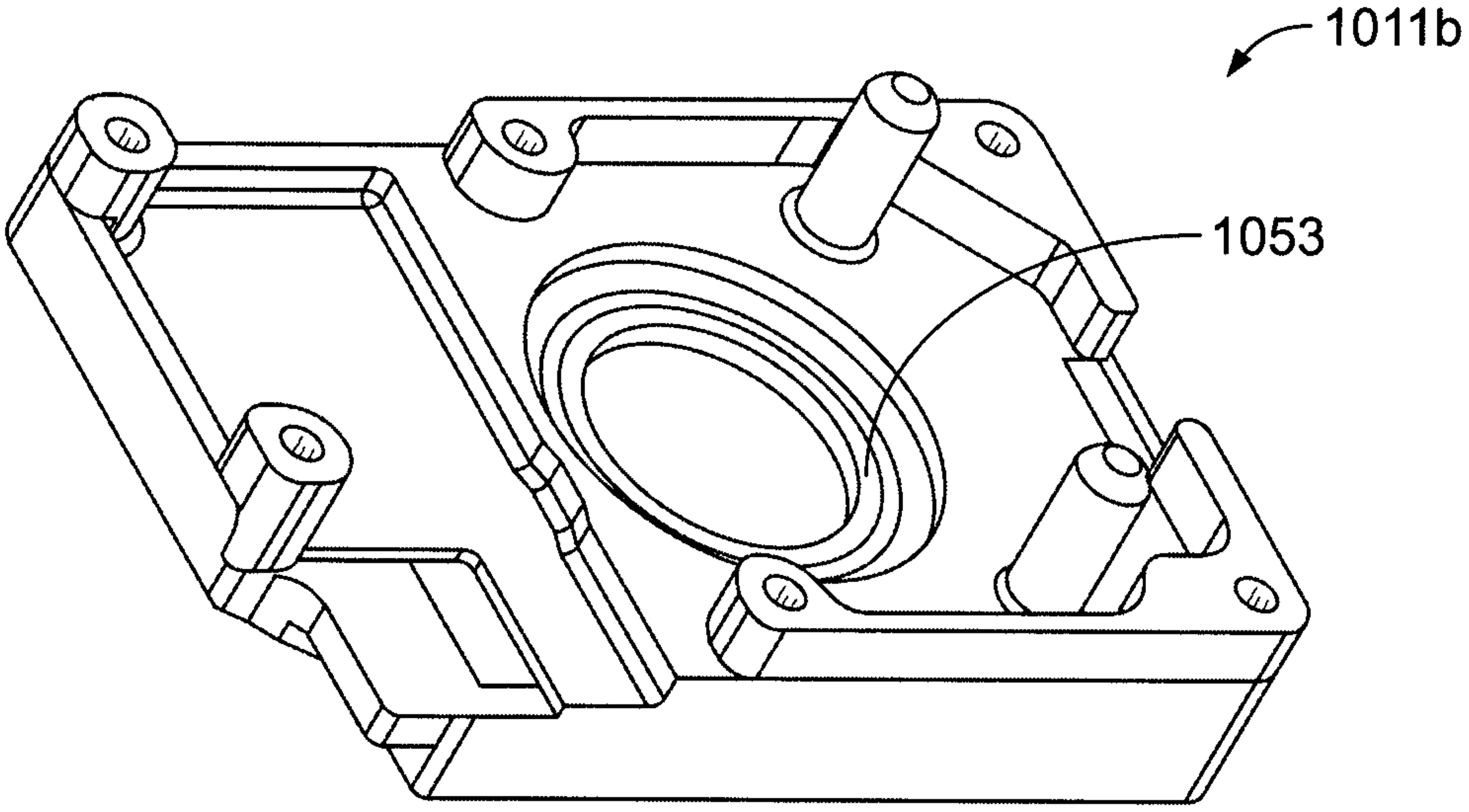


FIG. 13A

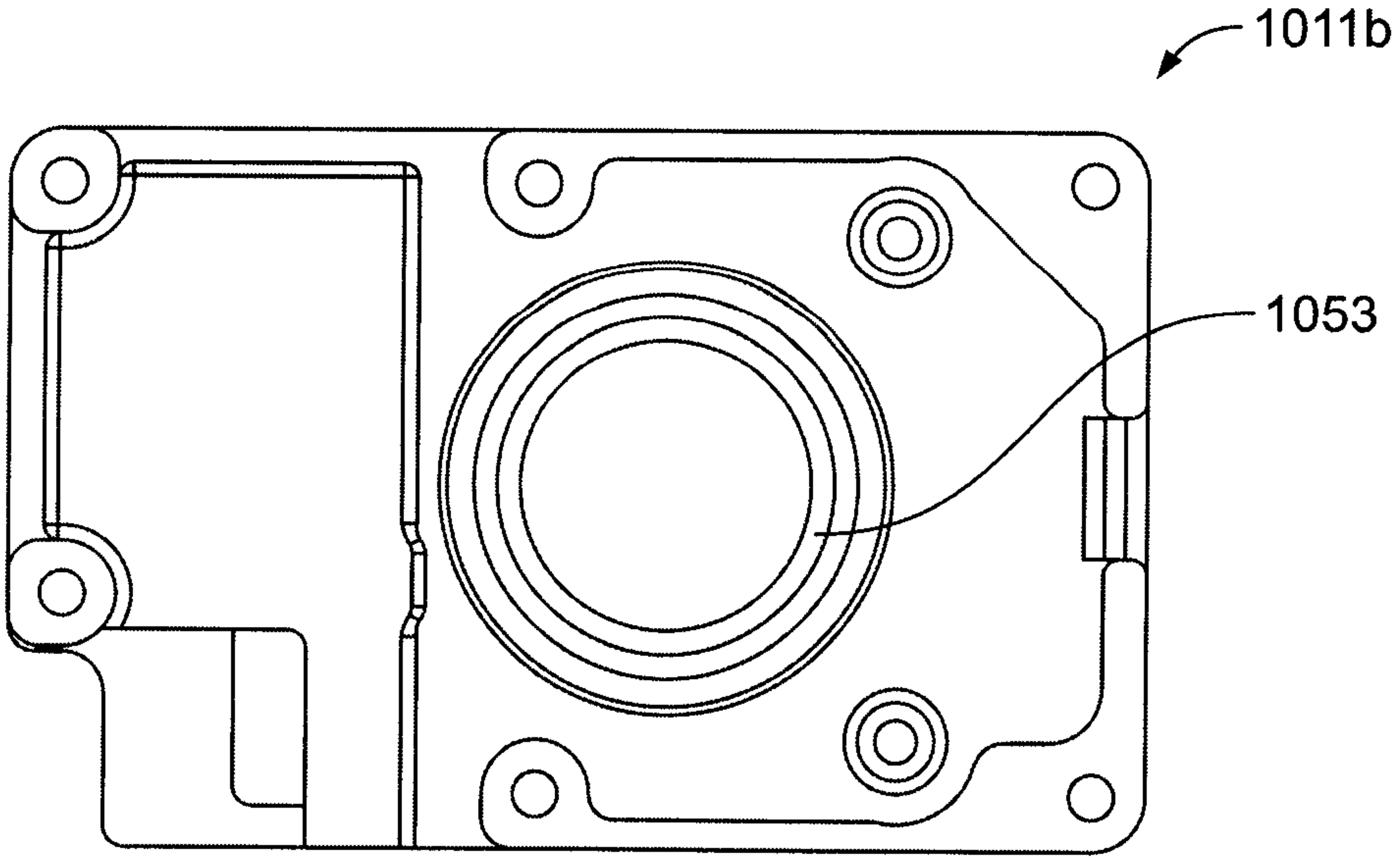


FIG. 13B

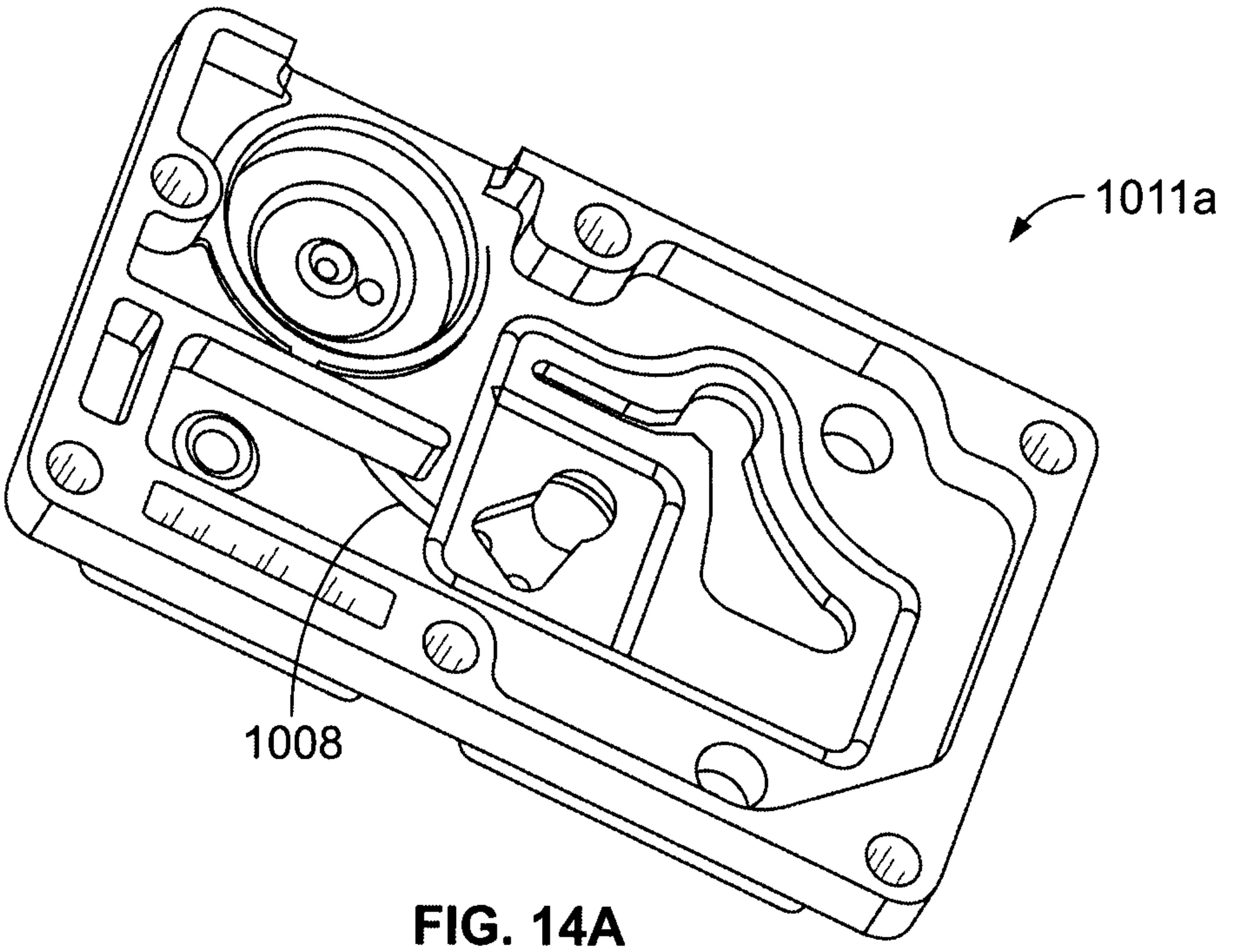


FIG. 14A

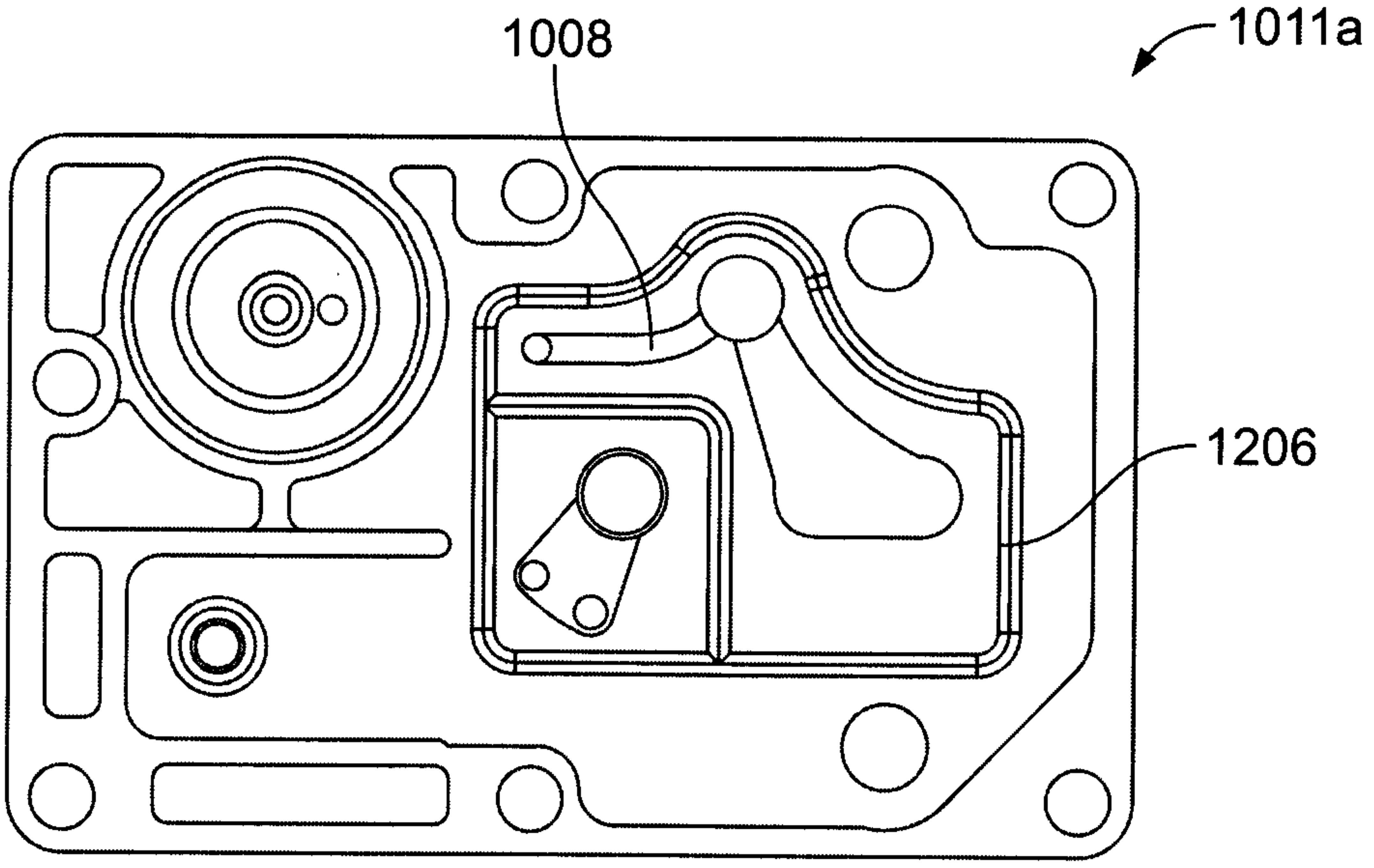


FIG. 14B

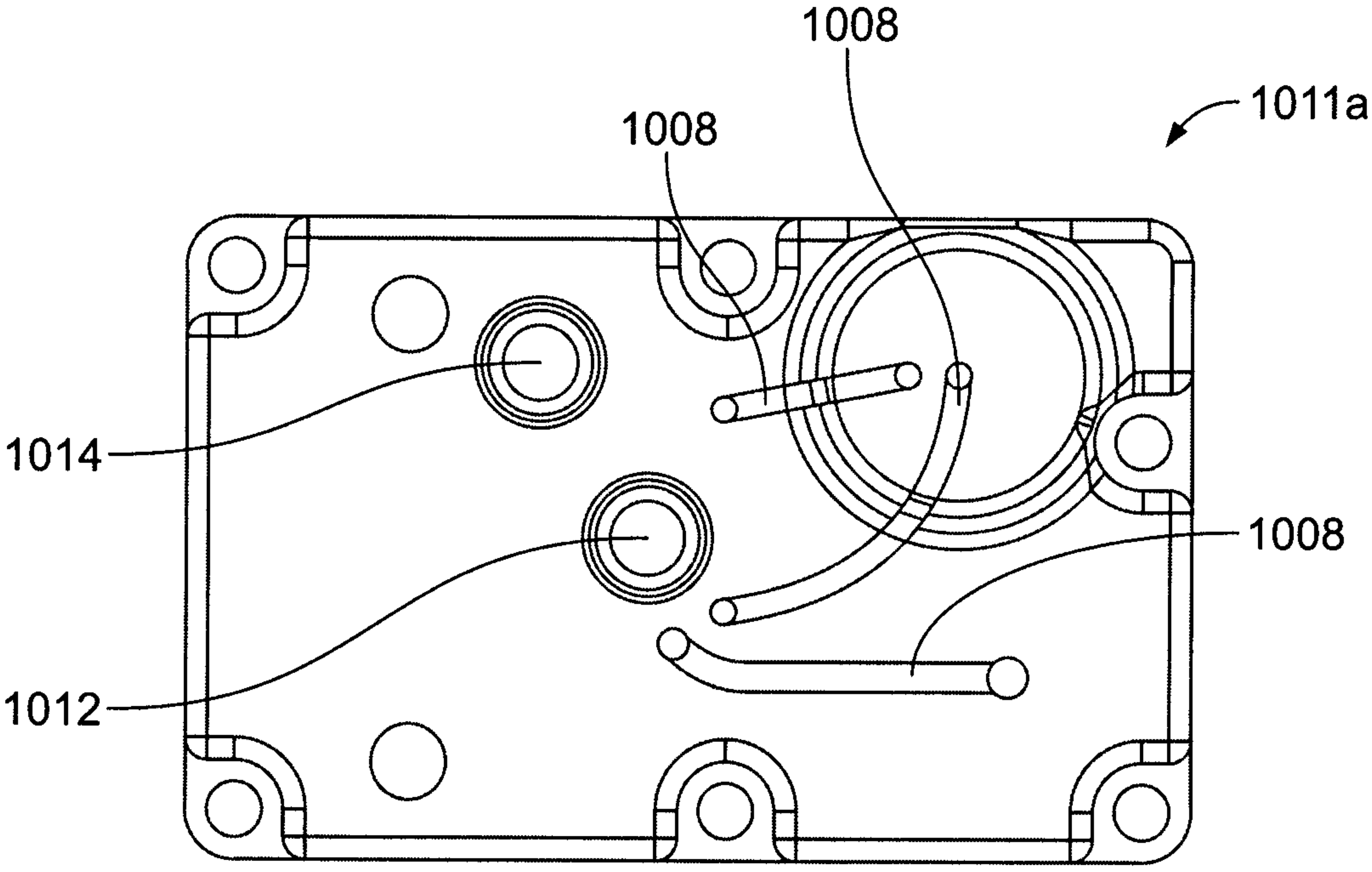


FIG. 14C

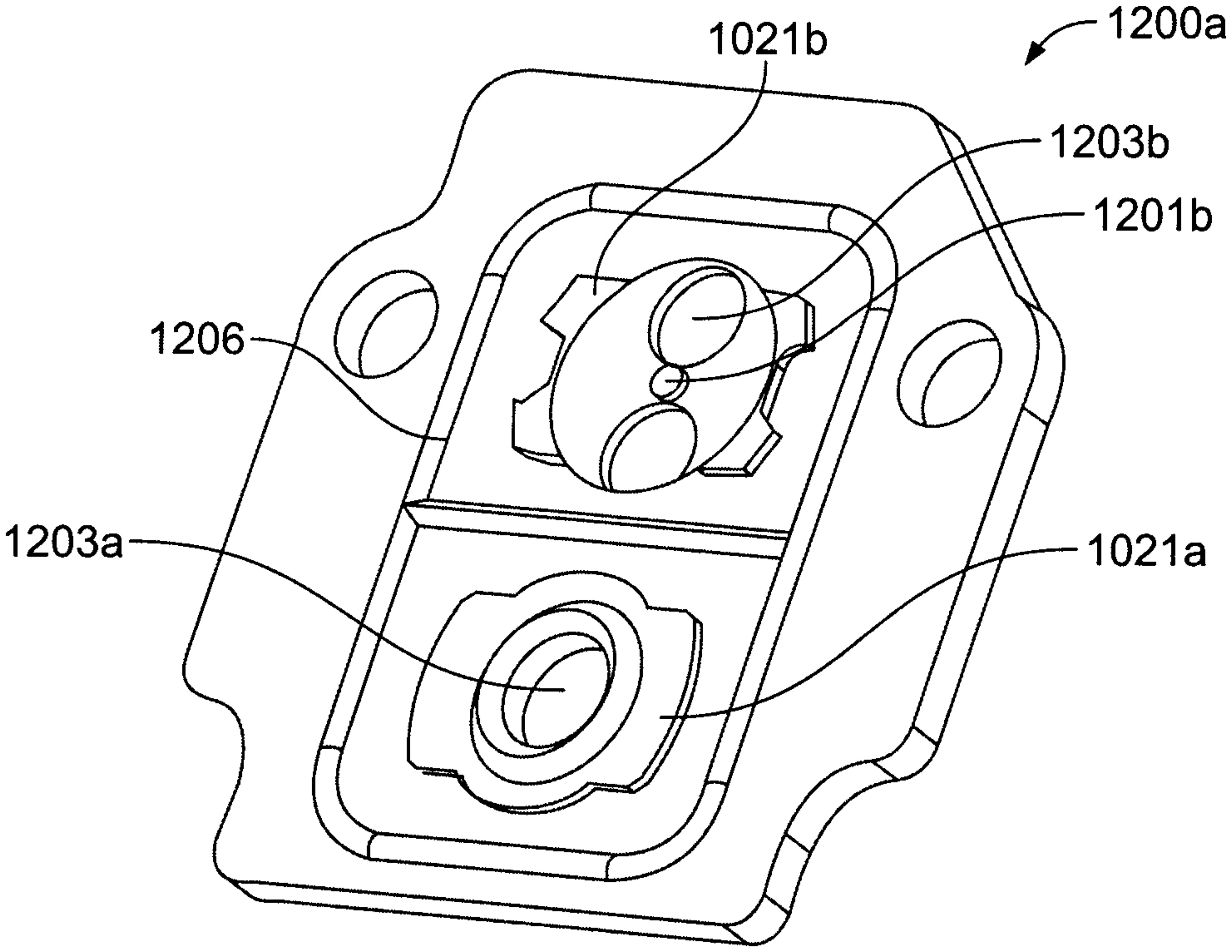


FIG. 15A

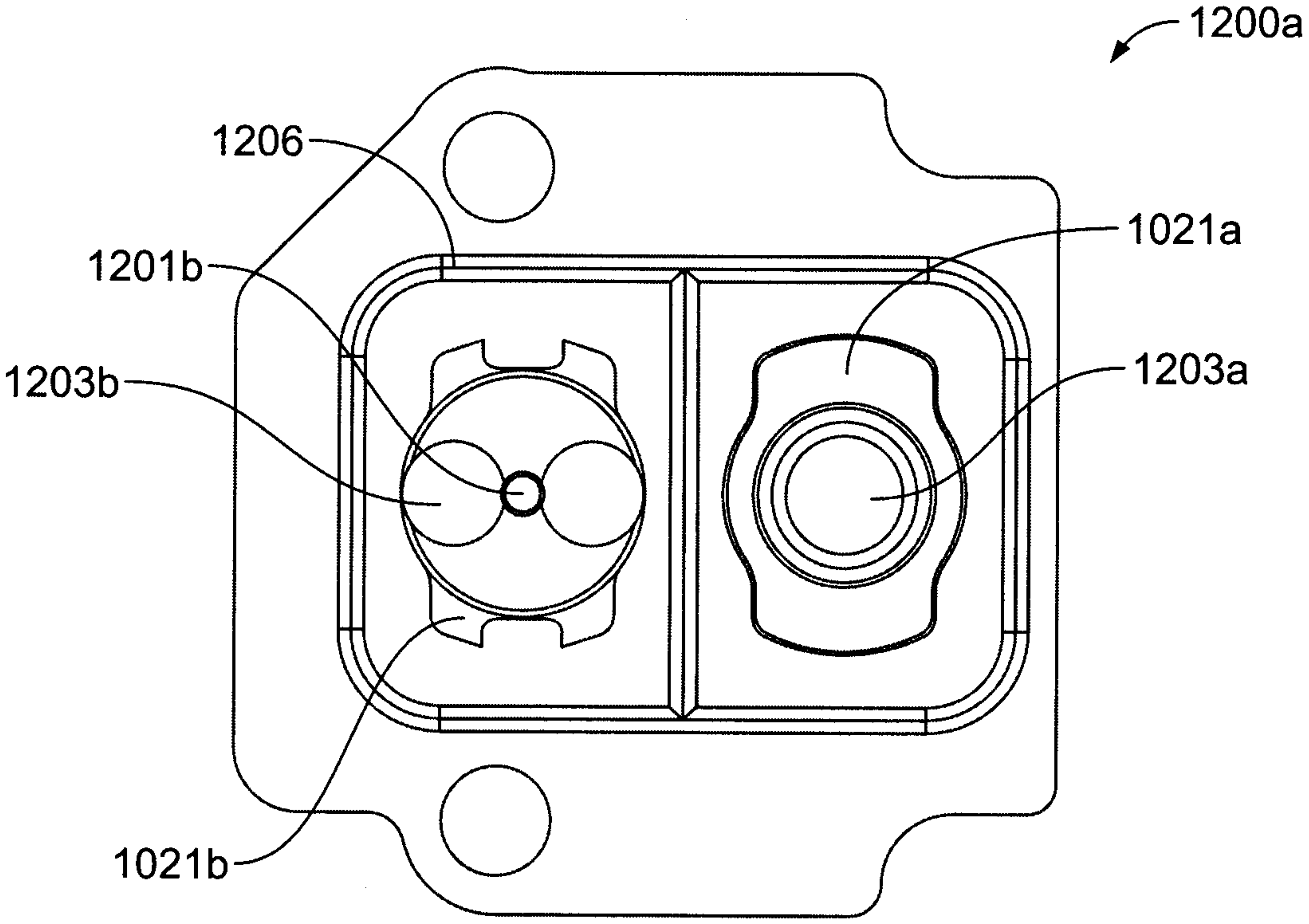


FIG. 15B

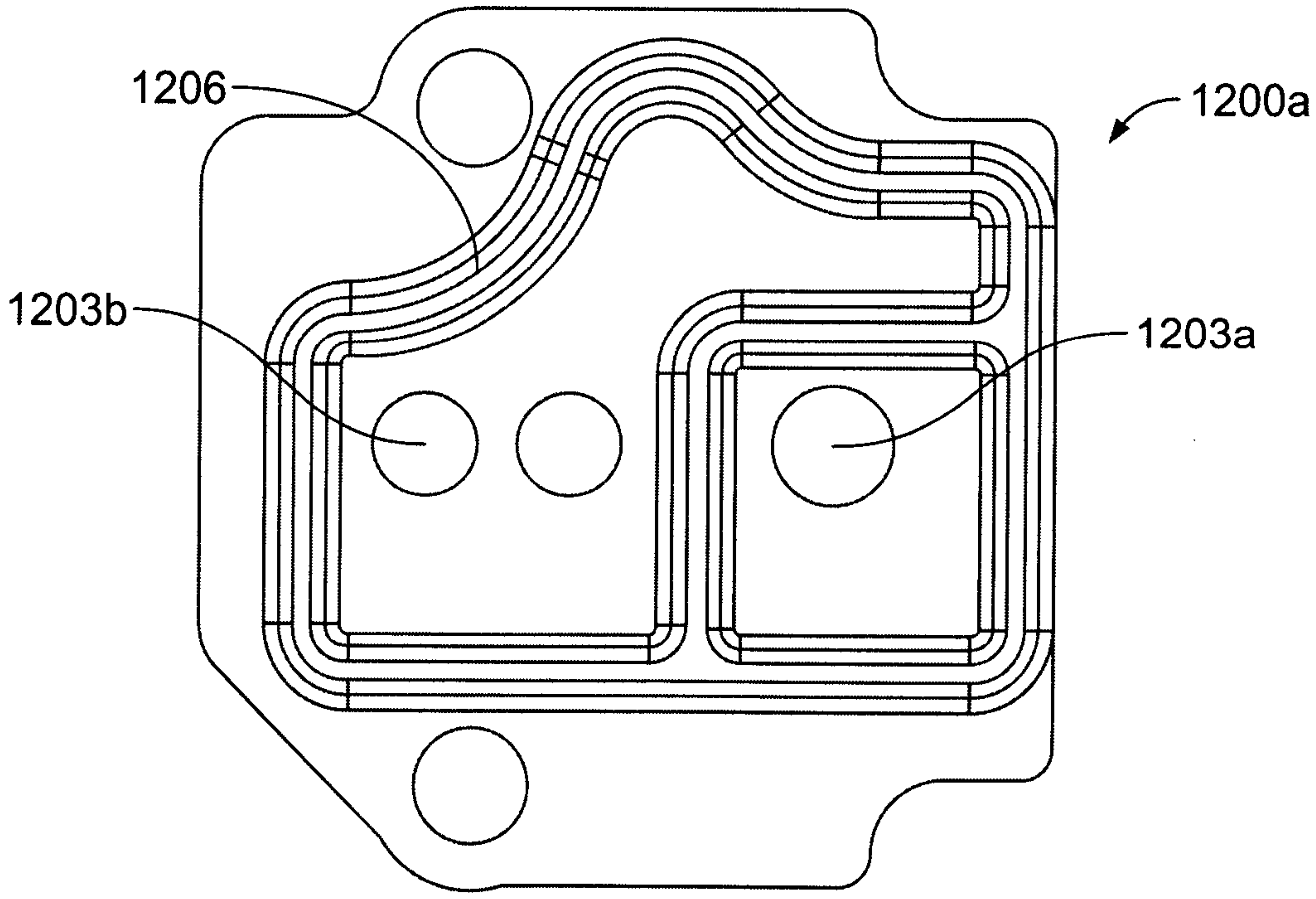


FIG. 15C

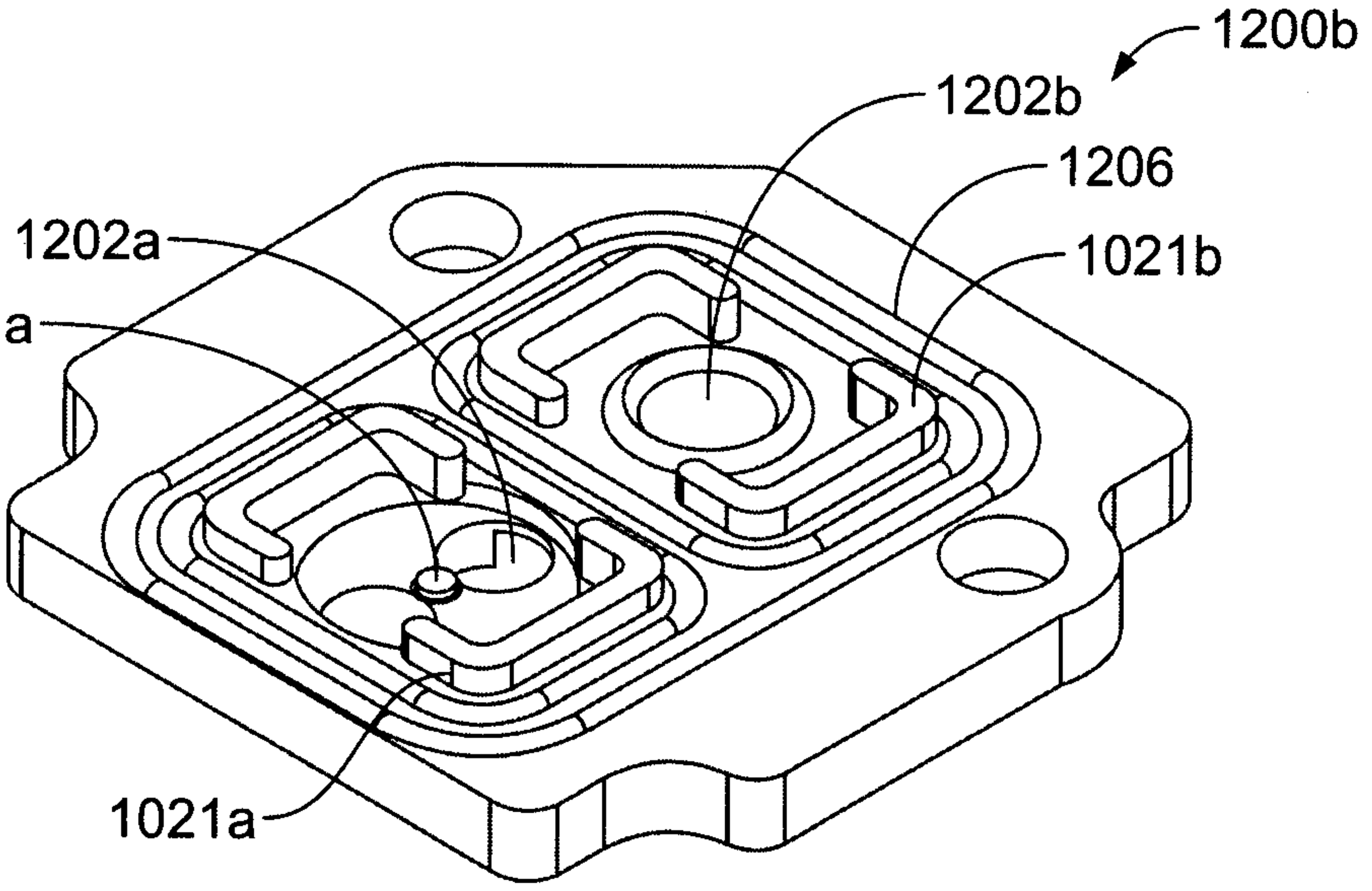


FIG. 16A

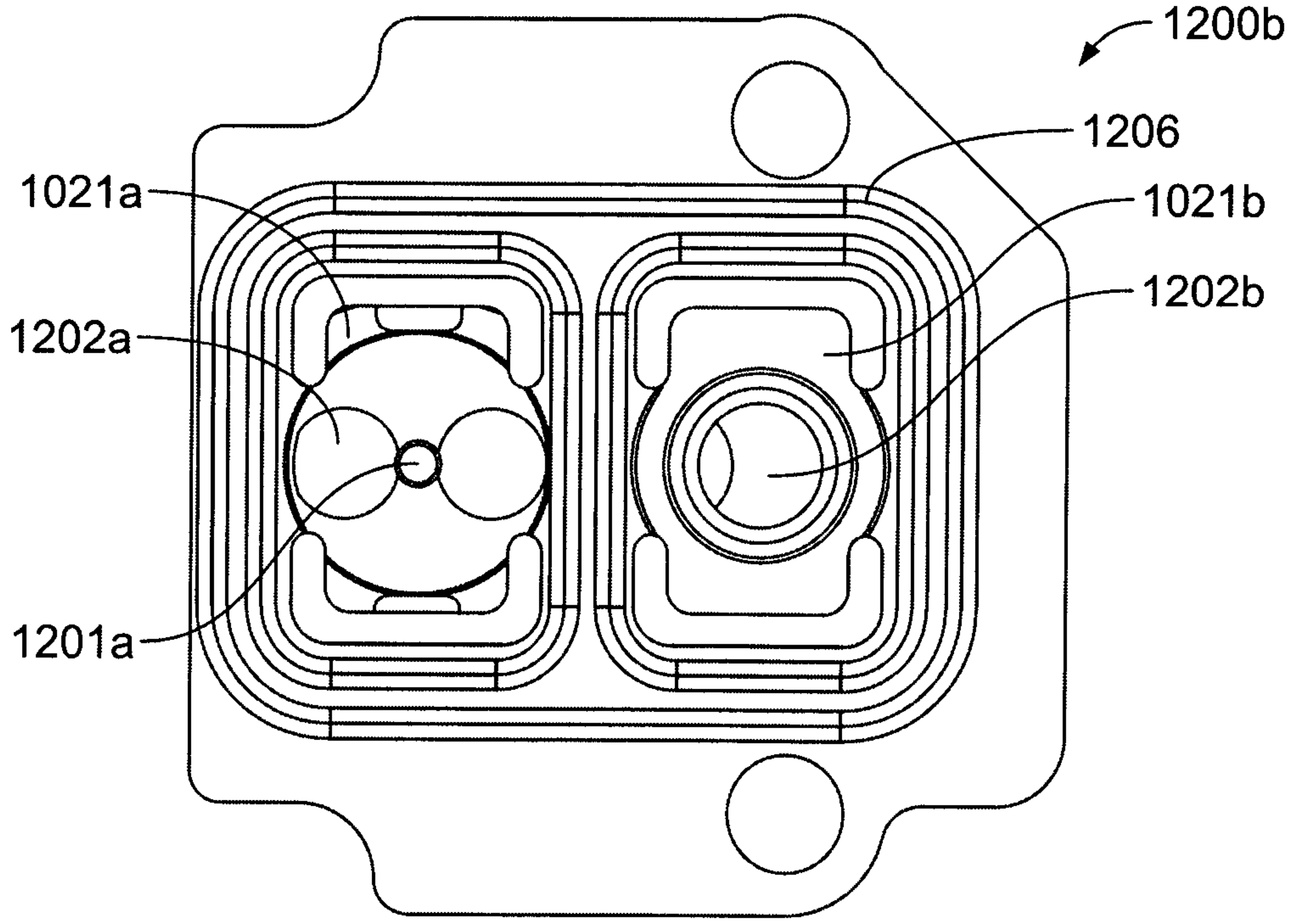
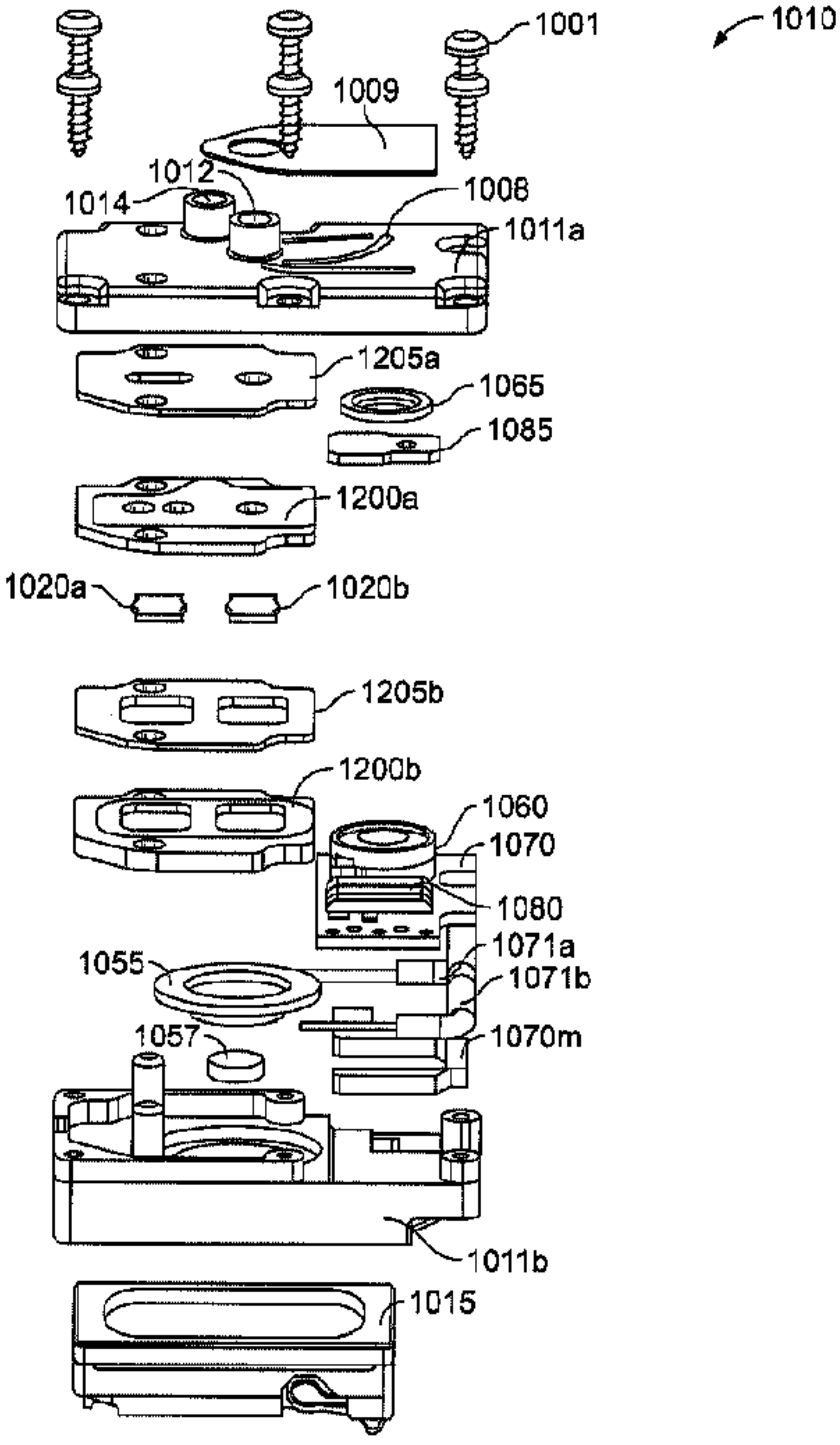


FIG. 16B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