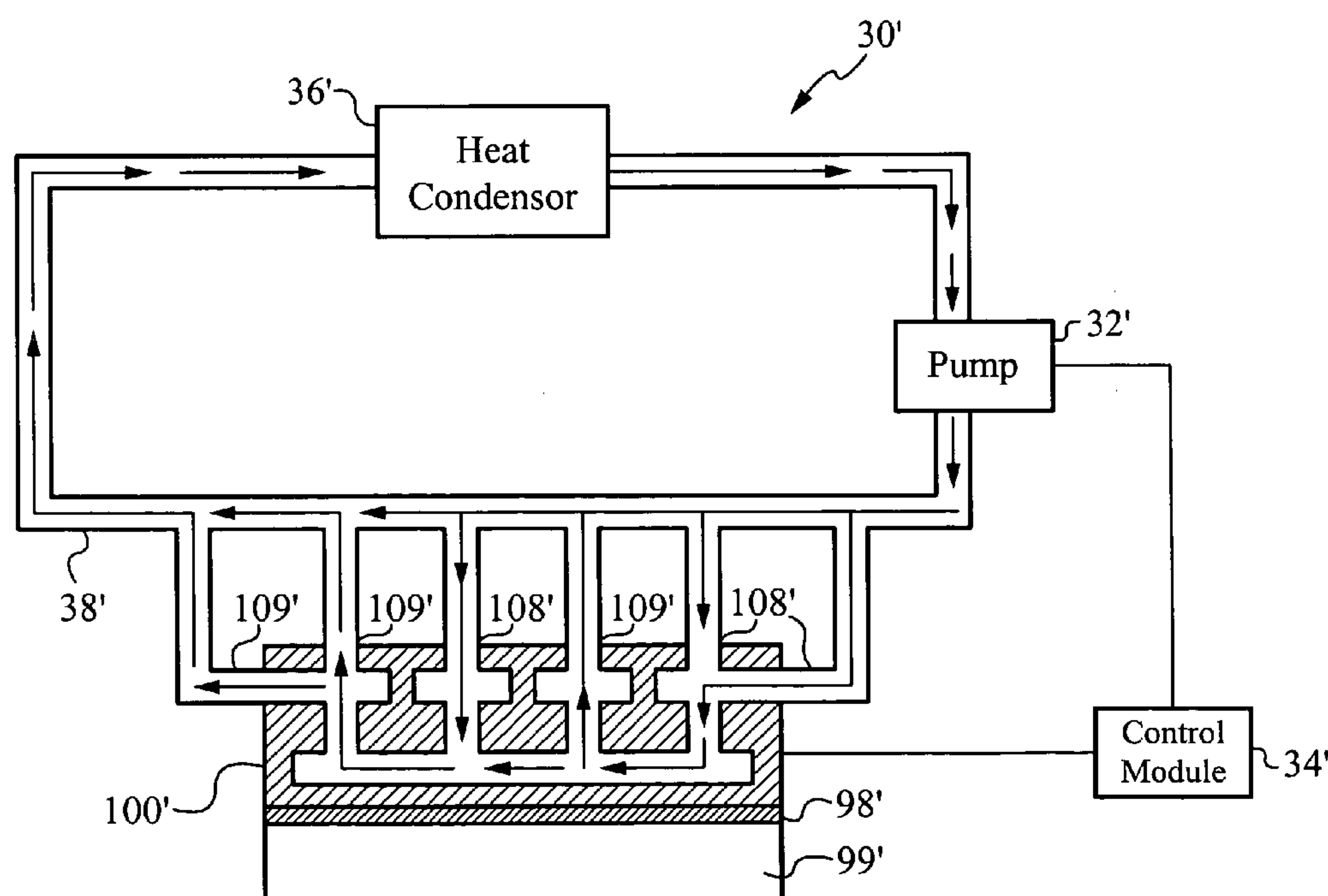
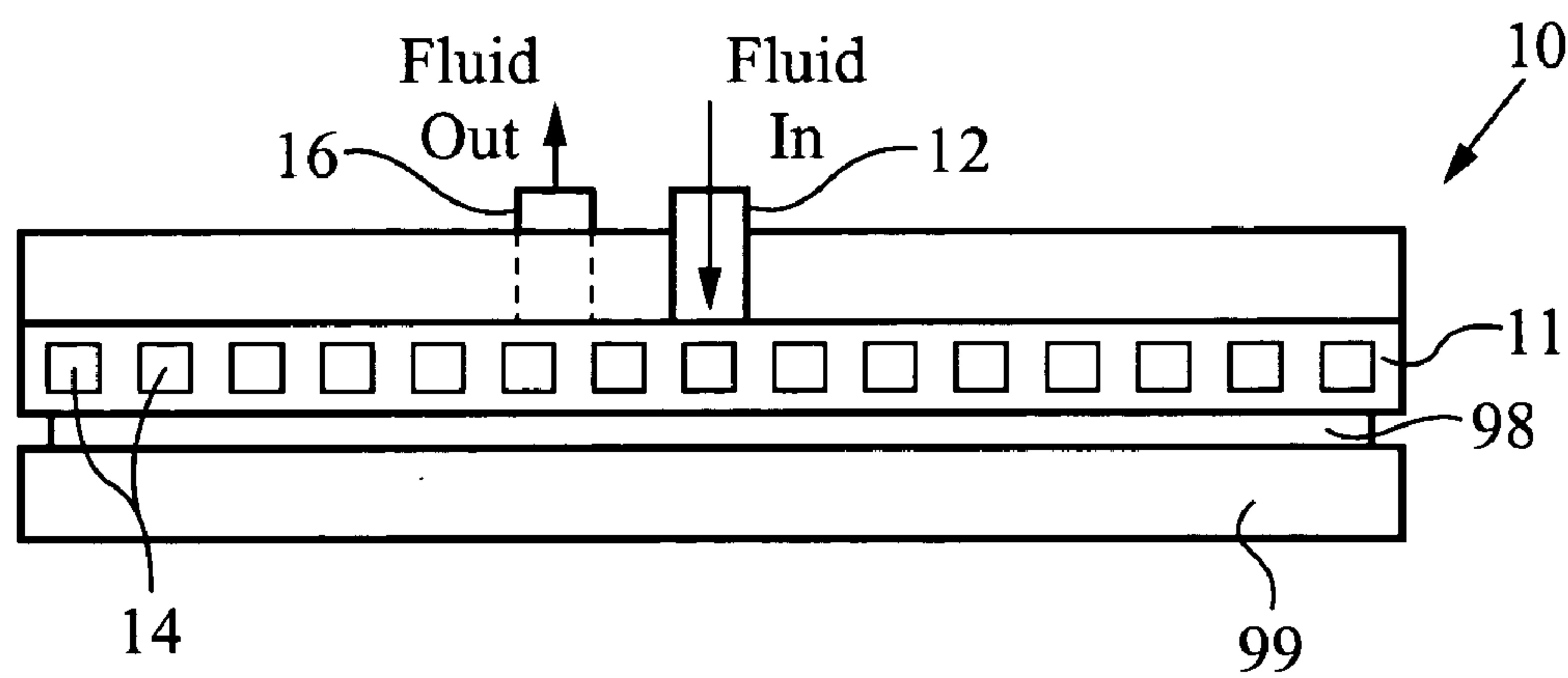


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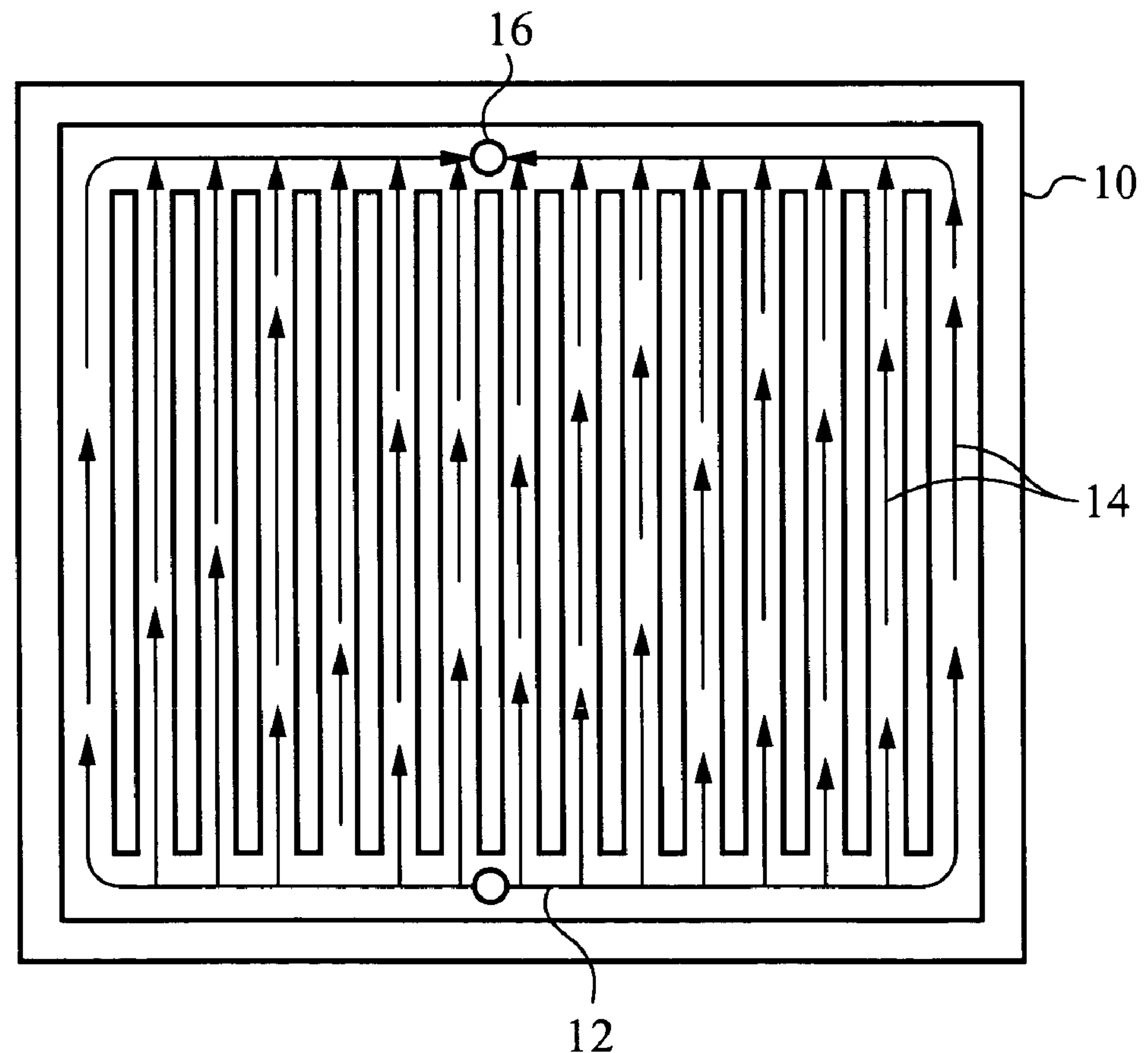
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filed on Oct. 6, 2003, which is a continuation-in-part  
of application No. 10/439,635, filed on May 16, 2003.(60) Provisional application No. 60/423,009, filed on Nov.  
1, 2002. Provisional application No. 60/442,383, filed  
on Jan. 24, 2003. Provisional application No. 60/455,  
729, filed on Mar. 17, 2003.**Publication Classification**(51) **Int. Cl.<sup>7</sup>** ..... **F28F 7/00**(52) **U.S. Cl.** ..... **165/80.4**(57) **ABSTRACT**

A heat exchanger and method of manufacturing thereof comprises an interface layer for cooling a heat source. The interface layer is coupled to the heat source and is configured to pass fluid therethrough. The heat exchanger further comprises a manifold layer that is coupled to the interface layer. The manifold layer includes at least one first port that is coupled to a first set of individualized holes which channel fluid through the first set. The manifold layer includes at least one second port coupled to a second set of individualized holes which channel fluid through the second set. The first set of holes and second set of holes are arranged to provide a minimized fluid path distance between the first and second ports to adequately cool the heat source. Preferably, each hole in the first set is positioned a closest optimal distance to an adjacent hole the second set.

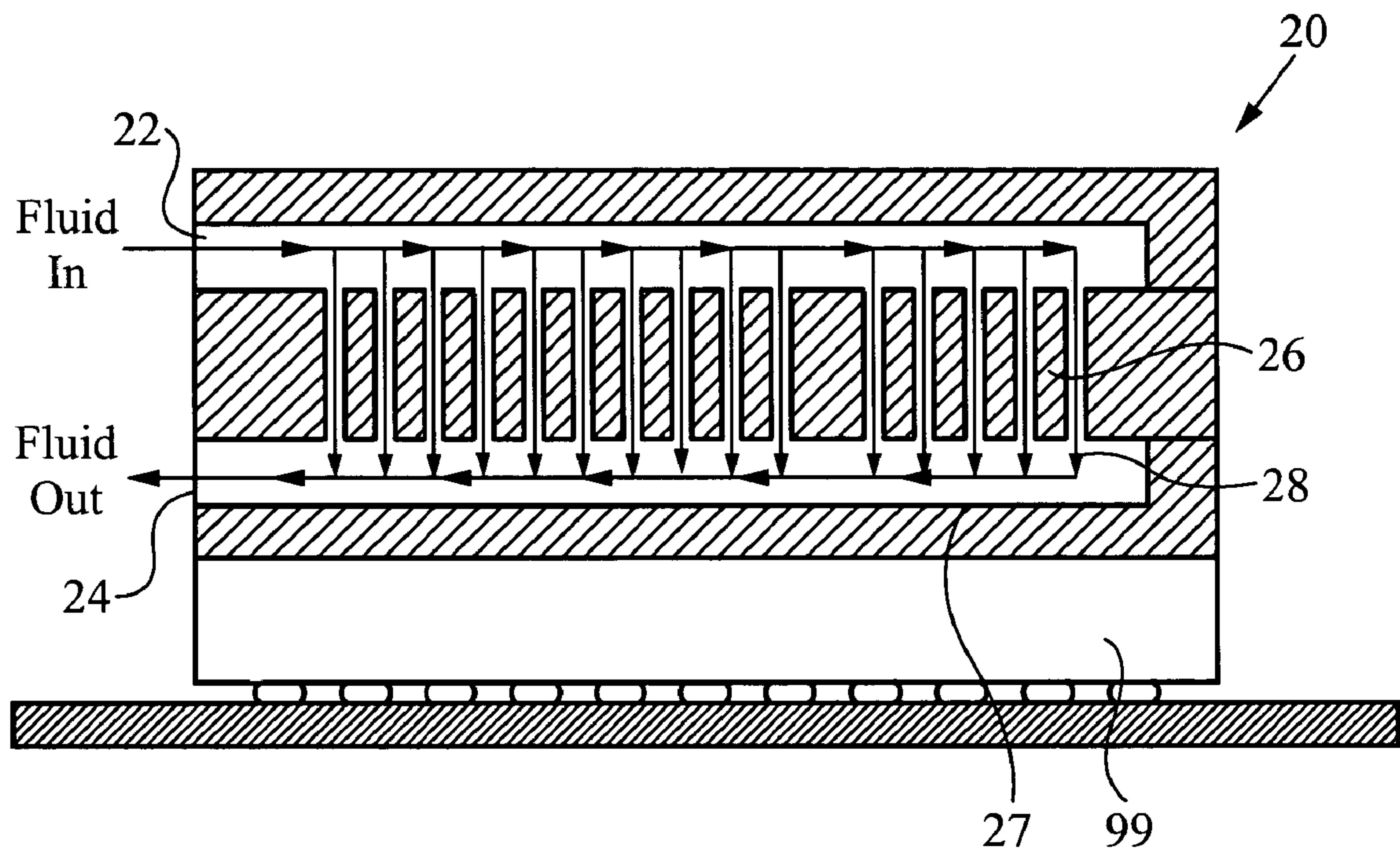




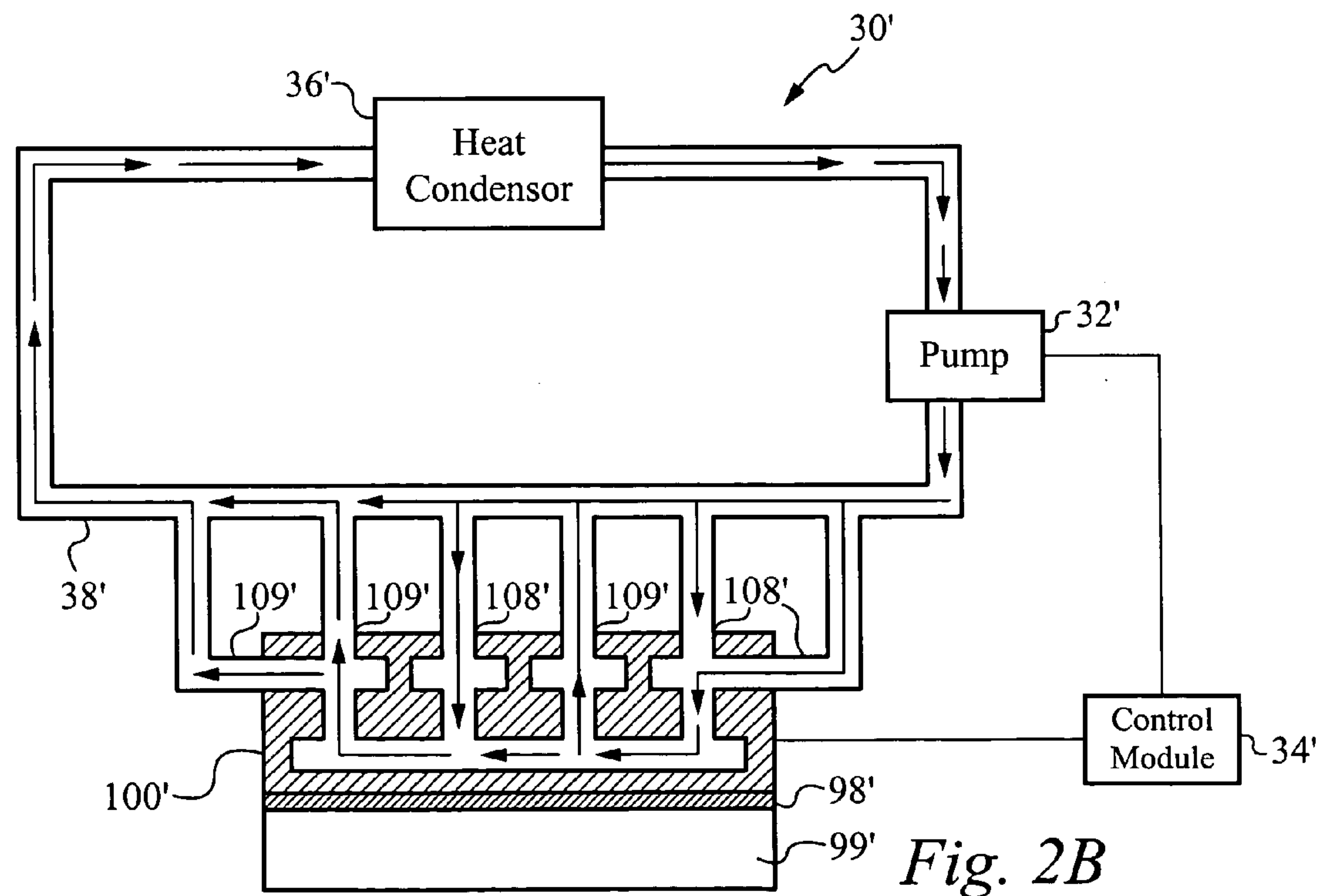
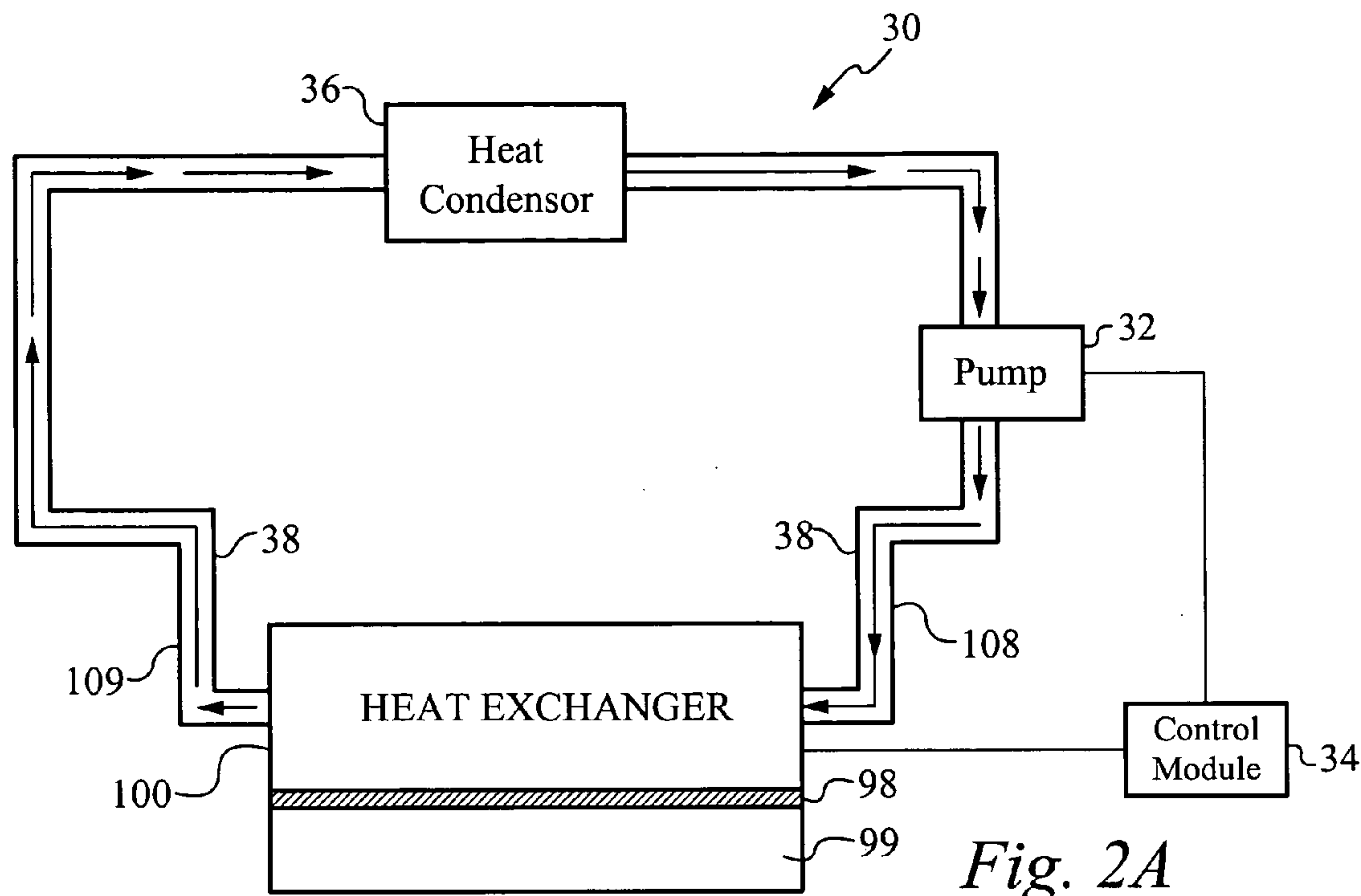
*Fig. 1A* (PRIOR ART)

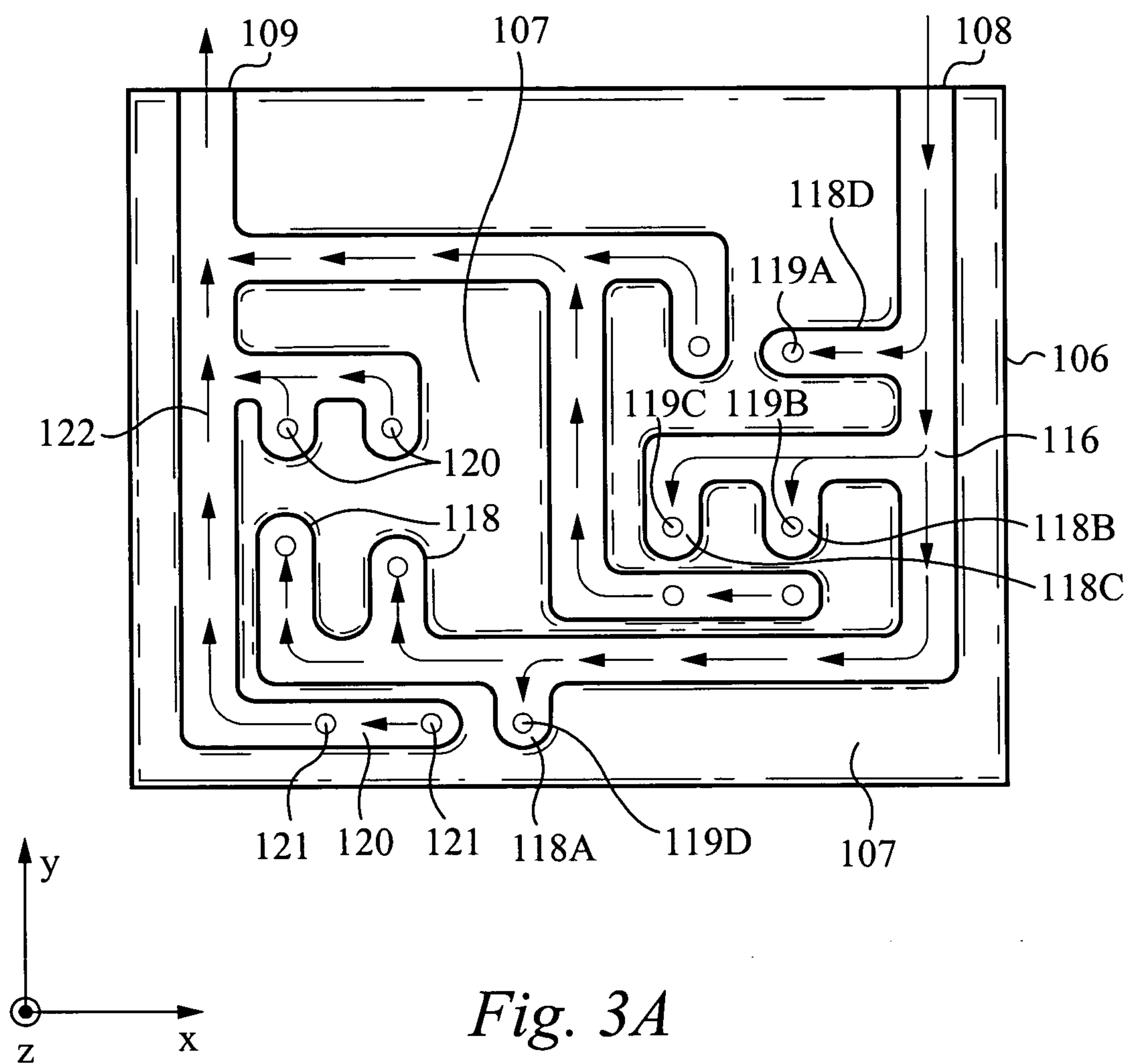


*Fig. 1B* (PRIOR ART)



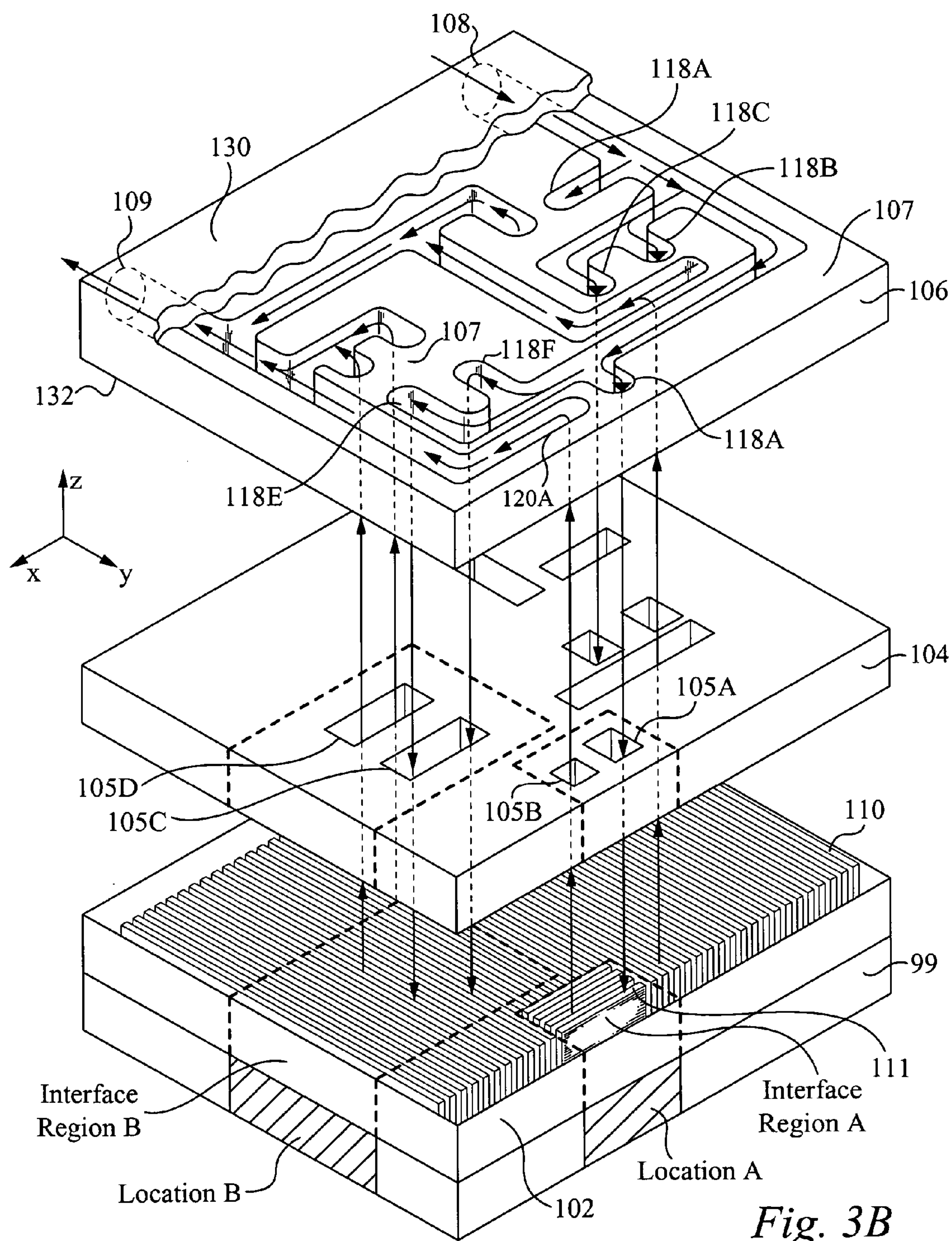
*Fig. 1C* (PRIOR ART)





*Fig. 3A*





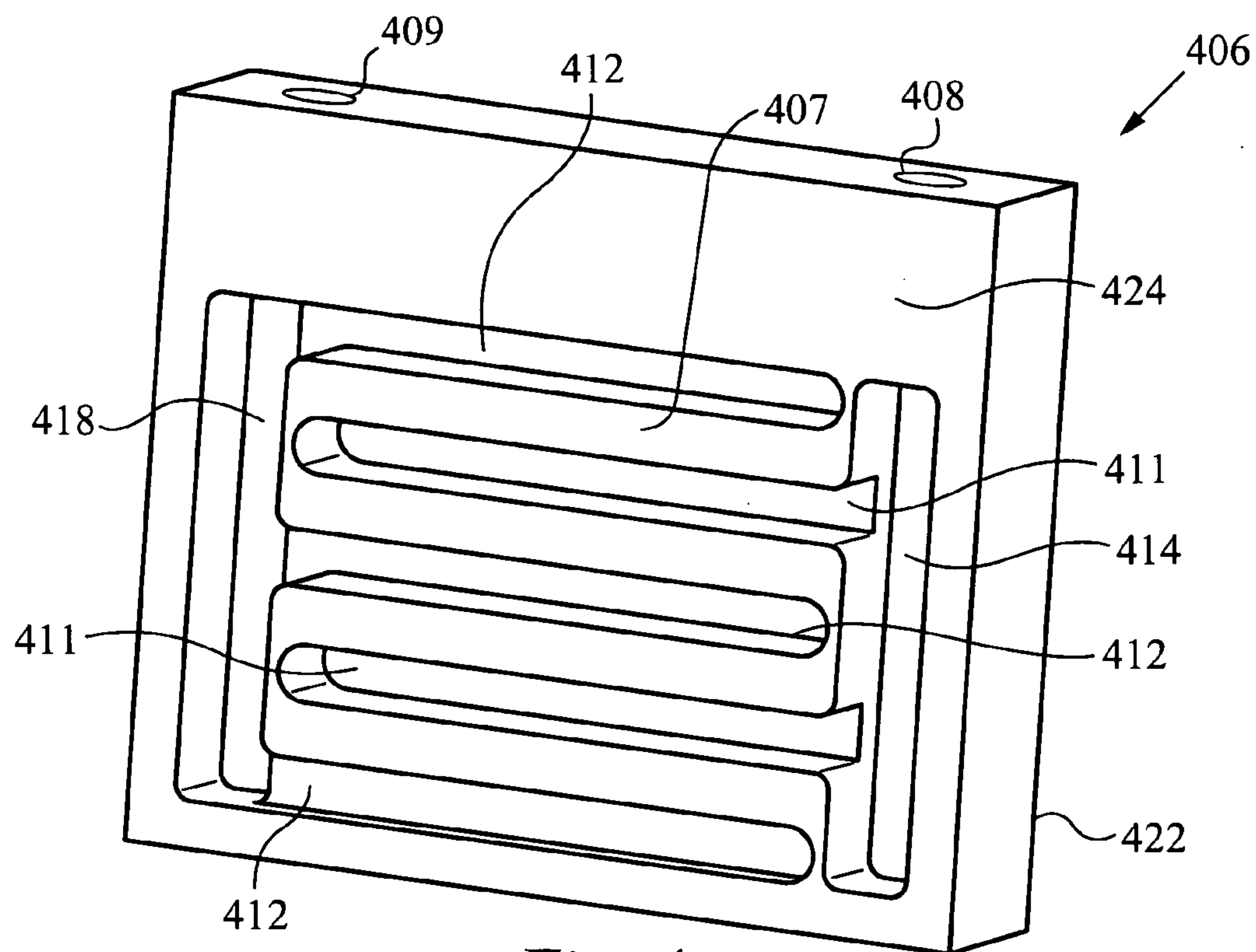


Fig. 4

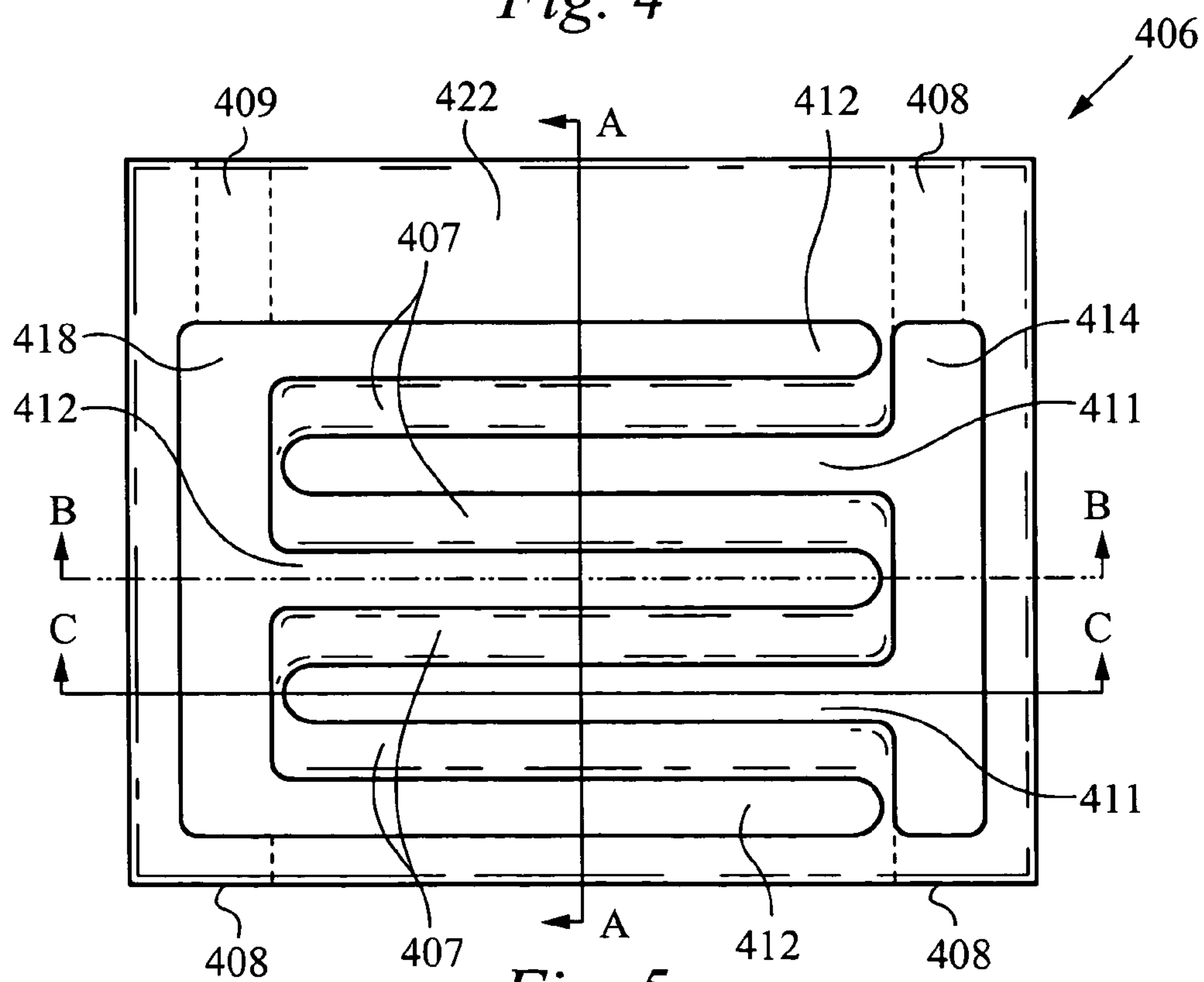


Fig. 5

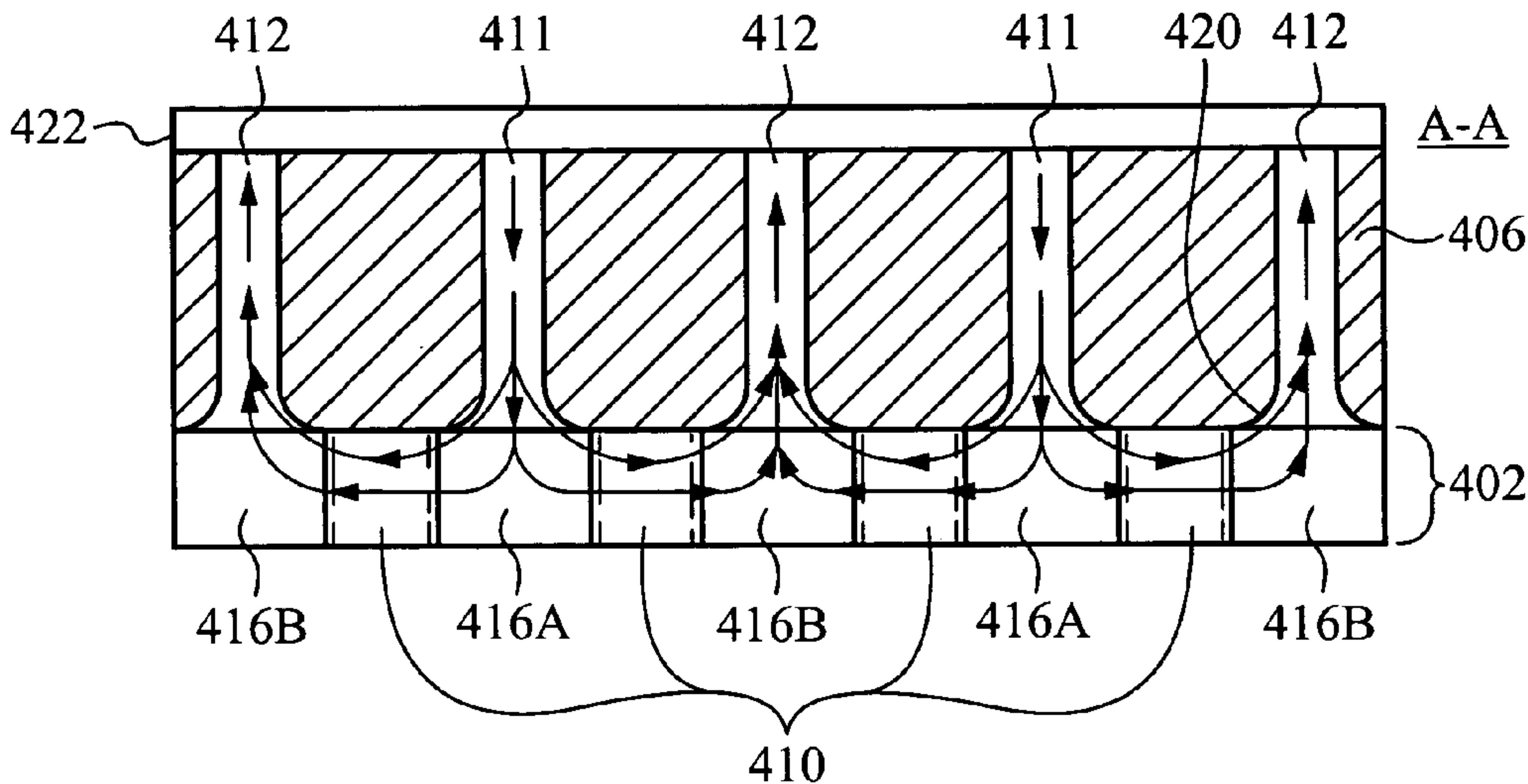


Fig. 6A

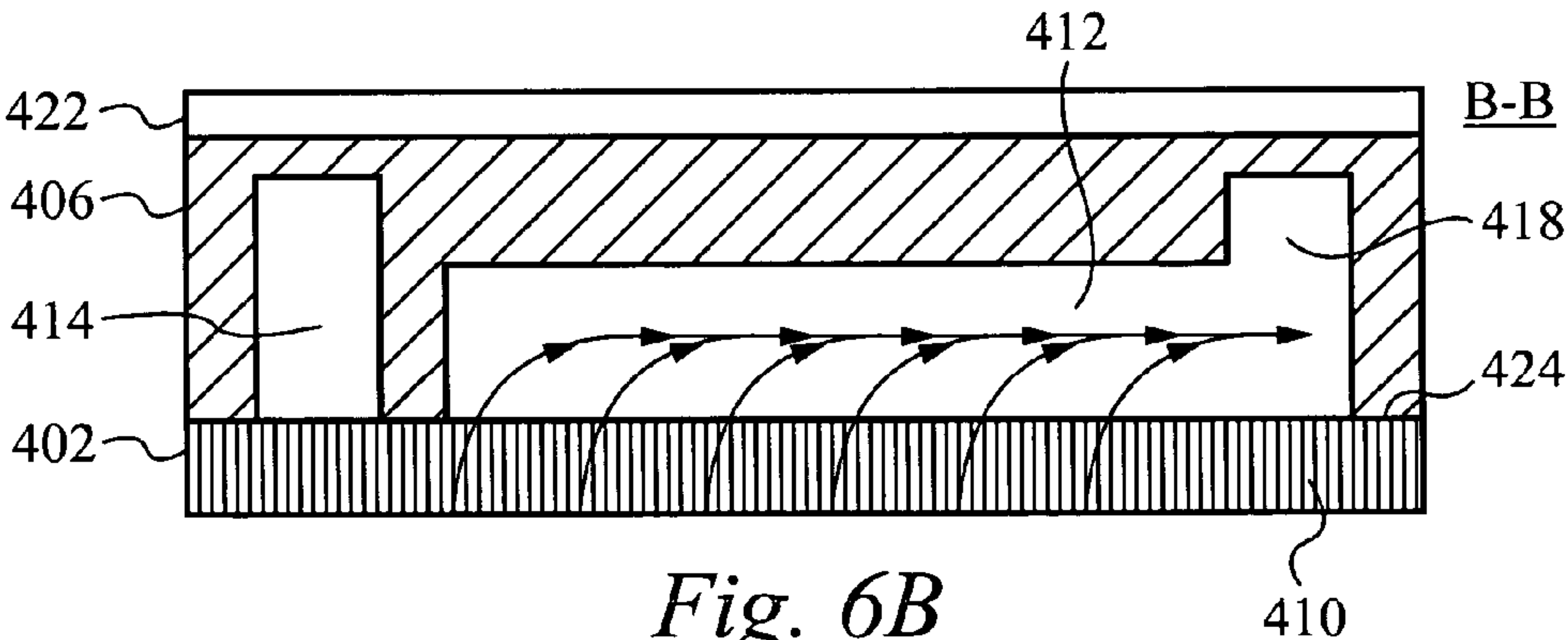


Fig. 6B

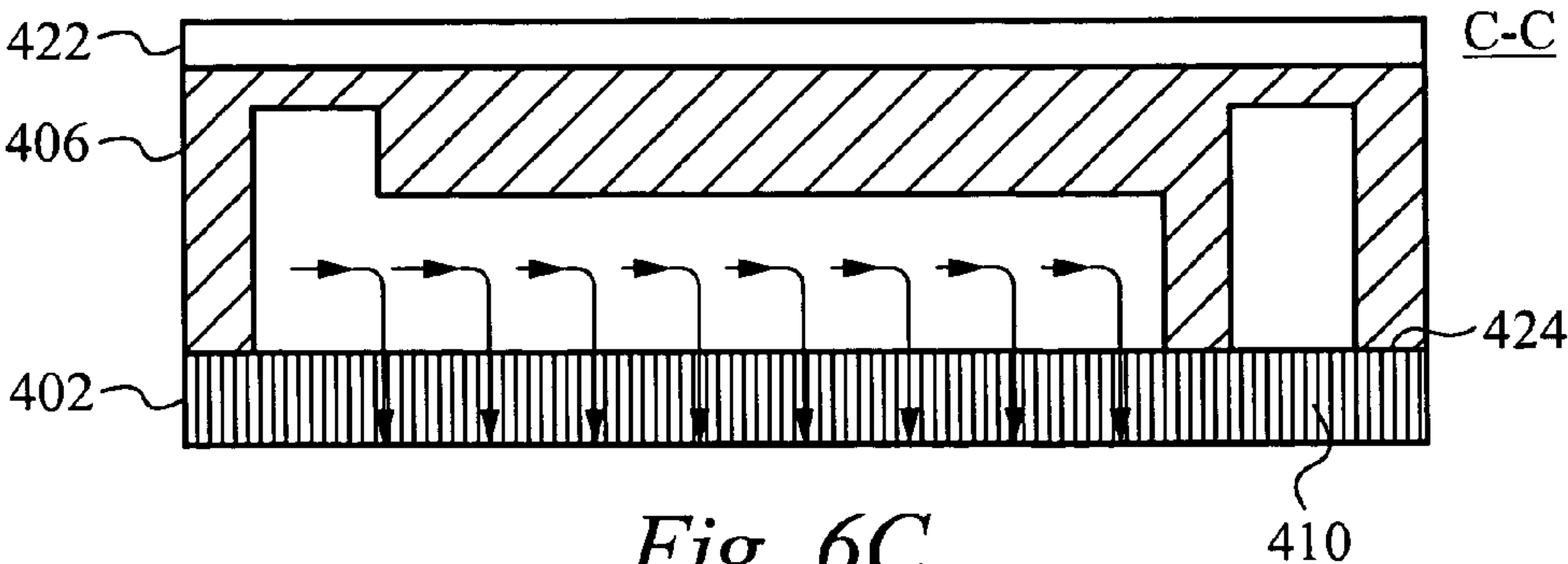
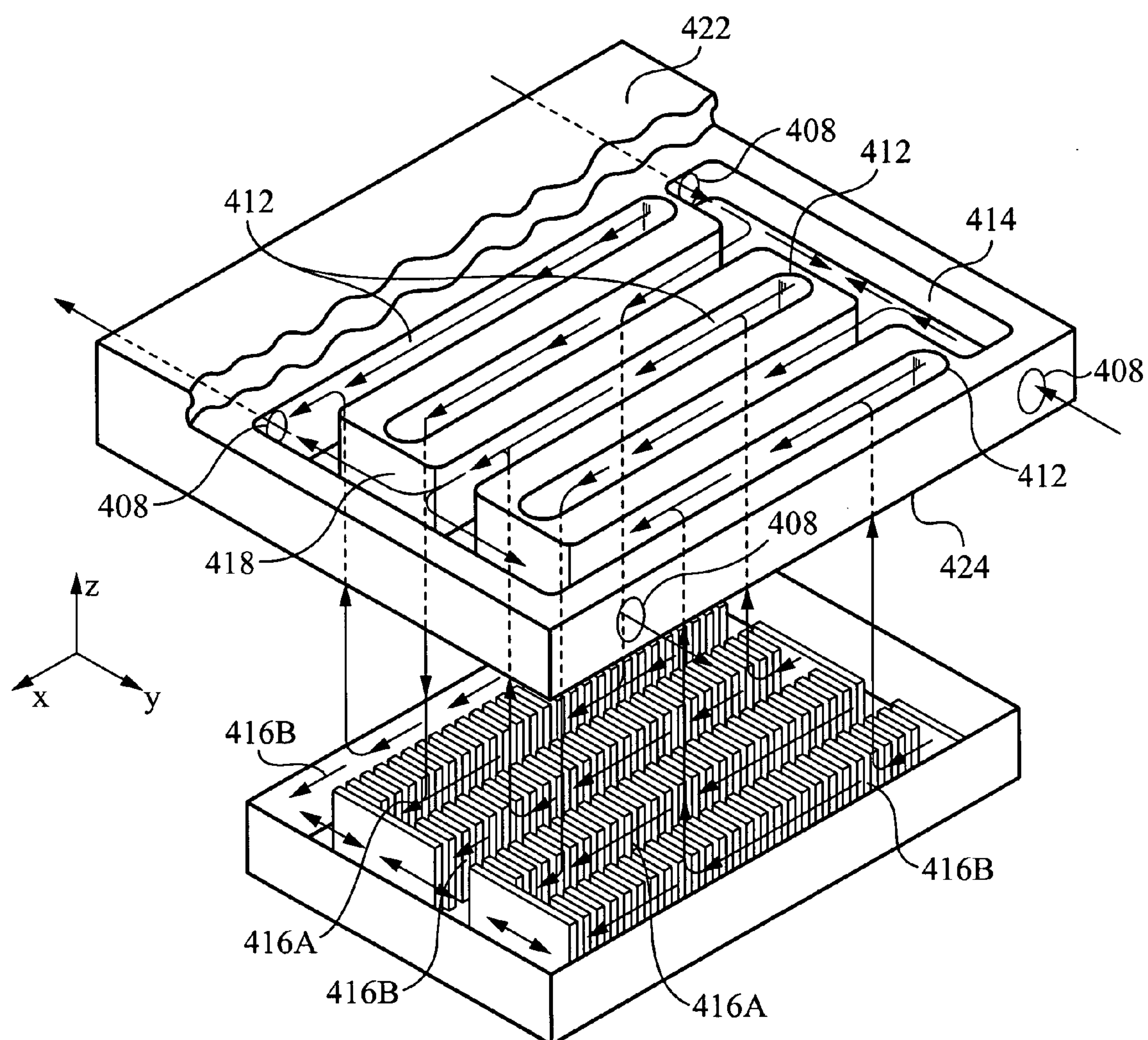
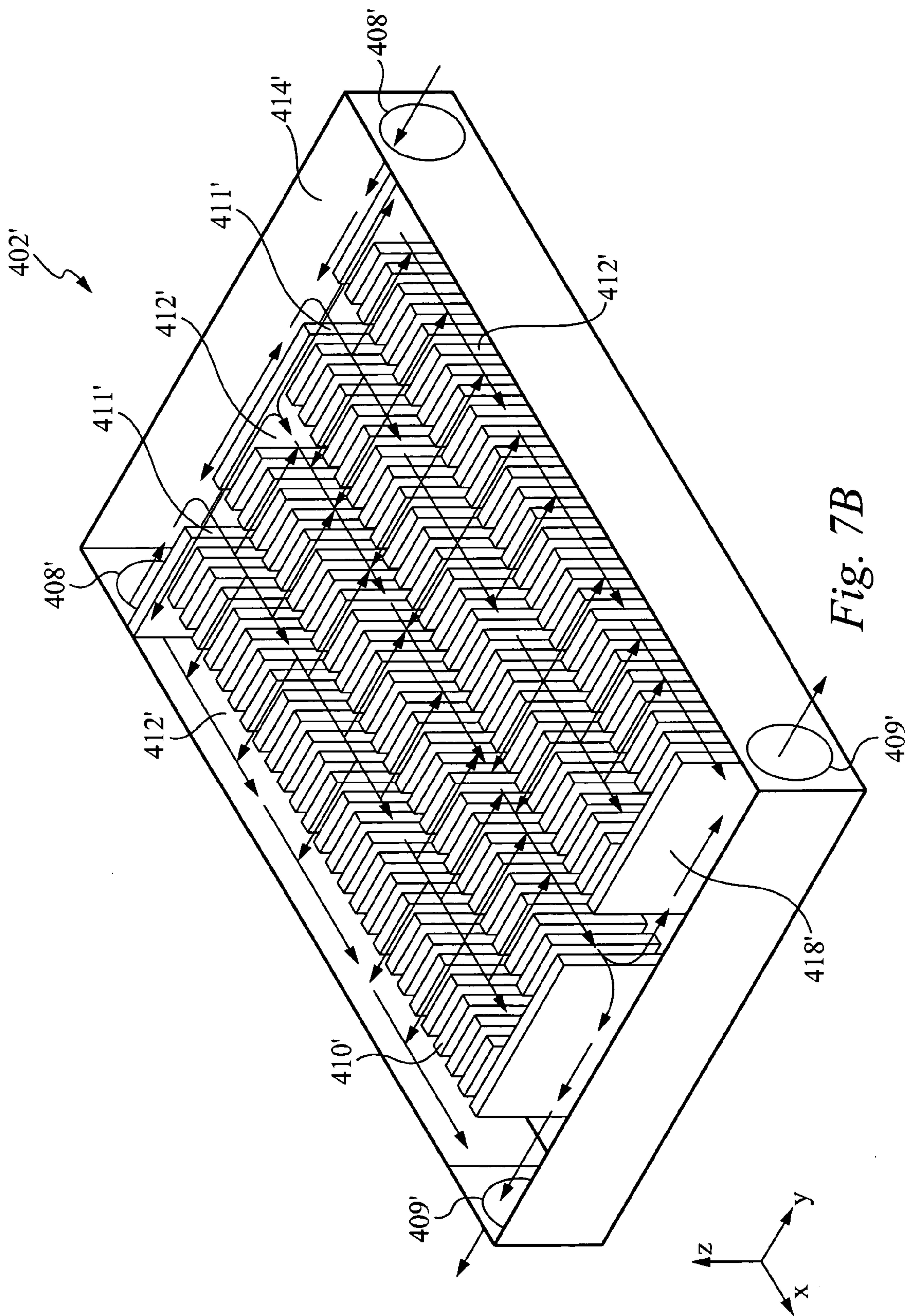


Fig. 6C





*Fig. 7A*



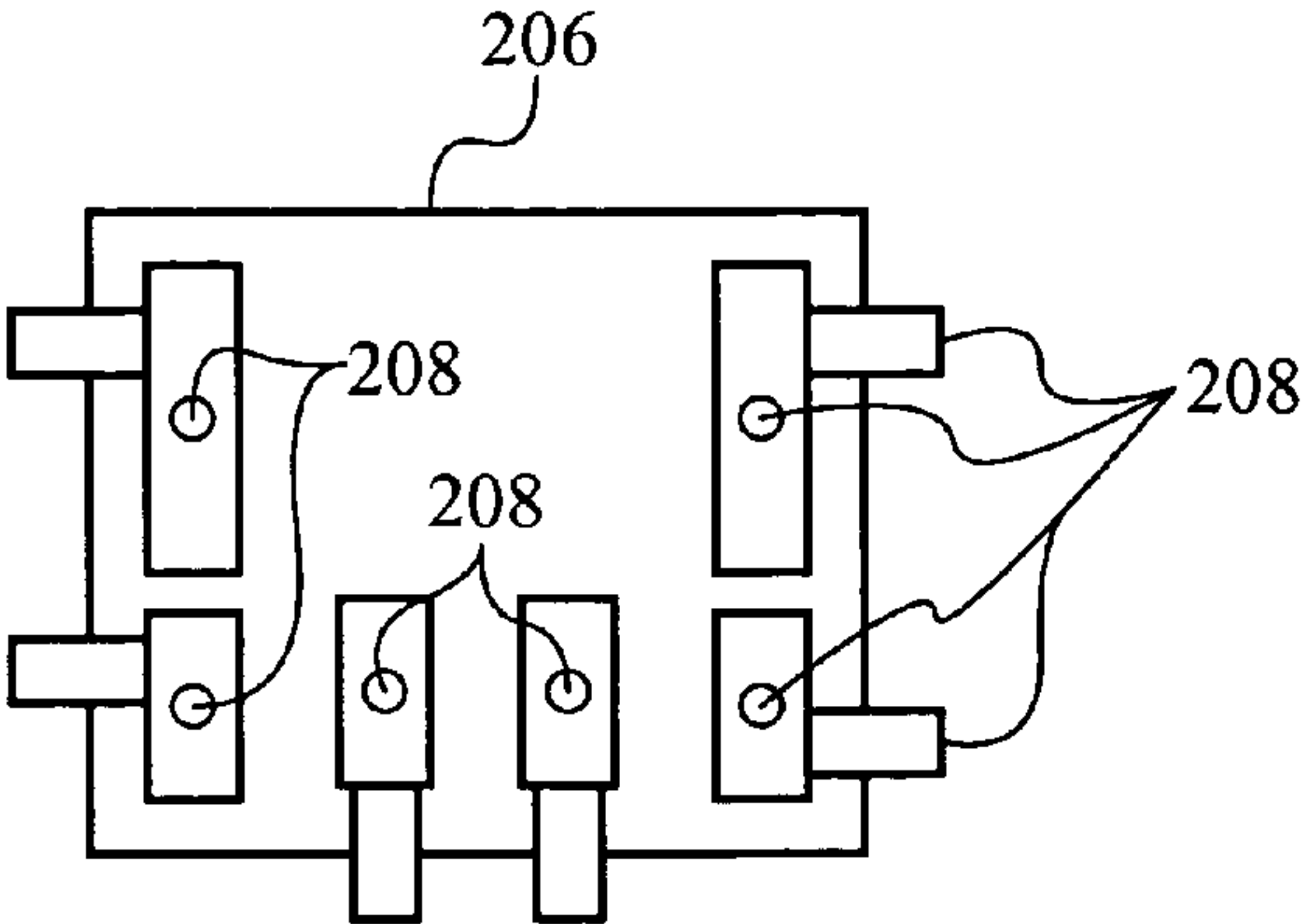


Fig. 8A

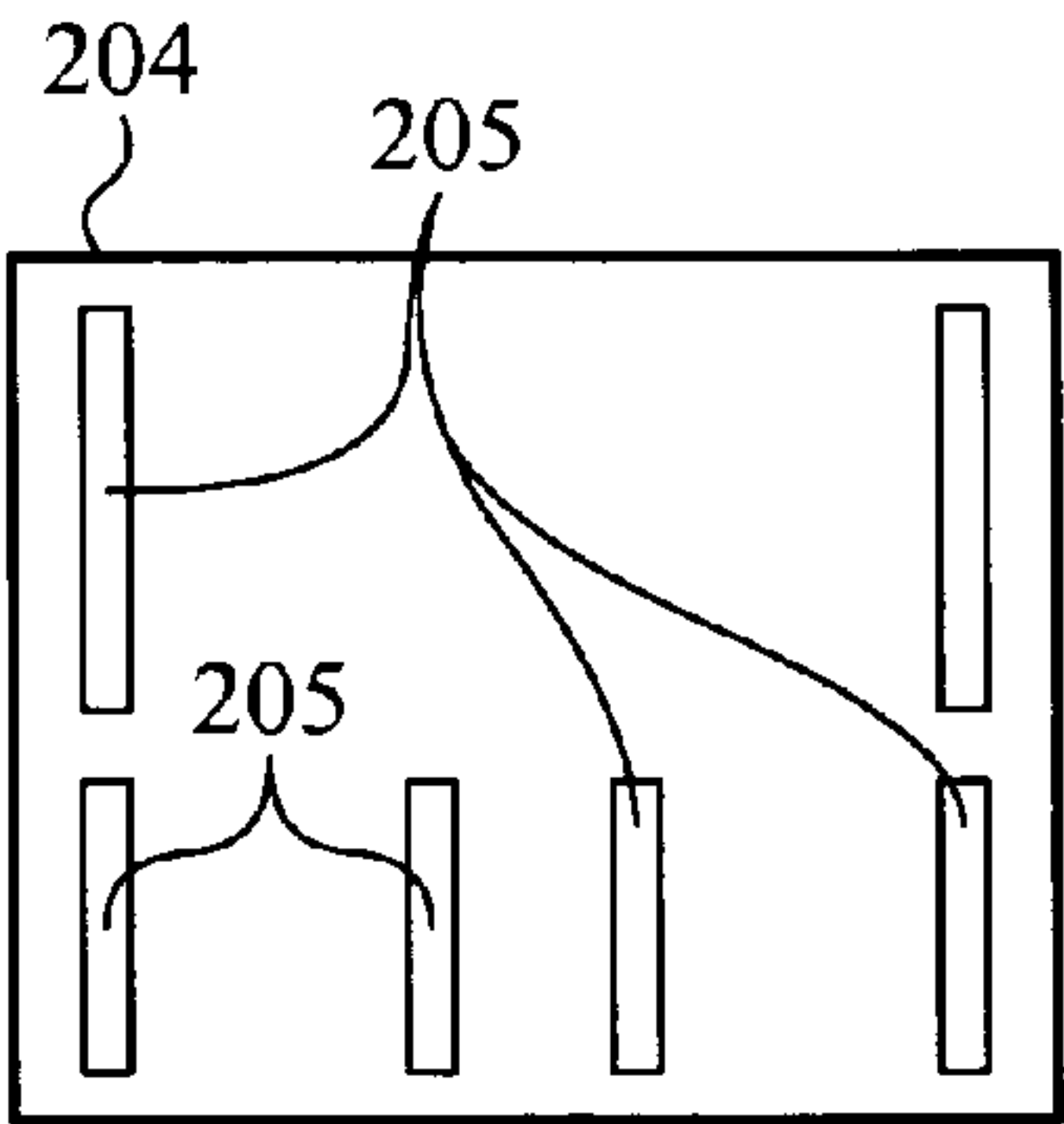


Fig. 8B

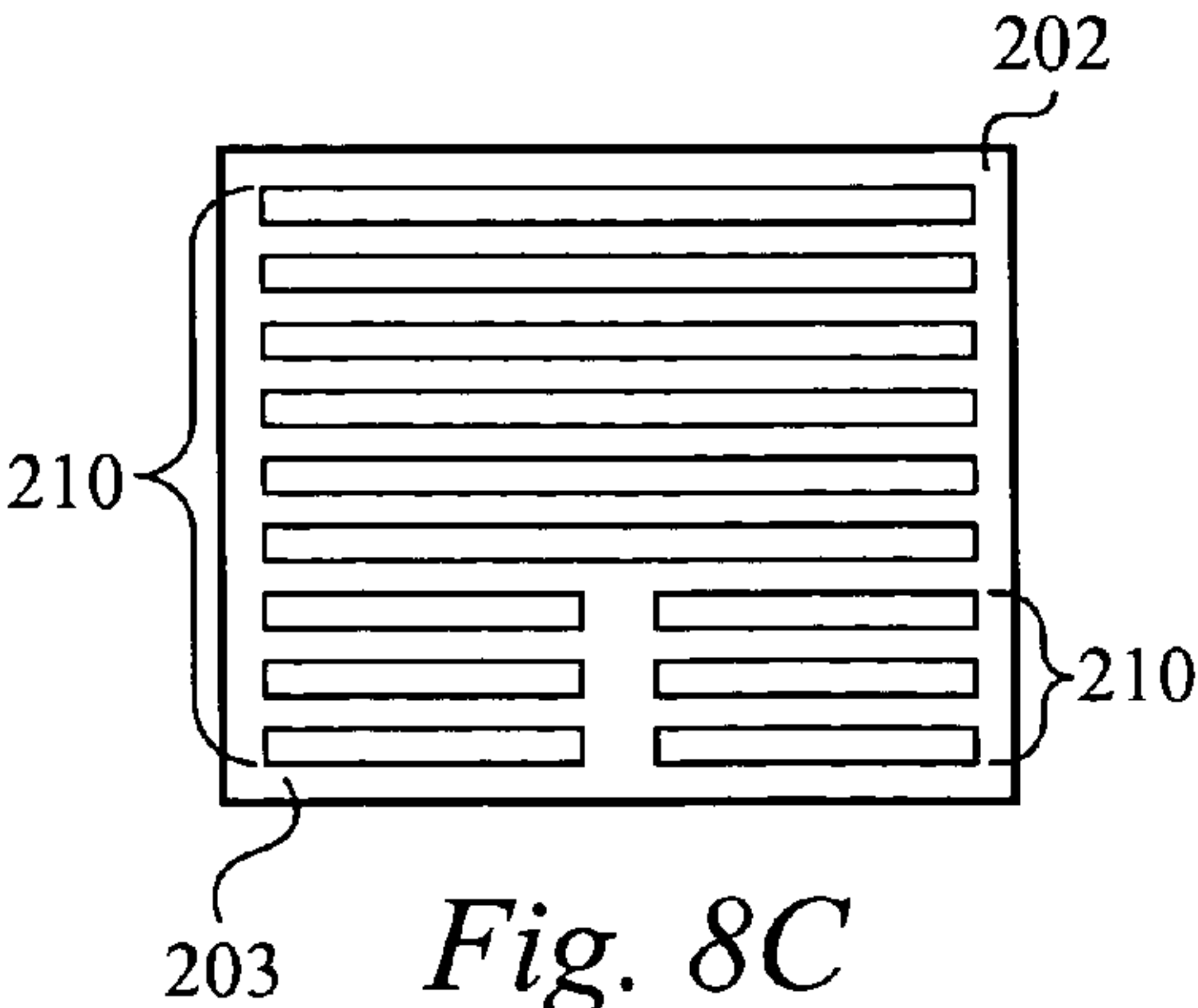


Fig. 8C

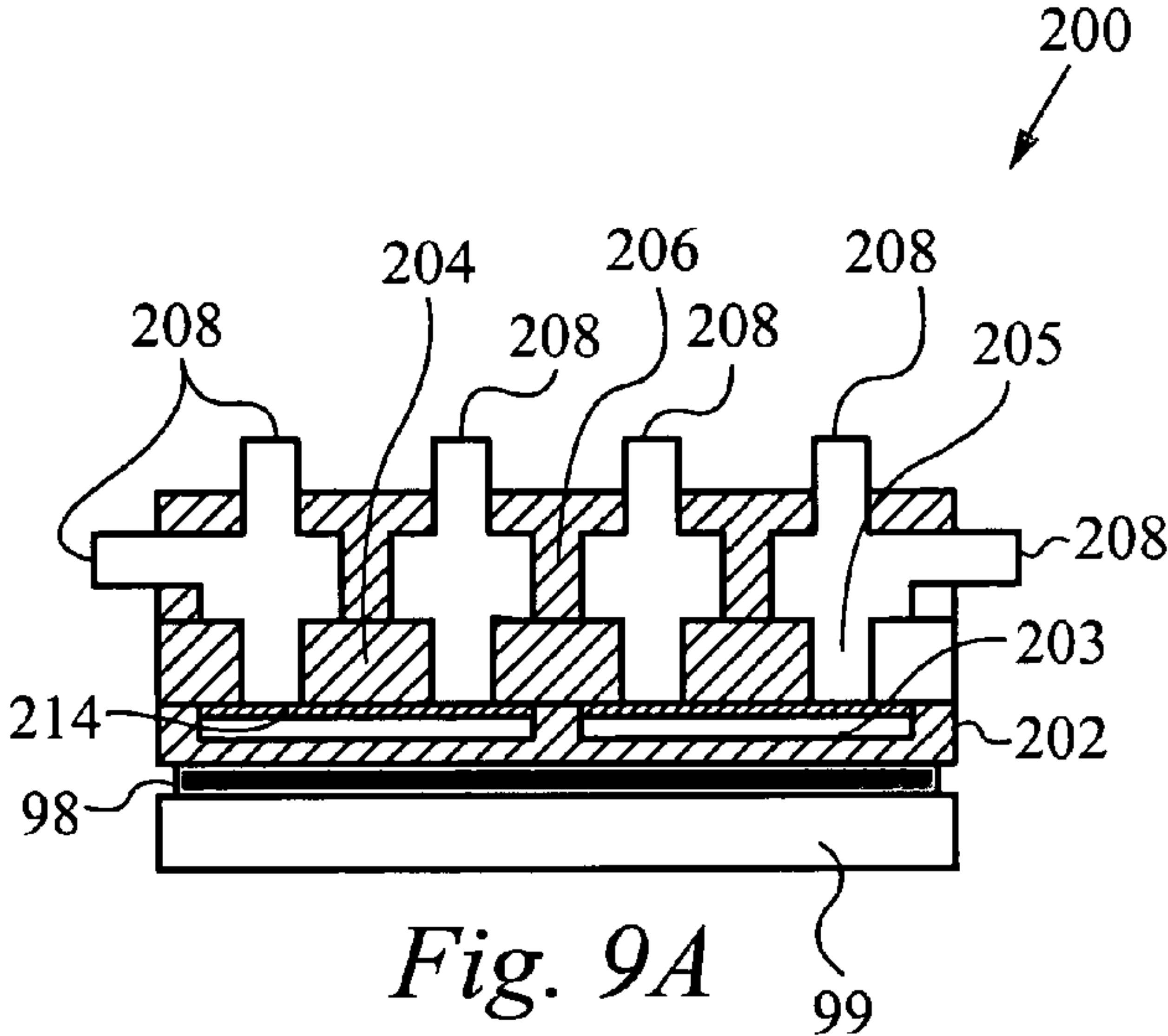


Fig. 9A

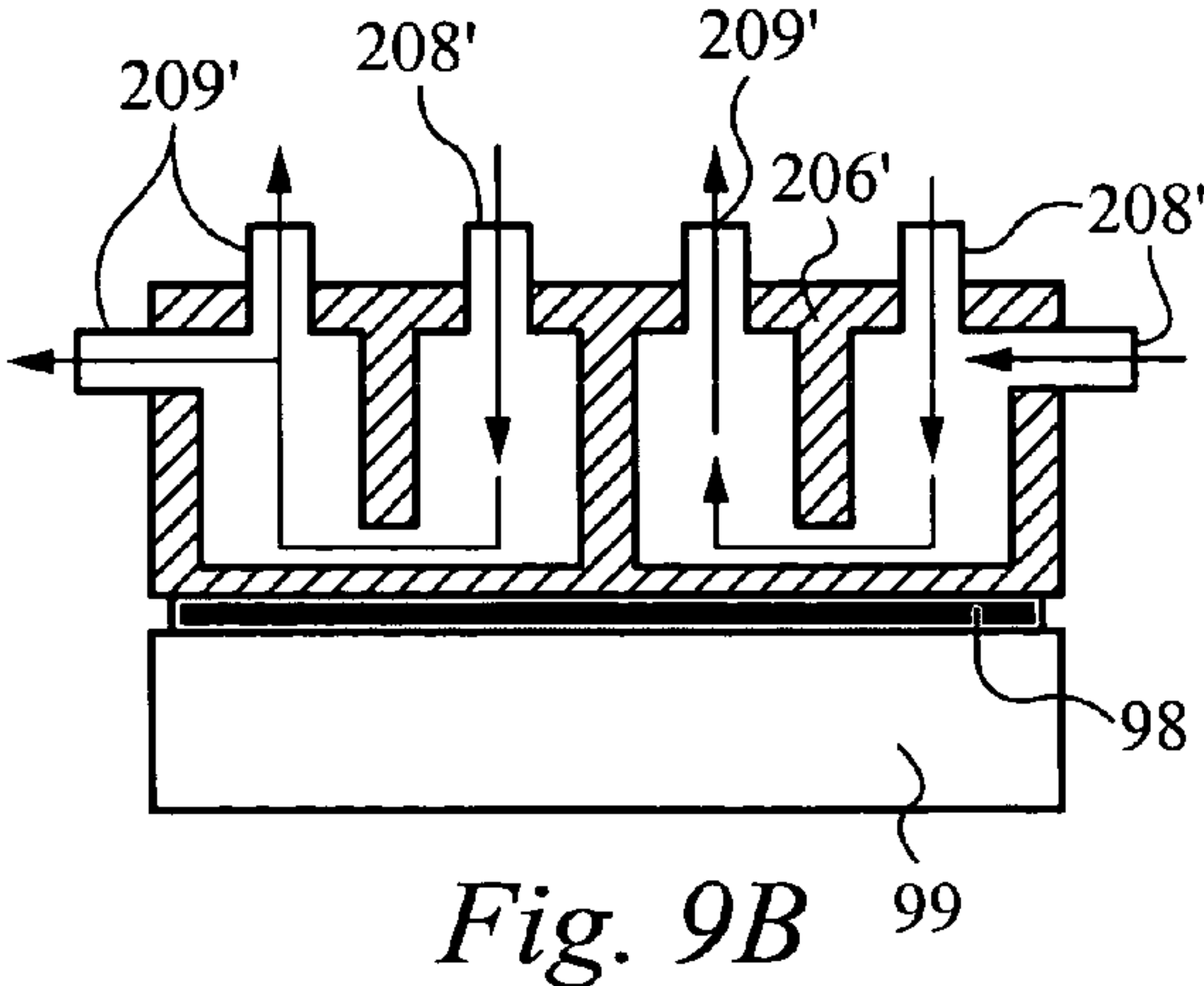
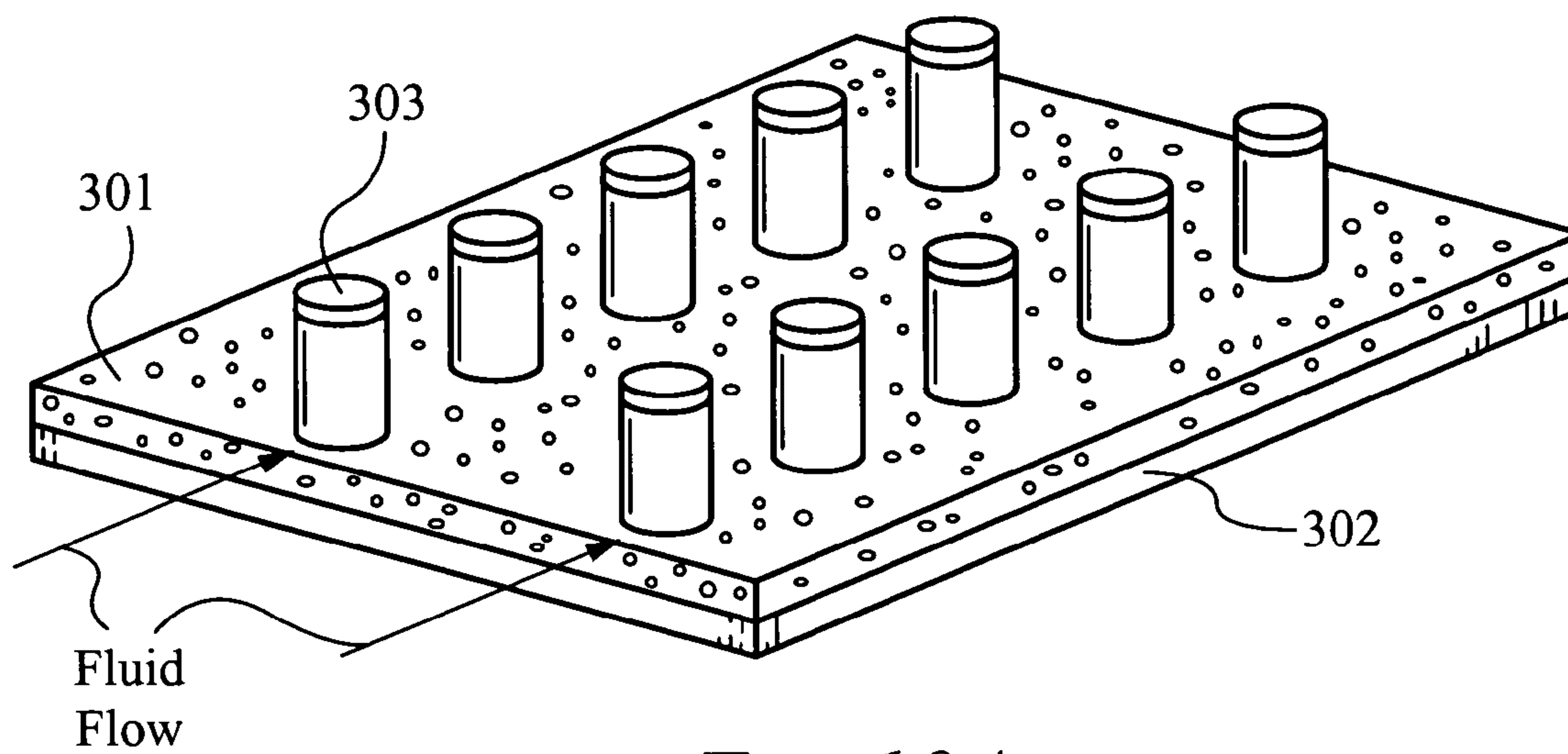


Fig. 9B



*Fig. 10A*



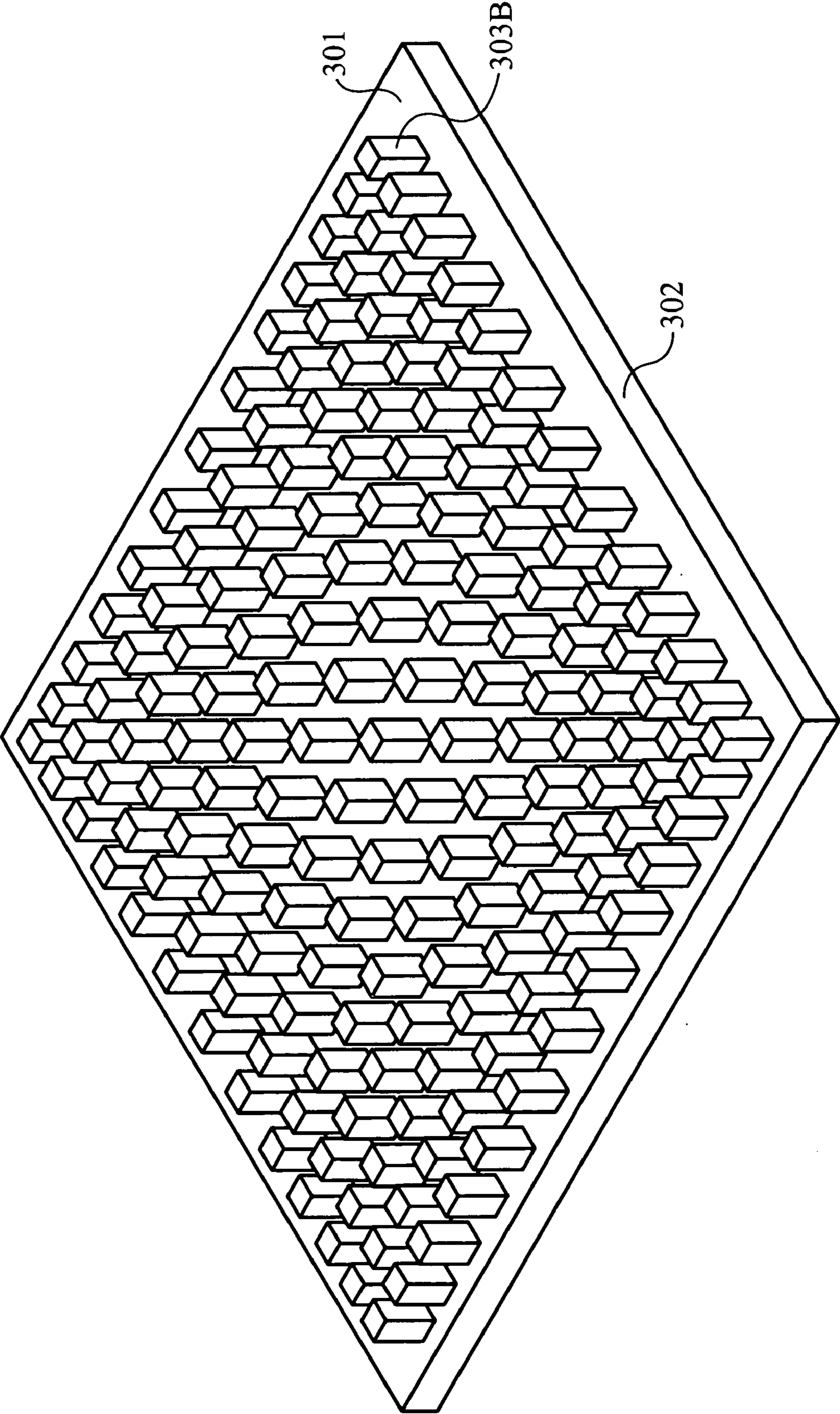
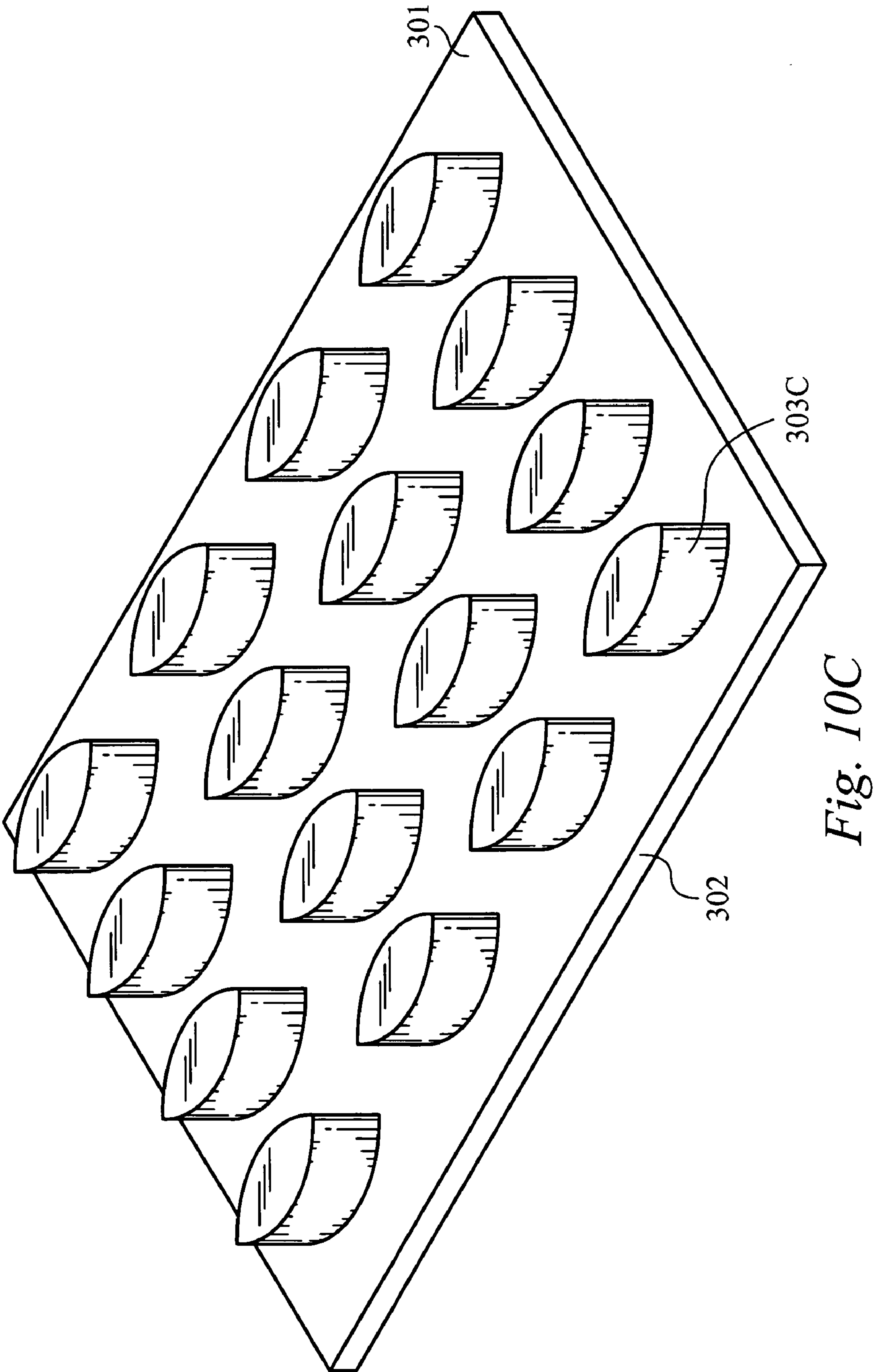
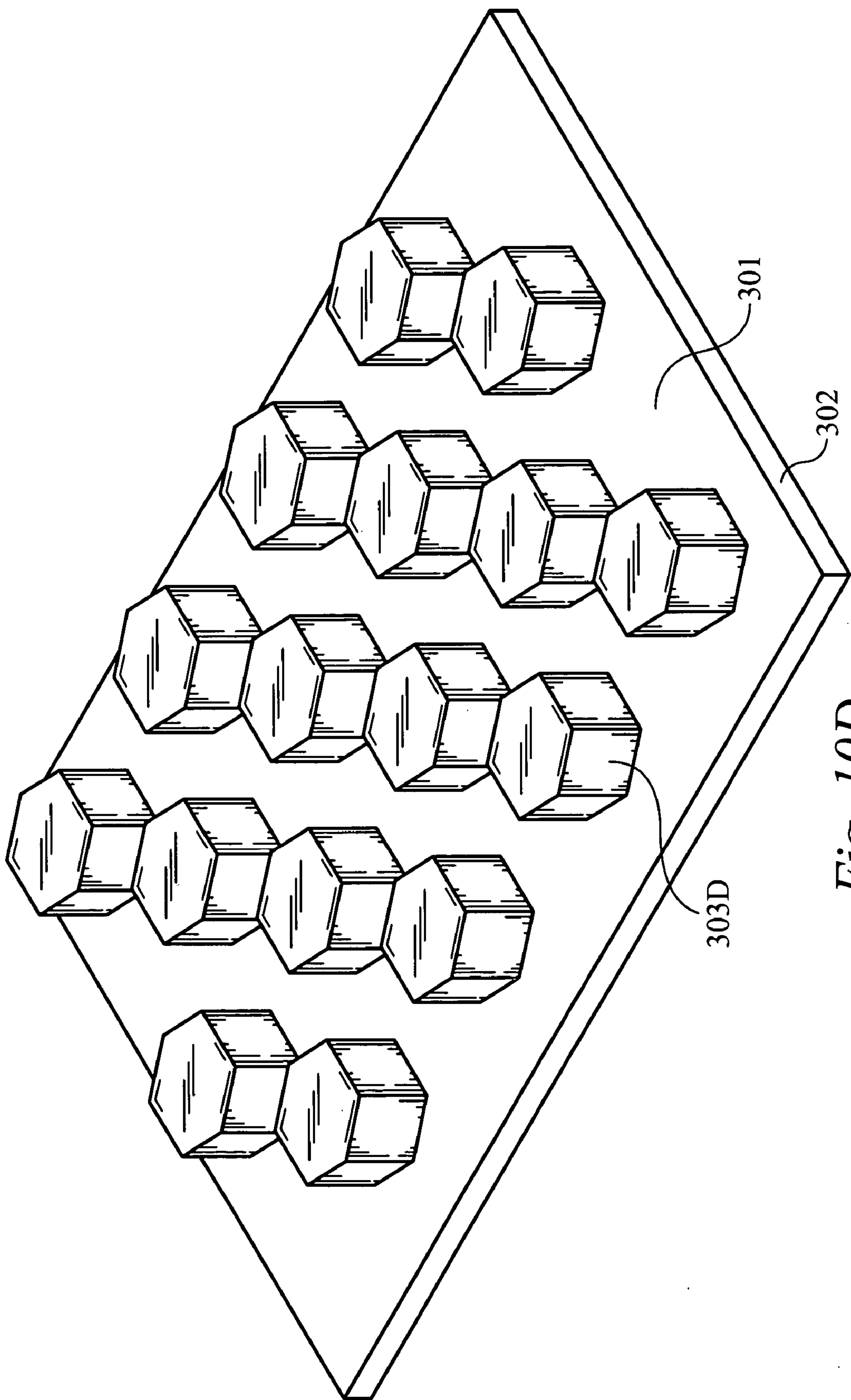


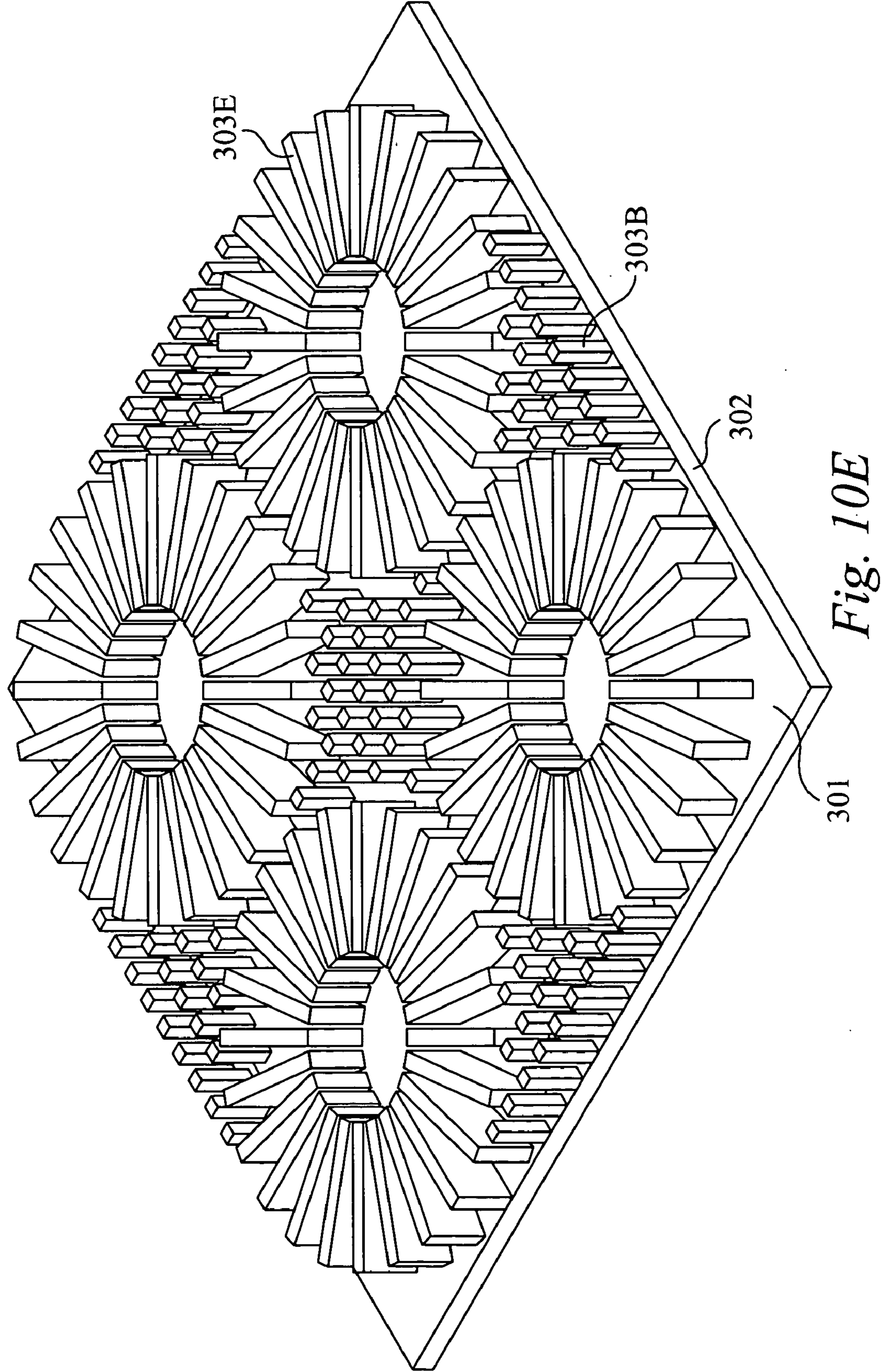
Fig. 10B





*Fig. 10D*







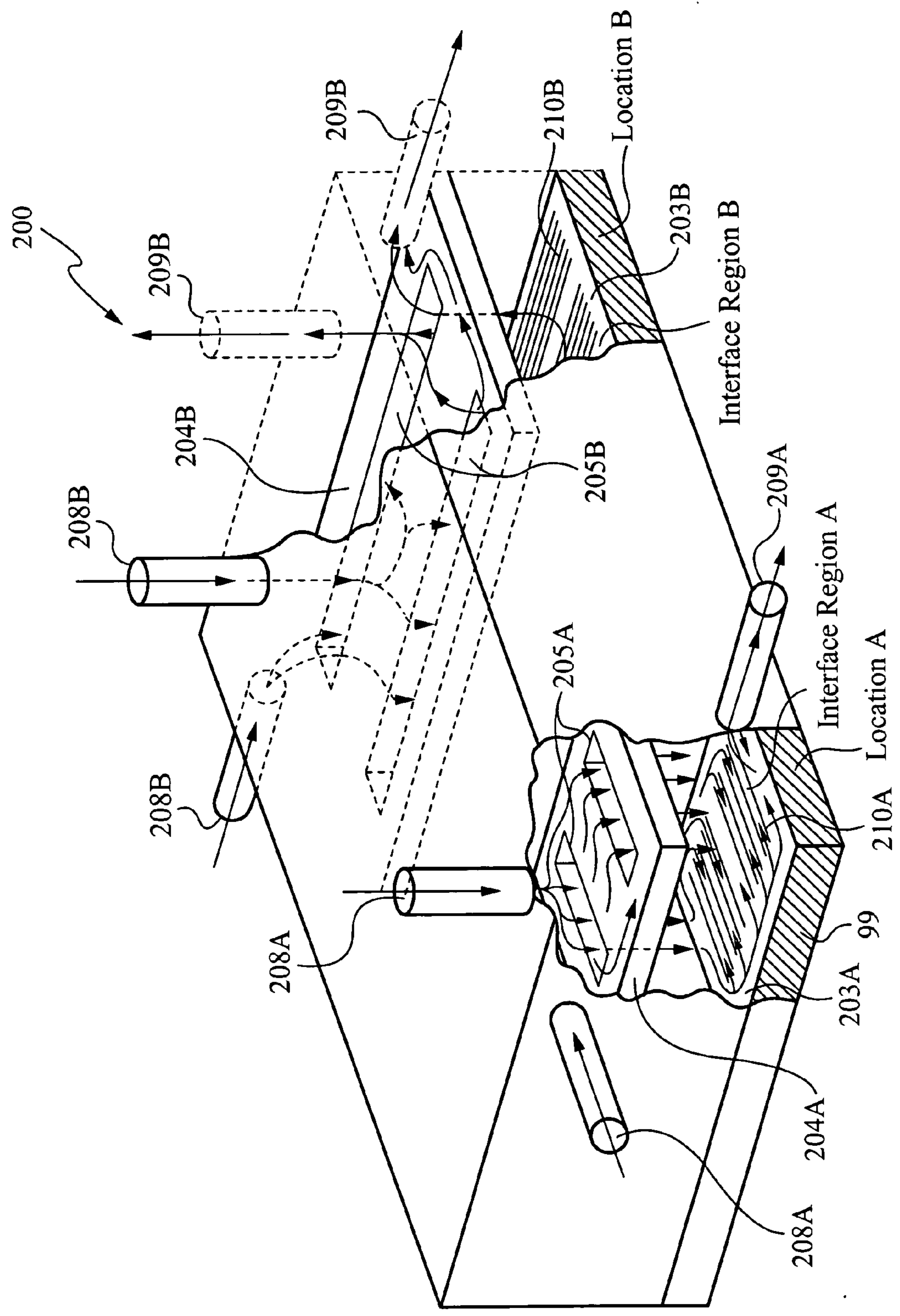
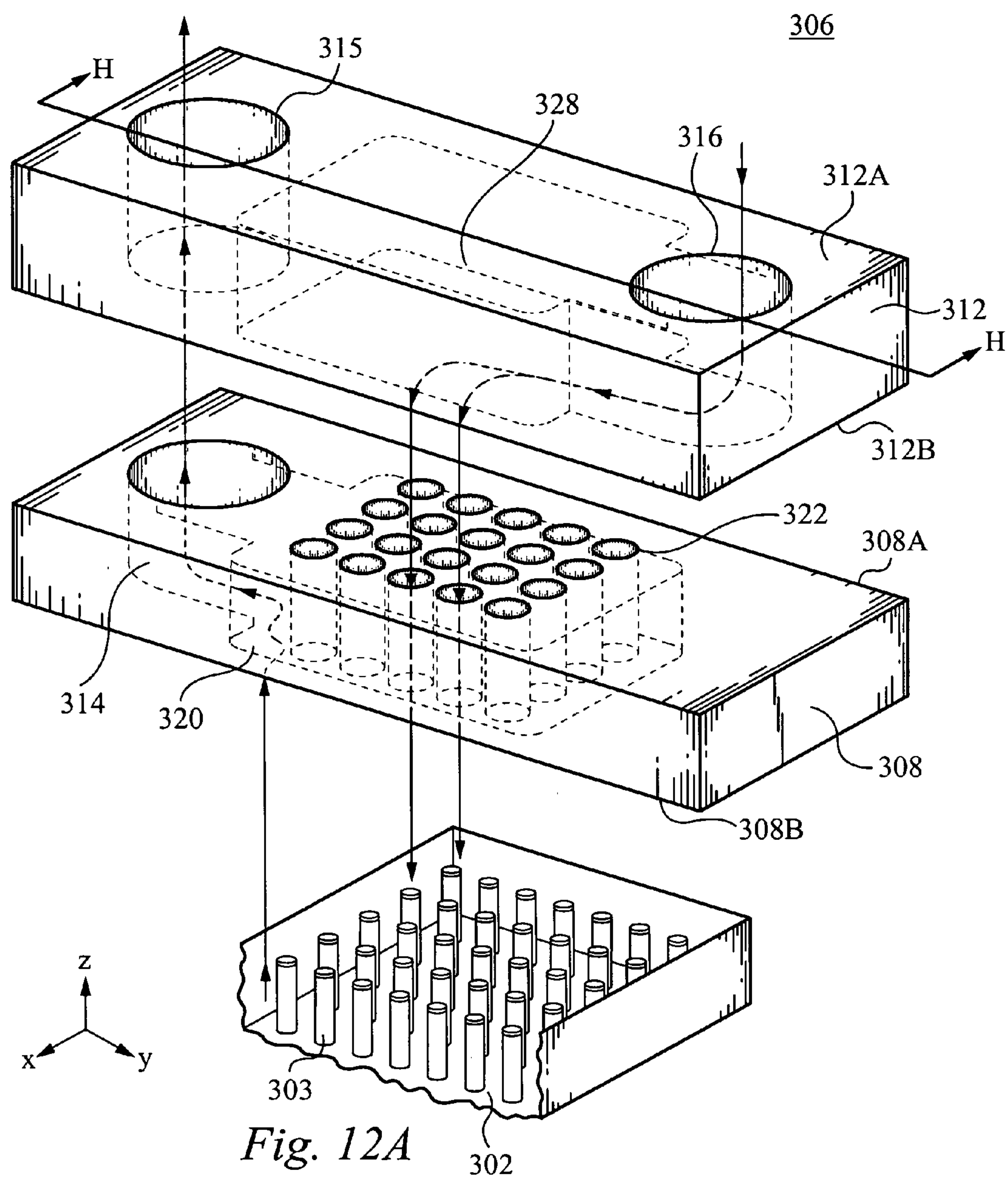
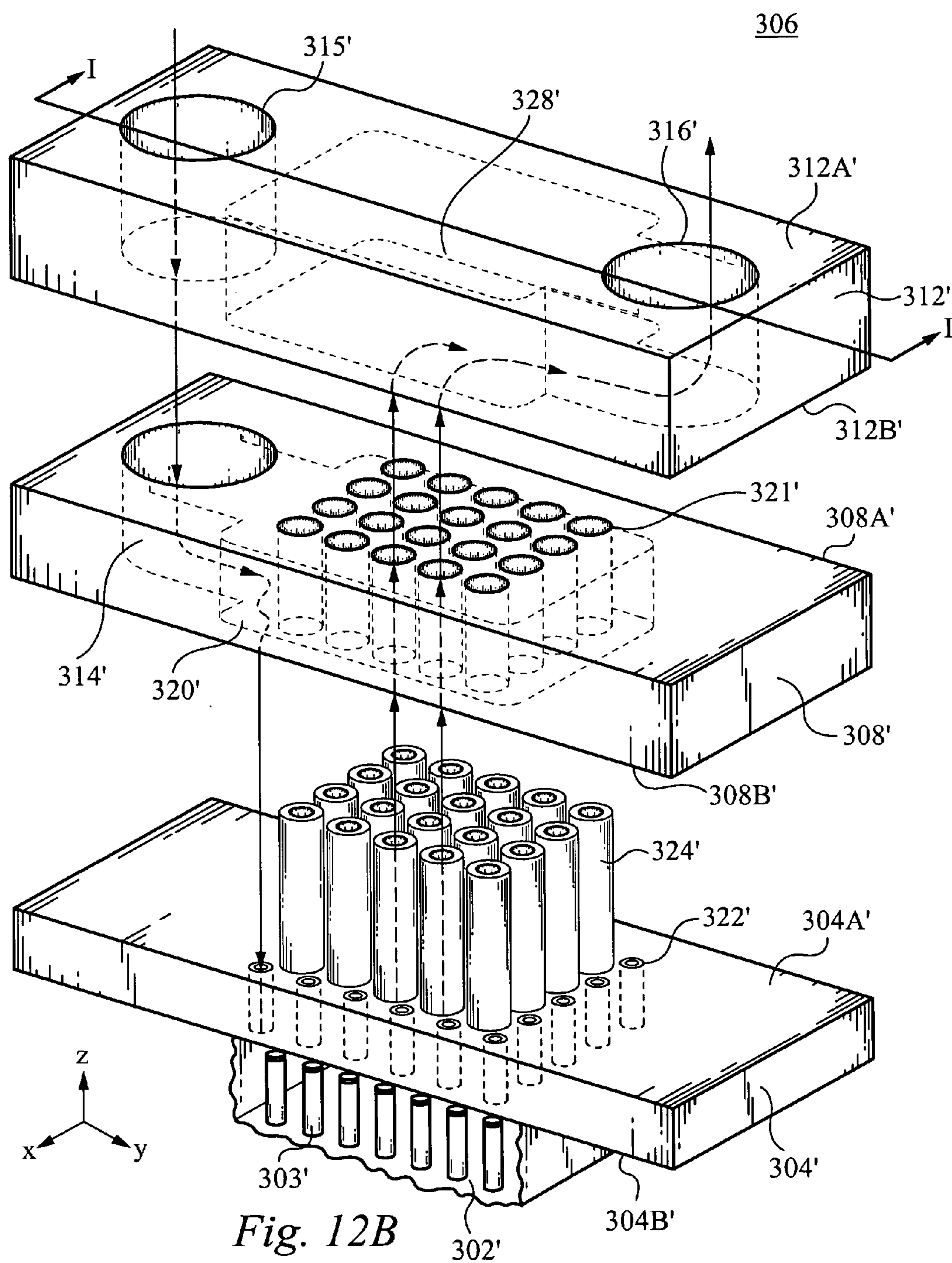
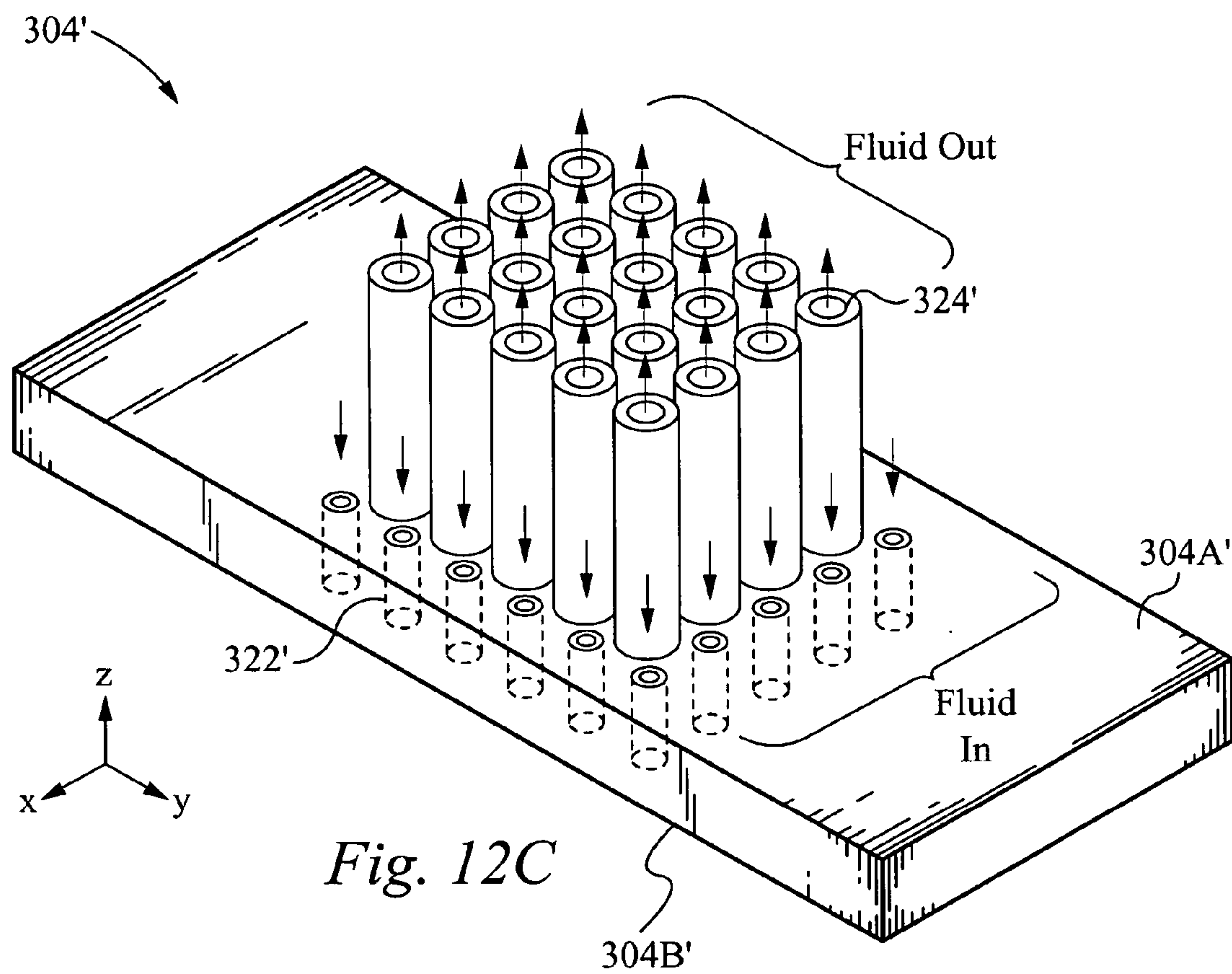


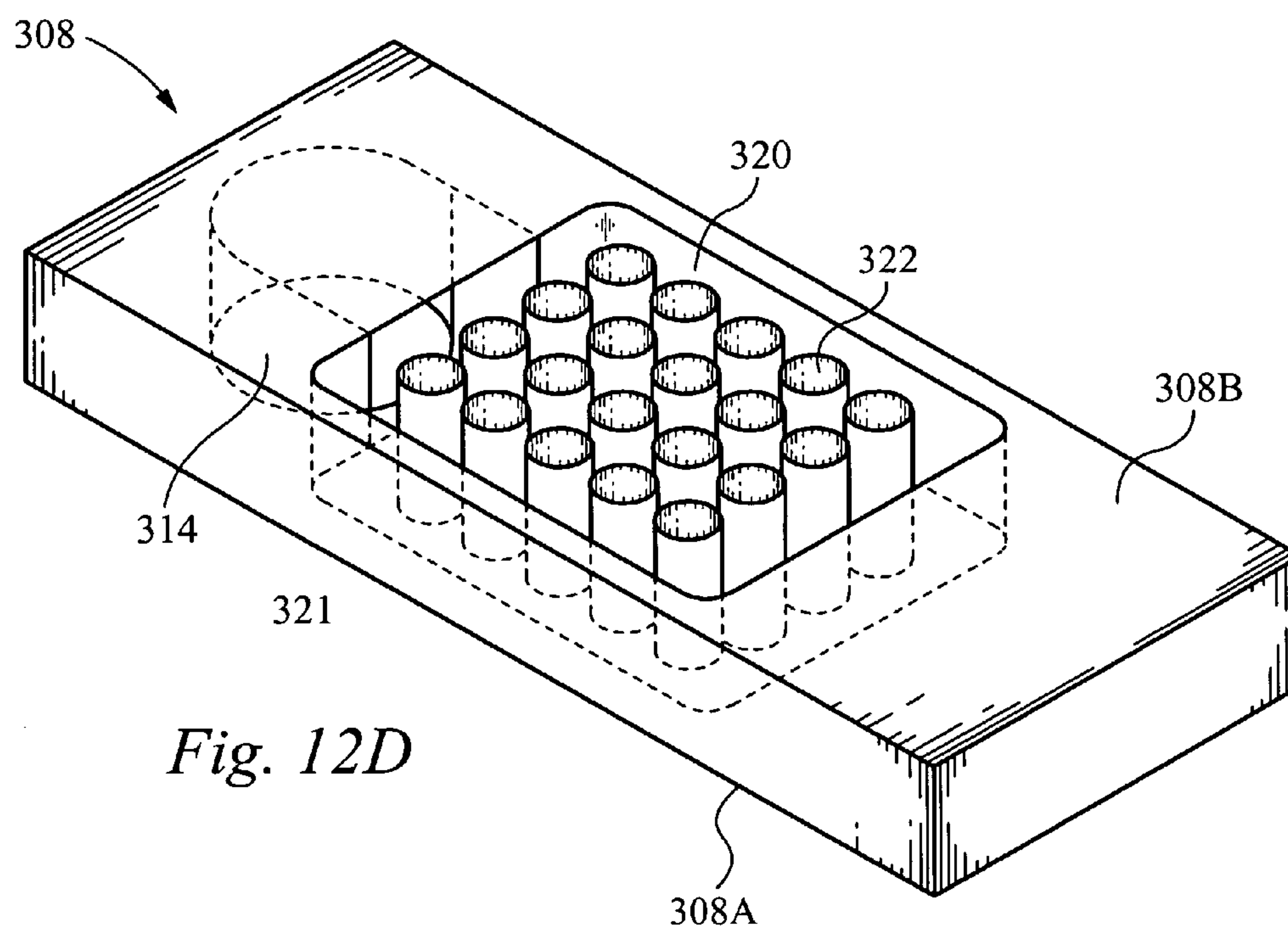
Fig. 11



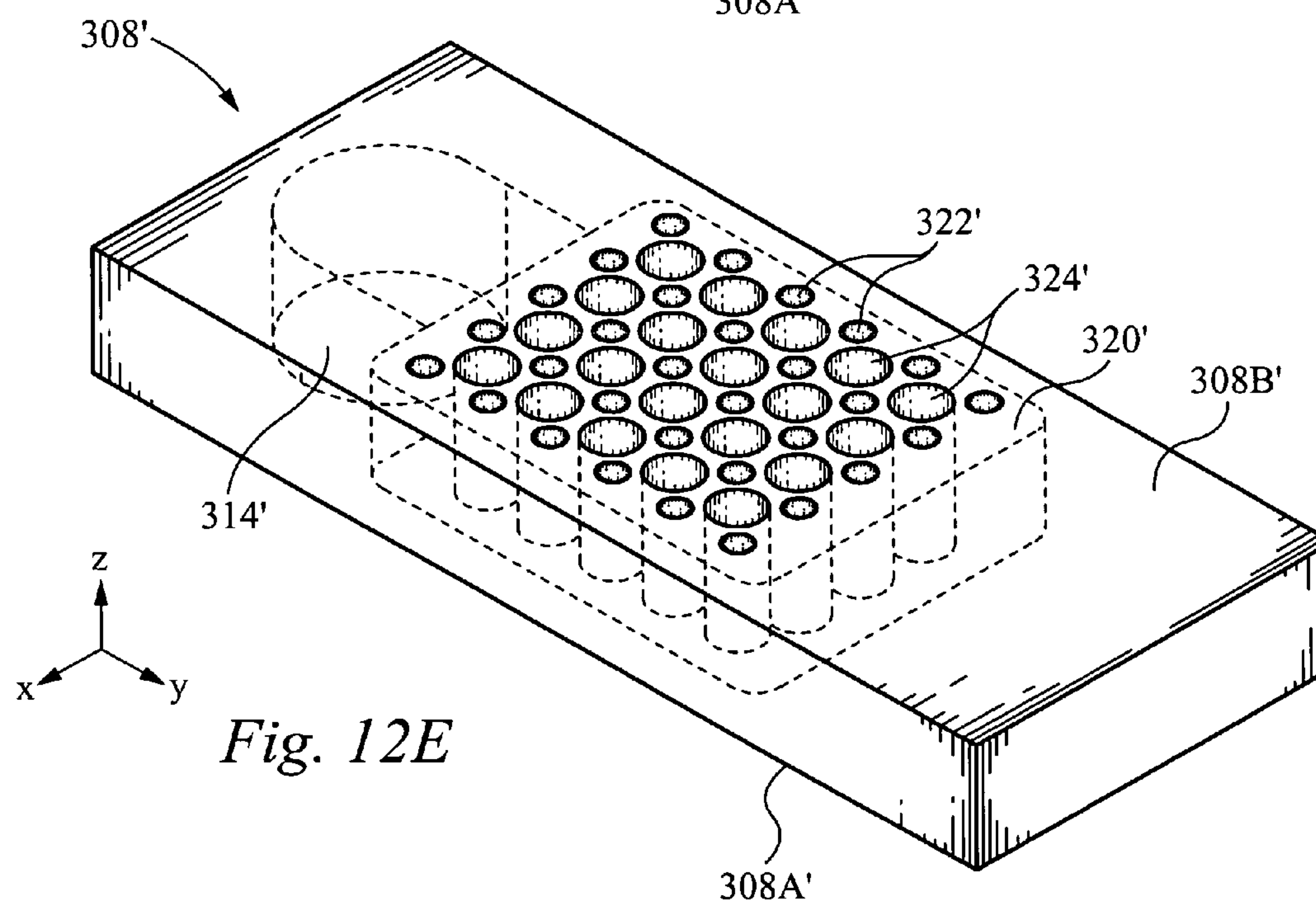




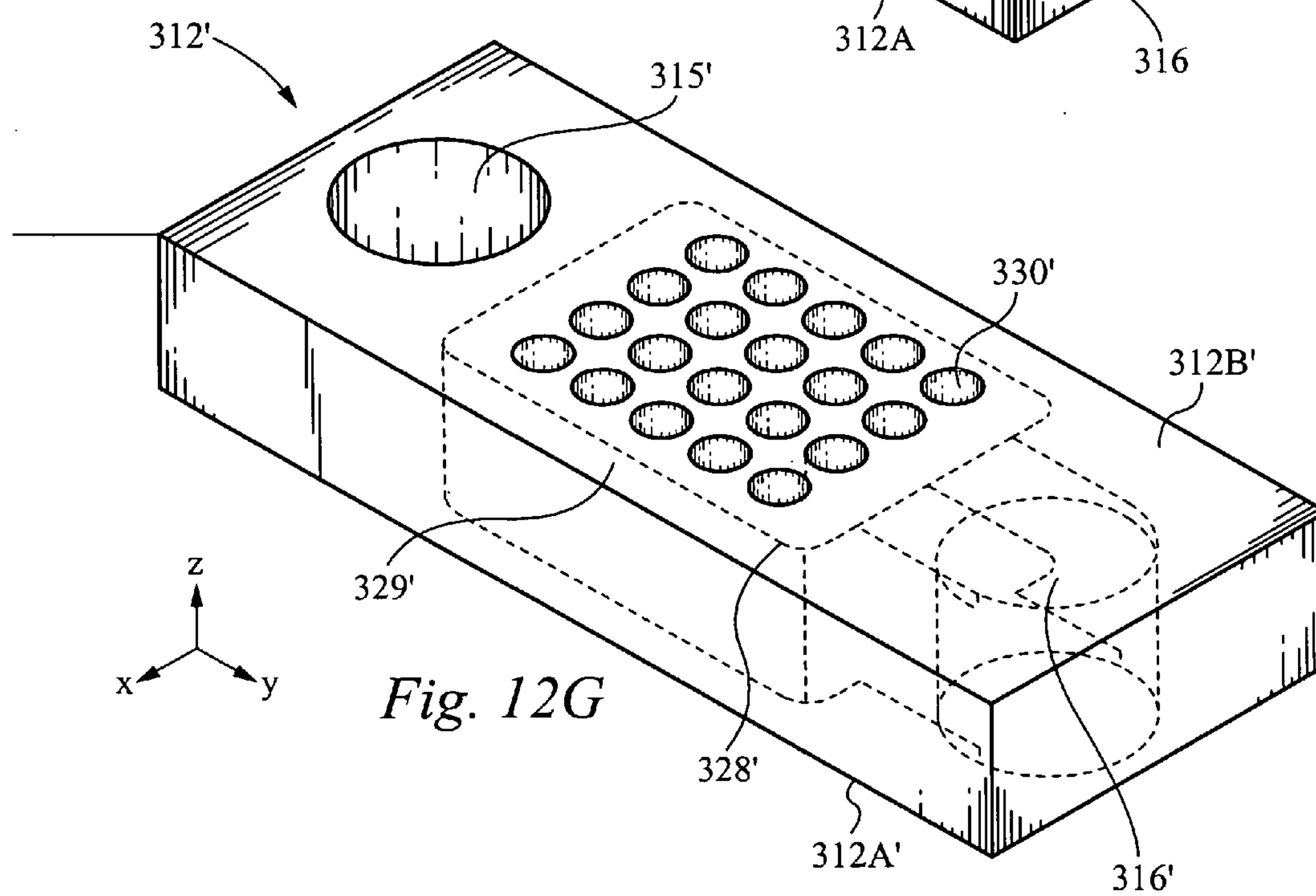
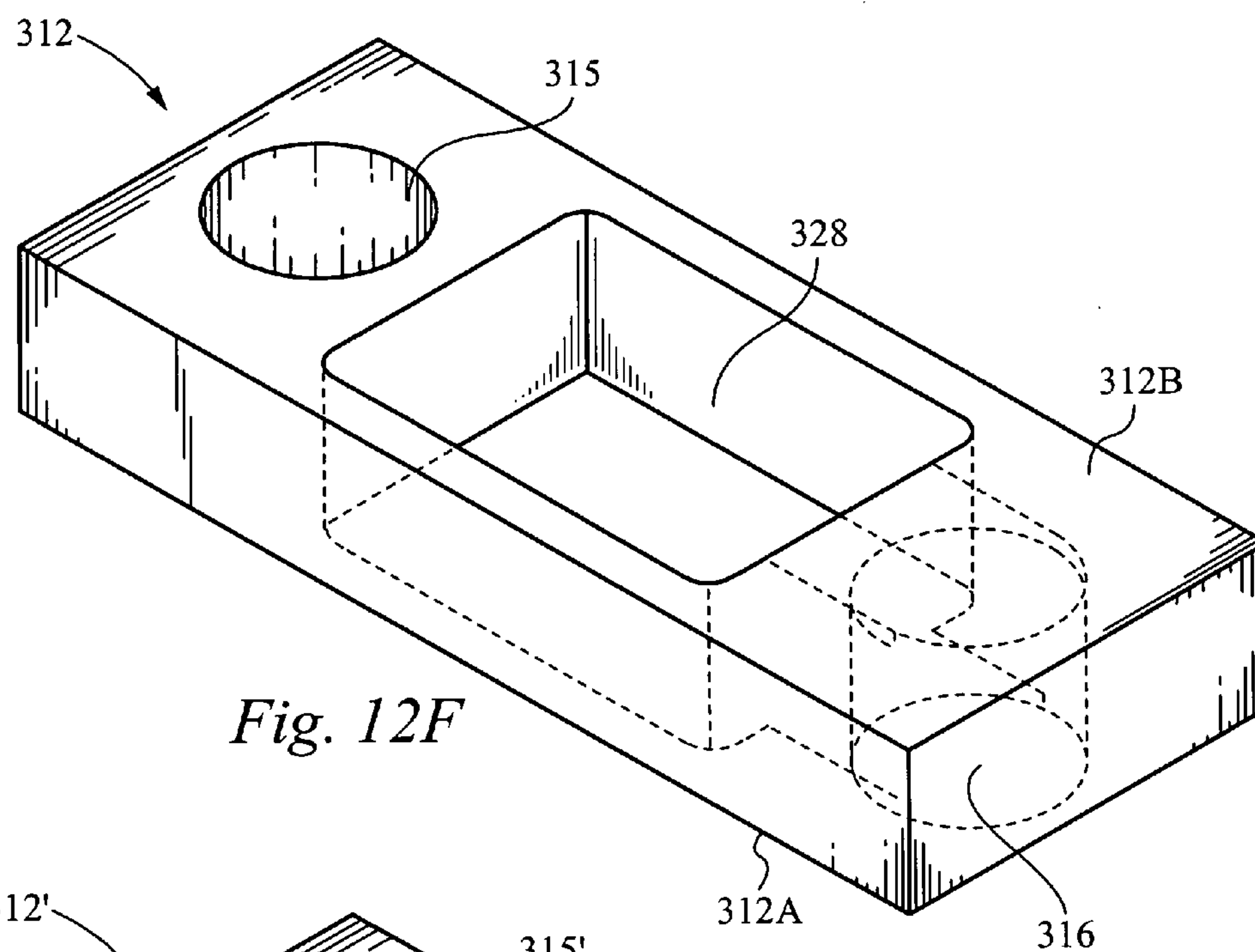


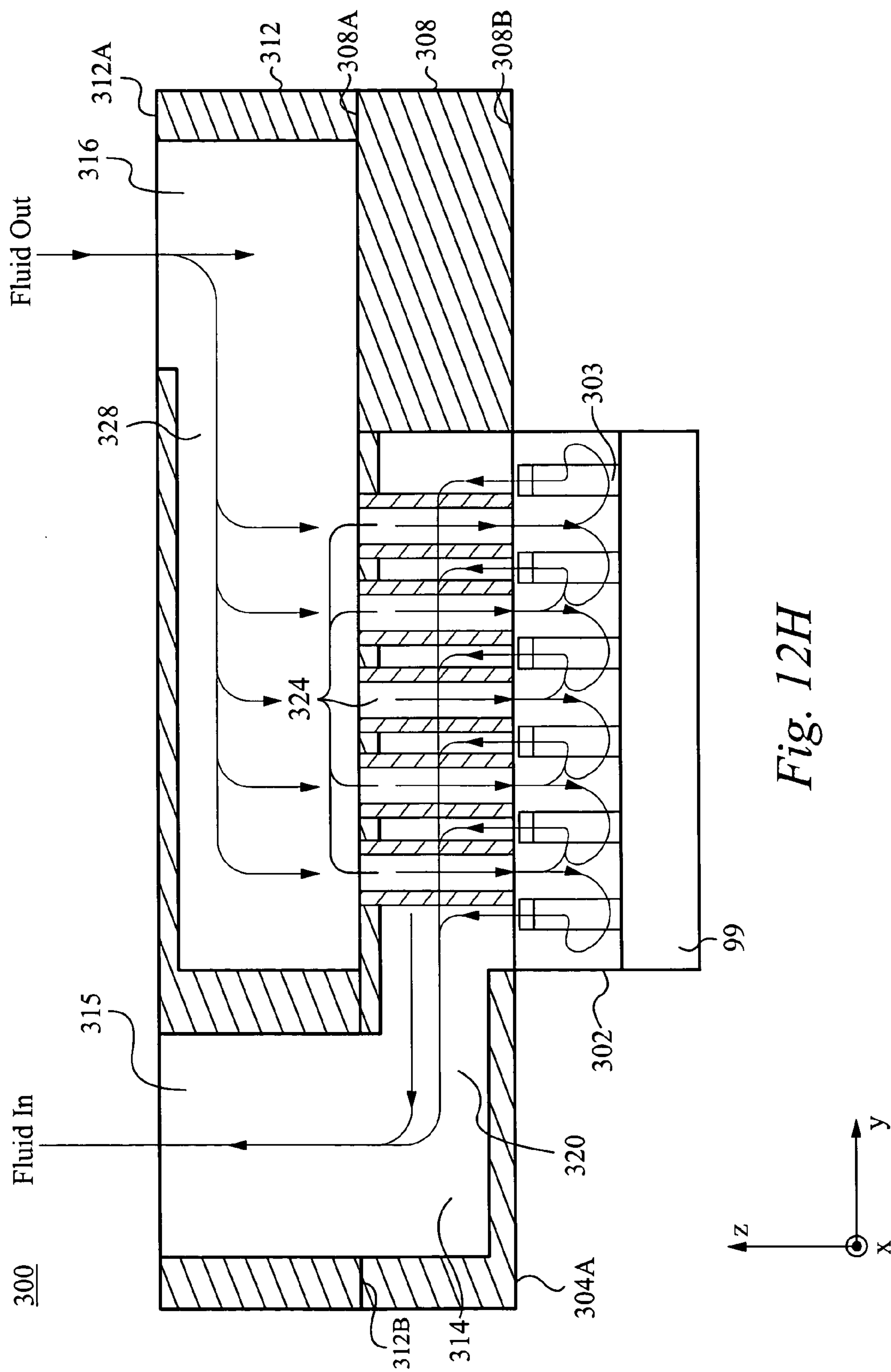


*Fig. 12D*



*Fig. 12E*





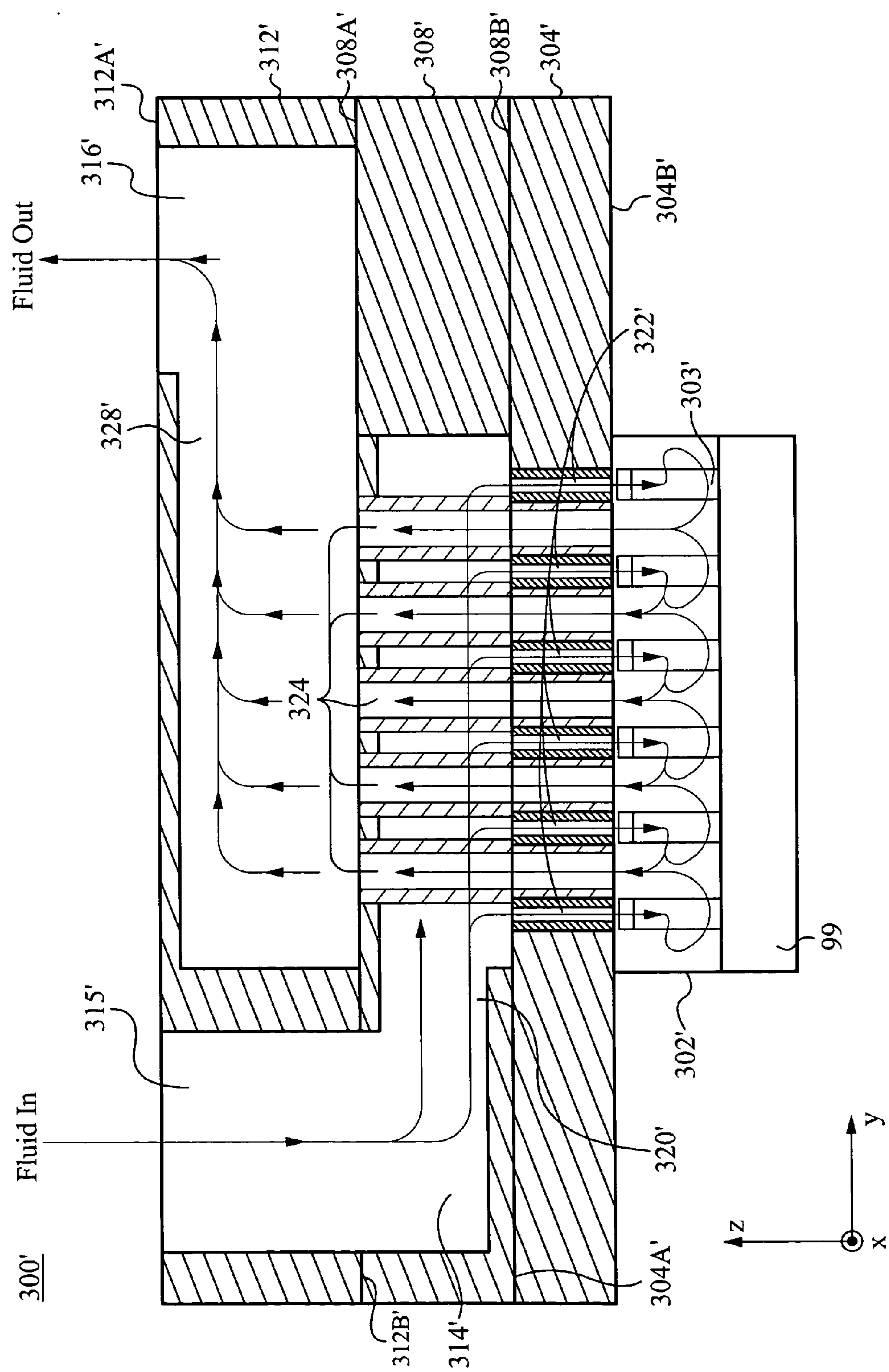


Fig. 12I



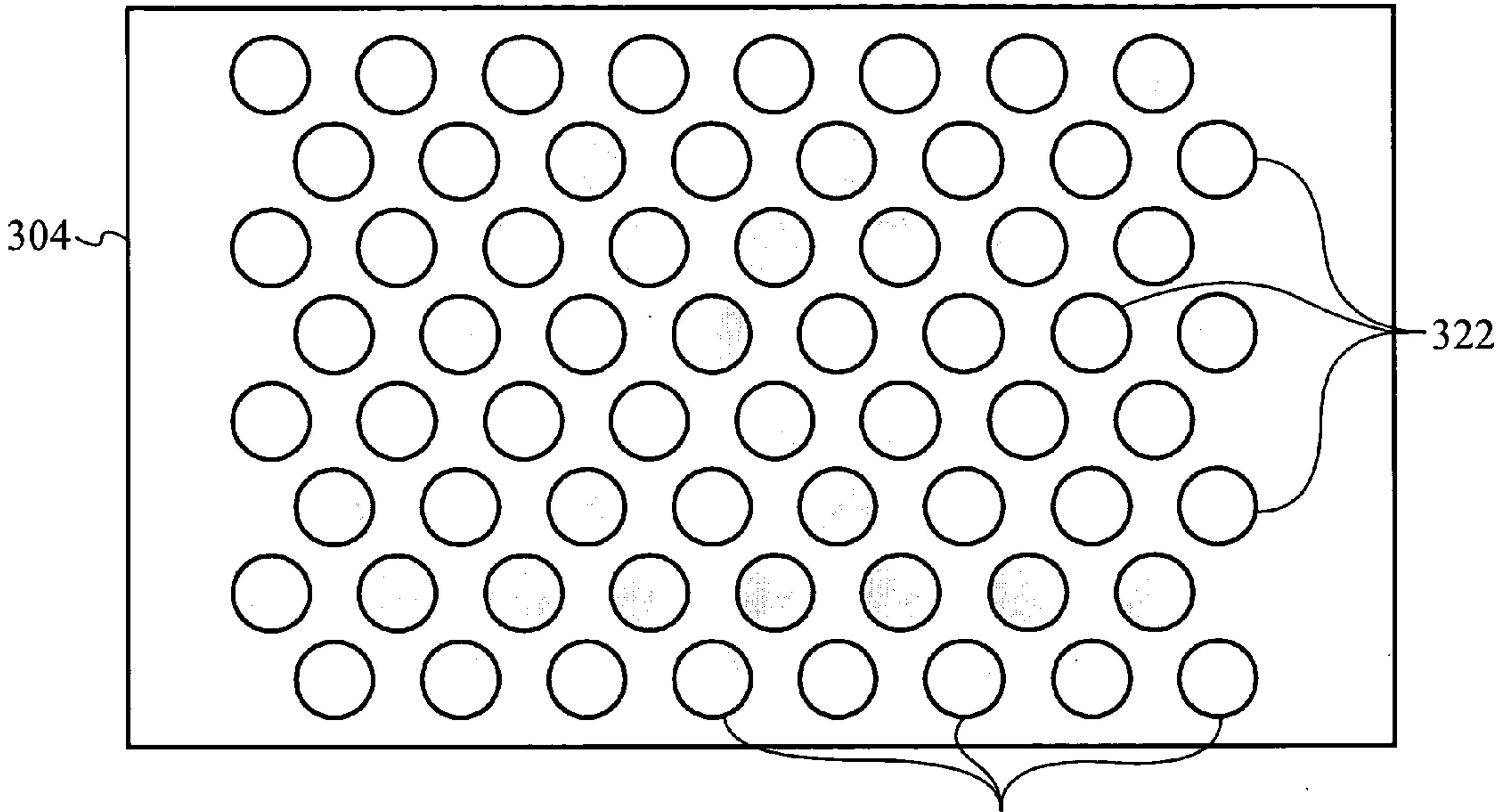


Fig. 13

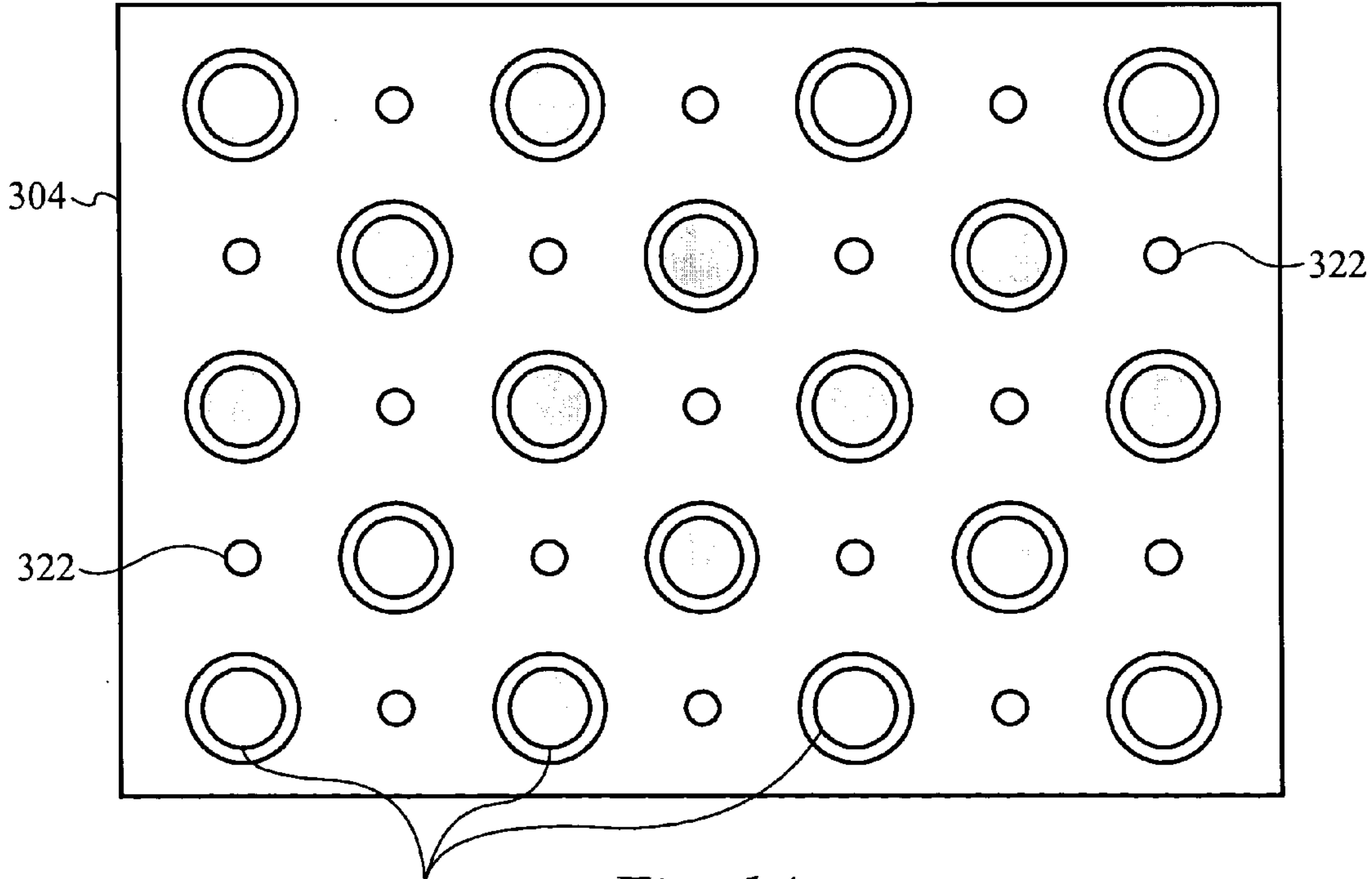
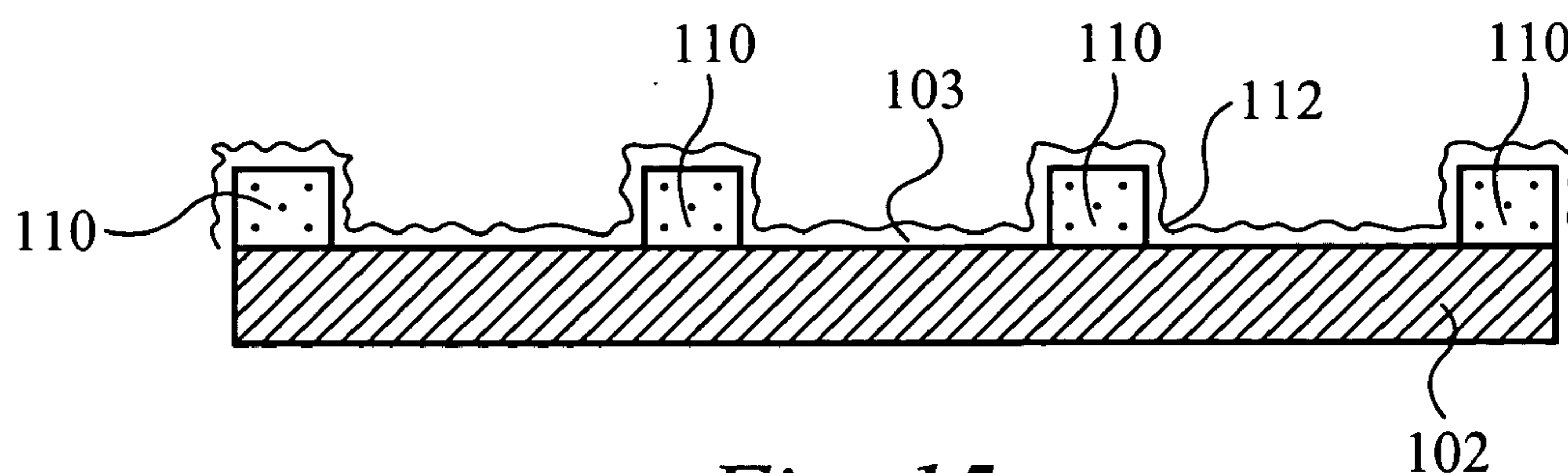
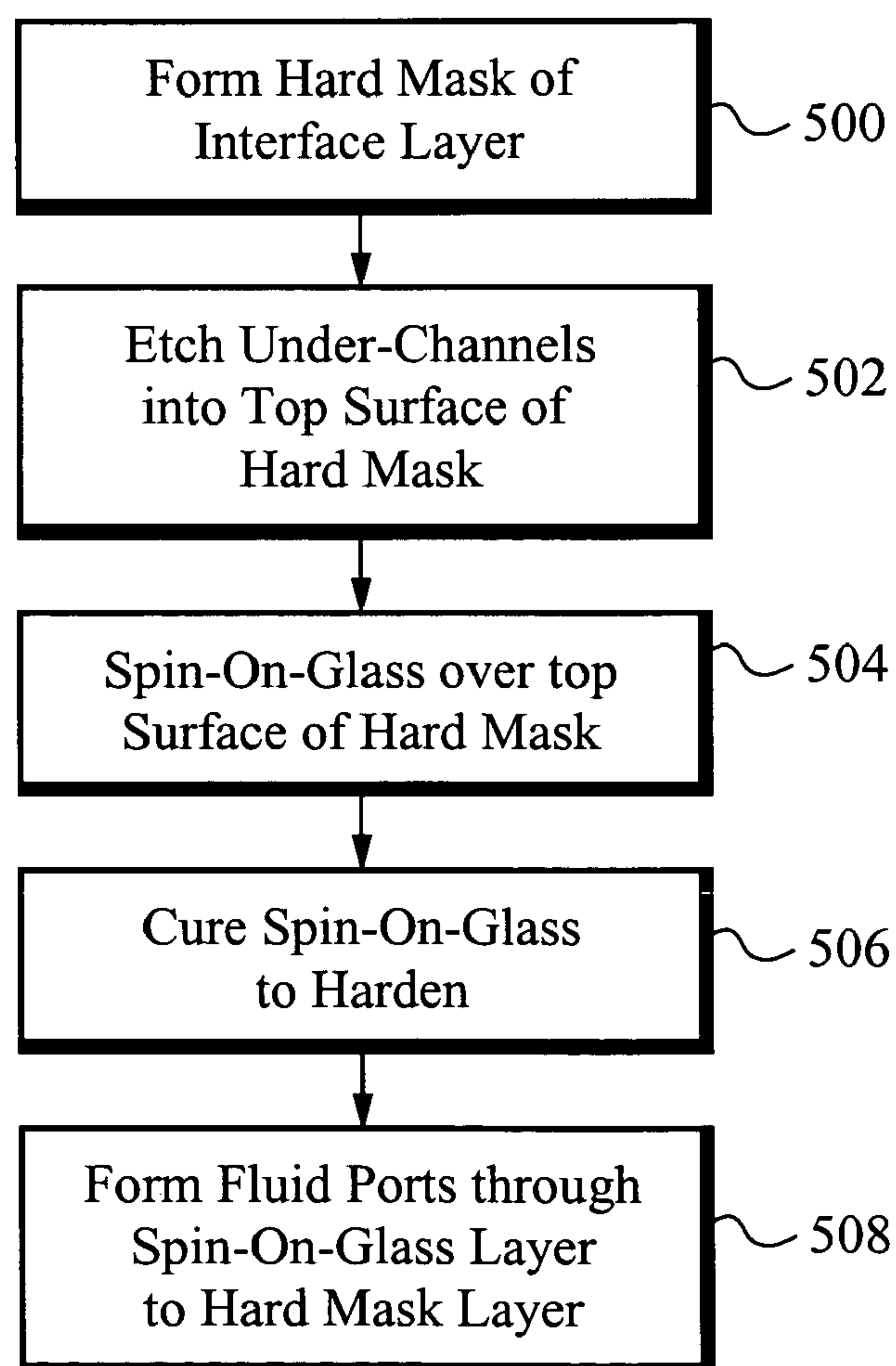


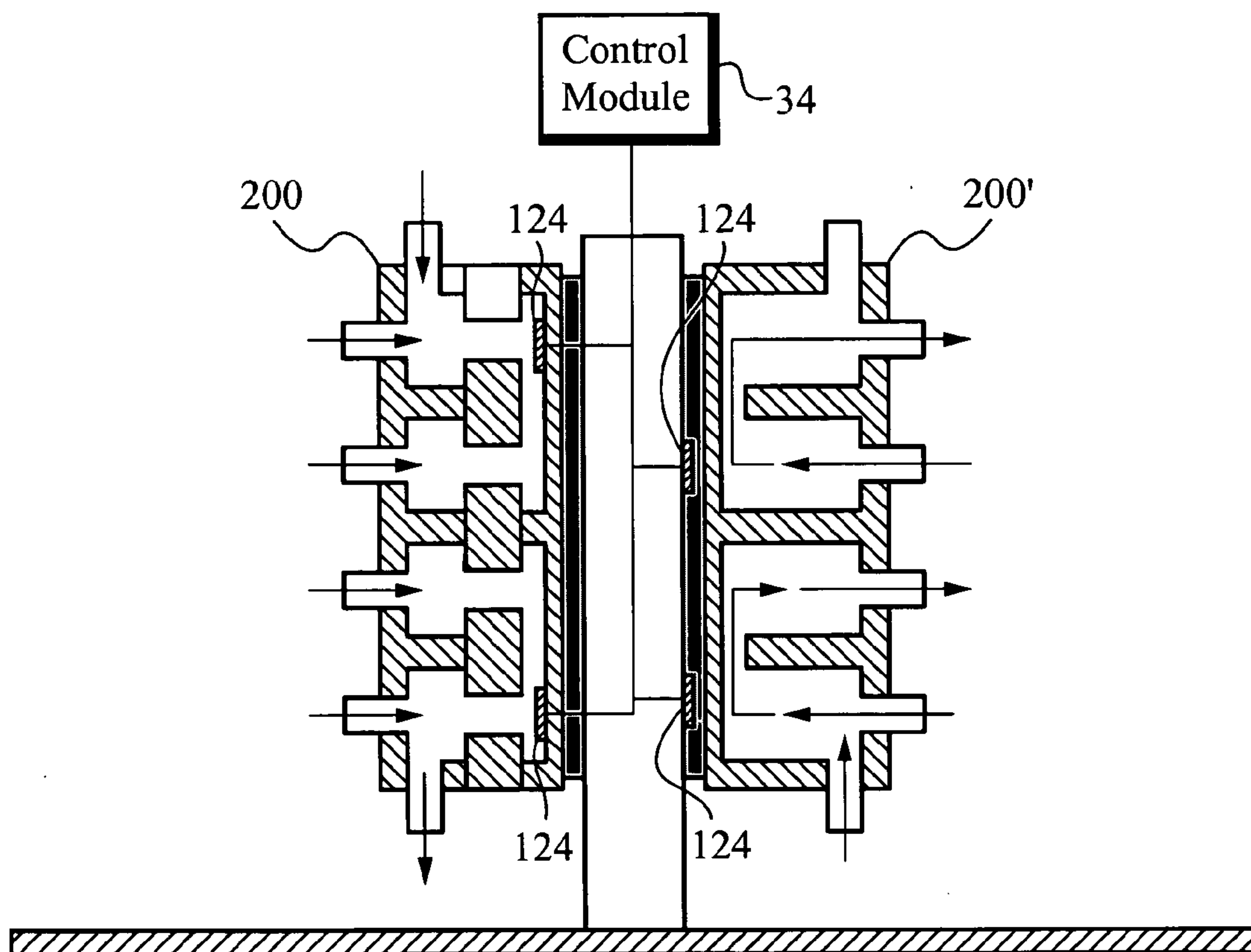
Fig. 14



*Fig. 15*



*Fig. 16*



*Fig. 17*



# METHOD AND APPARATUS FOR EFFICIENT VERTICAL FLUID DELIVERY FOR COOLING A HEAT PRODUCING DEVICE

## RELATED APPLICATIONS

[0001] This Patent Application is a continuation in part of U.S. patent application Ser. No. 10/680,584, filed Oct. 6, 2003, and entitled "METHOD AND APPARATUS FOR EFFICIENT VERTICAL FLUID DELIVERY FOR COOLING A HEAT PRODUCING DEVICE", hereby incorporated by reference, which is a continuation in part of U.S. patent application, Ser. No. 10/439,635, filed May 16, 2003 and entitled, "METHOD AND APPARATUS FOR FLEXIBLE FLUID DELIVERY FOR COOLING DESIRED HOT SPOTS IN A HEAT PRODUCING DEVICE", hereby incorporated by reference, which claims priority under 35 U.S.C. 119 (e) of the co-pending U.S. Provisional Patent Application, Ser. No. 60/423,009, filed Nov. 1, 2002 and entitled, "METHODS FOR FLEXIBLE FLUID DELIVERY AND HOTSPOT COOLING BY MICROCHANNEL HEAT SINKS", hereby incorporated by reference, as well as co-pending U.S. Provisional Patent Application, Ser. No. 60/442,383, filed Jan. 24, 2003 and entitled, "OPTIMIZED PLATE FIN HEAT EXCHANGER FOR CPU COOLING", which is also hereby incorporated by reference and co-pending U.S. Provisional Patent Application, Ser. No. 60/455,729, filed Mar. 17, 2003 and entitled, "MICROCHANNEL HEAT EXCHANGER APPARATUS WITH POROUS CONFIGURATION AND METHOD OF MANUFACTURING THEREOF", which is hereby incorporated by reference. U.S. patent application Ser. No. 10/680,584 also claims priority under 35 U.S.C. 119 (e) of the co-pending U.S. Provisional Patent Application, Ser. No. 60/423,009, filed Nov. 1, 2002 and entitled, "METHODS FOR FLEXIBLE FLUID DELIVERY AND HOTSPOT COOLING BY MICROCHANNEL HEAT SINKS", hereby incorporated by reference, as well as co-pending U.S. Provisional Patent Application, Ser. No. 60/442,383, filed Jan. 24, 2003 and entitled, "OPTIMIZED PLATE FIN HEAT EXCHANGER FOR CPU COOLING", hereby incorporated by reference, and co-pending U.S. Provisional Patent Application, Ser. No. 60/455,729, filed Mar. 17, 2003 and entitled, "MICROCHANNEL HEAT EXCHANGER APPARATUS WITH POROUS CONFIGURATION AND METHOD OF MANUFACTURING THEREOF", which is hereby incorporated by reference.

## FIELD OF THE INVENTION

[0002] The invention relates to a method and apparatus for cooling a heat producing device in general, and specifically, to a method and apparatus for efficient vertical fluid delivery in cooling an electronic device with minimal pressure drop within the heat exchanger.

## BACKGROUND OF THE INVENTION

[0003] Since their introduction in the early 1980s, microchannel heat sinks have shown much potential for high heat-flux cooling applications and have been used in the industry. However, existing microchannels include conventional parallel channel arrangements which are not well suited for cooling heat producing devices which have spatially-varying heat loads. Such heat producing devices have areas which produce more heat than others. These hotter

areas are hereby designated as "hot spots" whereas the areas of the heat source which do not produce as much heat are hereby termed, "warm spots".

[0004] FIGS. 1A and 1B illustrate a side view and top view of a prior art heat exchanger 10 which is coupled to an electronic device 99, such as a microprocessor via a thermal interface material 98. As shown in FIGS. 1A and 1B, fluid generally flows from a single inlet port 12 and flows along the bottom surface 11 in between the parallel microchannels 14, as shown by the arrows, and exits through the outlet port 16. Although the heat exchanger 10 cools the electronic device 99, the fluid flows from the inlet port 12 to the outlet port 16 in a uniform manner. In other words, the fluid flows substantially uniformly along the entire bottom surface 11 of the heat exchanger 10 and does not supply more fluid to areas in the bottom surface 11 which correspond with hot spots in the device 99. In addition, the temperature of liquid flowing from the inlet generally increases as it flows along the bottom surface 11 of the heat exchanger. Therefore, regions of the heat source 99 which are downstream or near the outlet port 16 are not supplied with cool fluid, but actually warmer fluid or two-phase fluid which has already been heated upstream. In effect, the heated fluid actually propagates the heat across the entire bottom surface 11 of the heat exchanger and region of the heat source 99, whereby fluid near the outlet port 16 is so hot that it becomes ineffective in cooling the heat source 99. This increase in heat causes two-phase flow instabilities in which the boiling of fluid along the bottom surface 11 forces fluid away from the areas where the most heat is generated. In addition, the heat exchanger 10 having only one inlet 12 and one outlet 16 forces fluid to travel along the long parallel microchannels 14 in the bottom surface 11 for the entire length of the heat exchanger 10, thereby creating a large pressure drop due to the length the fluid must travel. The large pressure drop formed in the heat exchanger 10 makes pumping fluid to the heat exchanger 10 difficult and augments the instabilities.

[0005] FIG. 1C illustrates a side view diagram of a prior art multi-level heat exchanger 20. Fluid enters the multi-level heat exchanger 20 through the port 22 and travels downward through multiple jets 28 in the middle layer 26 to the bottom surface 27 and out port 24. In addition, the fluid traveling along the jets 28 does not uniformly flow down to the bottom surface 27. In addition, the heat exchanger in FIG. 1C exhibits the same problems discussed above with regard to the heat exchanger 10 in FIGS. 1A and 1B.

[0006] What is needed is a heat exchanger which is configured to achieve a small pressure drop between the inlet and outlet fluid ports while efficiently cooling the heat source. What is needed is a microchannel heat exchanger which is configured to achieve proper temperature uniformity in the heat source. What is also needed is a heat exchanger which is configured to achieve proper temperature uniformity in light of hot spots in the heat source.

## SUMMARY OF THE INVENTION

[0007] In one aspect of the invention, a heat exchanger comprises an interface layer in contact with the heat source and configured to pass fluid therethrough to cool the heat source, the interface layer includes a thickness within a range of about 0.3 to about 1.0 millimeters, and a manifold layer coupled to the interface layer, the manifold layer



further comprising a first set of individualized fluid paths for channeling fluid to the interface layer, the individual fluid paths in the first set positioned to minimize pressure drop within the heat exchanger. The manifold layer can also include a second set of individualized fluid paths for channeling fluid from the interface layer. The manifold layer can also include a first port for providing fluid to the first set of individualized fluid paths and a second port for removing fluid channeled from the second set of individualized fluid paths. The first set of fluid paths can be arranged to provide a minimized fluid path distance along the interface layer to cool a predetermined region of the heat source to a desired temperature. The first set and second set of fluid paths can be arranged to provide a minimized fluid path distance between the first and second ports to cool a predetermined region of the heat source to a desired temperature. The fluid can be in single phase flow conditions. At least a portion of the fluid can be in two phase flow conditions. At least a portion of the fluid can undergo a transition between single and two phase flow conditions in the heat exchanger. The manifold layer can also include a circulation level having the first and second fluid paths extending therethrough, the circulation level coupled to the interface layer and configured to separably channel fluid to and from the interface layer via the first and second set of fluid paths. Each of the fluid paths in the first set can include a cylindrical protrusion in communication therewith, each cylindrical protrusion extending from the circulation level at a predetermined height. The manifold layer can also include a first level configured to channel fluid between the first port and the first set of fluid paths, and a second level coupled to the first level and configured to channel fluid between the second port and the second set of fluid paths wherein fluid channeled via the first level is kept separate from the fluid channeled via the second level in the manifold layer. The first level can also include a first corridor in communication with the first port and the first set of fluid paths, wherein fluid in the first corridor flows directly to the first set of fluid paths. The second level can also include a second corridor in communication with the second port and the second set of fluid paths wherein fluid in the second set flows directly to the second corridor. The first set of fluid paths can be thermally insulated from the second set of fluid paths to prevent heat transfer therebetween. The first set and the second set of fluid paths can be arranged in a uniform manner along at least one dimension. The first set and second set of fluid paths can be arranged in a non-uniform manner along at least one dimension. Each fluid paths in the first set can be positioned a closest optimal distance to one another. The first set and second set of fluid paths can be positioned to cool at least one interface hot spot region in the heat source. At least one of the first fluid paths can flow via a plurality of first holes, wherein at least one first hole in the plurality has a first dimension substantially equivalent to a second dimension of at least one hole in the second set of fluid paths. At least one of the first fluid paths can flow via a plurality of first holes, wherein at least one first hole in the plurality has a first dimension different than a second dimension of at least one second hole in the second set of fluid paths. The interface layer can be made of a material having a thermal conductivity of at least 100 W/mk. The interface layer can include a coating thereupon, wherein the coating provides an appropriate thermal conductivity of at least 10 W/m-K. The interface layer can also include a plurality of pillars config-

ured in a predetermined pattern along the interface layer. At least one of the plurality of pillars can have an area dimension within the range of and including  $(10 \text{ micron})^2$  and  $(100 \text{ micron})^2$ . At least one of the plurality of pillars can have a height dimension within the range of and including 50 microns and 2 millimeters. At least two of the plurality of pillars can have separate from each other by a spacing dimension within the range of and including 10 to 150 microns. The plurality of pillars can include a coating thereupon, wherein the coating has an appropriate thermal conductivity of at least 10 W/m-K. At least one of the plurality of pillars can include at least varying dimension along a predetermined direction. An appropriate number of pillars can be disposed in a predetermined area along the interface layer. At least a portion of the interface layer can have a roughened surface. The plurality of pillars can include a coating thereupon, wherein the coating has an appropriate thermal conductivity of at least 10 W/m-K. The heat exchanger can also include a porous microstructure disposed along the interface layer. The porous microstructure can have a porosity within the range of and including 50 to 80 percent. The porous microstructure can have an average pore size within the range of and including 10 to 200 microns. The porous microstructure can have a height dimension within the range of and including 0.25 to 2.00 millimeters. The porous microstructure can include at least one pore having a varying dimension along a predetermined direction. The heat exchanger can also include a plurality of microchannels disposed in a predetermined configuration along the interface layer. At least one of the plurality of microchannels can have an area dimension within the range of and including  $(10 \text{ micron})^2$  and  $(100 \text{ micron})^2$ . At least one of the plurality of microchannels can have a height dimension within the range of and including 50 microns and 2 millimeters. At least two of the plurality of microchannels can be separate from each other by a spacing dimension within the range of and including 10 to 150 microns. At least one of the plurality of microchannels can have a width dimension within the range of and including 10 to 100 microns. The plurality of microchannels can include a coating thereupon, wherein the coating has an appropriate thermal conductivity of at least 10 W/m-K. The interface layer can be coupled to the heat source. The interface layer can be integrally formed to the heat source. The heat source can be an integrated circuit. An overhang dimension can be within the range of and including 0 to 15 millimeters.

[0008] In another aspect of the present invention, a heat exchanger configured to cool a heat source comprises an interface layer in contact with the heat source and configured to pass fluid therethrough, the interface layer includes a thickness within a range of about 0.3 to about 1.0 millimeters, and a manifold layer coupled to the interface layer, the manifold layer further comprising a first level having a plurality of substantially vertical inlet paths for delivering fluid to the interface layer, wherein the inlet paths are arranged an optimal fluid travel distance from one another other, and a second level having at least one outlet path for removing fluid from the interface layer. The first level can also include at least one first port configured to channel fluid to the inlet paths. The second level can also include at least one second port configured to channel fluid from the at least one outlet path, wherein fluid in the second level flows separately from the fluid in the first level. The second level can also include a plurality of substantially vertical outlet



paths for removing fluid from the interface layer, the plurality of inlet and outlet paths arranged an optimal fluid travel distance apart from each other. The manifold layer can also include a circulation level coupled to the interface layer and having a plurality of first apertures extending vertically therethrough for channeling fluid along the inlet paths to the interface layer and a plurality of second apertures extending vertically therethrough for channeling fluid along the at least outlet path from the interface layer. The first level can also include an inlet fluid corridor within for horizontally channeling fluid from the first port to the first apertures. The second level can also include an outlet fluid corridor for horizontally channeling fluid from the second apertures to the second port. The first and second apertures can be individually arranged in a uniform manner along at least one dimension. The first and second fluid apertures can be individually arranged in a non-uniform manner along at least one dimension. The inlet paths and the at least one outlet paths can be separately sealed from one another in the manifold layer. The interface layer can be coupled to the heat source. The interface layer can be integrally formed to the heat source. The heat source can be an integrated circuit. The first and second apertures can be arranged to cool at least one interface hot spot cooling region in the heat source. At least one of the first apertures can have an inlet dimension substantially equivalent to an outlet dimension of at least one second apertures in the plurality. At least one of the first apertures can have an inlet dimension different than an outlet dimension of at least one of the second apertures in the plurality. The interface layer can be made of a material having a thermal conductivity of at least 100 W/mk. The interface layer can include a coating thereupon, wherein the coating provides an appropriate thermal conductivity of at least 10 W/m-K. The interface layer can also include a plurality of pillars disposed thereon in an appropriate pattern. At least one of the plurality of pillars can have an area dimension within the range of and including (10 micron)<sup>2</sup> and (100 micron)<sup>2</sup>. At least one of the plurality of pillars can have a height dimension within the range of and including 50 microns and 2 millimeters. At least two of the plurality of pillars can be separate from each other by a spacing dimension within the range of and including 10 to 150 microns. The plurality of pillars can include a coating thereupon, wherein the coating has an appropriate thermal conductivity of at least 10 W/m-K. At least one of the plurality of pillars can include at least varying dimension along a predetermined direction. An appropriate number of pillars can be disposed in a predetermined area along the interface layer. At least a portion of the interface layer can have a roughened surface. The plurality of pillars can include a coating thereupon, wherein the coating has an appropriate thermal conductivity of at least 10 W/m-K. The heat exchanger can also include a porous microstructure disposed along the interface layer. The porous microstructure can have a height dimension within the range of and including 0.25 to 2.00 millimeters. The porous microstructure can include at least one pore having a varying dimension along a predetermined direction. An average pore size in the porous microstructure can be within the range and including 10 microns and 200 microns. The porous microstructure can have a porosity in the range and including 50 to 80 percent. The interface layer can also include a plurality of microchannels disposed thereon in an appropriate pattern. At least one of the plurality of microchannels can have an

area dimension within the range of and including (10 micron)<sup>2</sup> and (100 micron)<sup>2</sup>. At least one of the plurality of microchannels can have a height dimension within the range of and including 50 microns and 2 millimeters. At least two of the plurality of microchannels can be separate from each other by a spacing dimension within the range of and including 10 to 150 microns. At least one of the plurality of microchannels can have a width dimension within the range of and including 10 to 100 microns. The plurality of microchannels can include a coating thereupon, wherein the coating has an appropriate thermal conductivity of at least 10 W/m-K. An overhang dimension can be within the range of and including 0 to 15 millimeters. The heat exchanger can also include a plurality of cylindrical protrusions extending an appropriate height from the circulation level, each protrusion in communication with the first apertures.

[0009] In yet another aspect of the present invention, an electronic device which produces heat comprises an integrated circuit, an interface layer for cooling heat produced by the electronic device, wherein the interface layer includes a thickness within a range of about 0.3 to about 1.0 millimeters, the interface layer integrally formed with the integrated circuit and configured to pass fluid therethrough and a manifold layer for circulating fluid with the interface layer, the manifold layer having at least one inlet fluid path for delivering fluid to the interface layer and at least one outlet fluid path for removing fluid from the interface layer, the at least one inlet fluid path and the at least one outlet fluid path arranged to provide an optimal minimum fluid travel distance apart from each other.

[0010] In still yet another aspect of the present invention, a closed loop system for cooling at least one integrated circuit comprises at least one heat exchanger for absorbing heat generated by the integrated circuit, the heat exchanger further comprises an interface layer in contact with the integrated circuit and configured to pass fluid therethrough, the interface layer includes a thickness within a range of about 0.3 to about 1.0 millimeters, and a manifold layer coupled to the interface layer, the manifold layer having at least one inlet fluid path for delivering fluid to the interface layer and at least one outlet fluid path for removing fluid from the interface layer, the at least inlet fluid path and the at least one outlet fluid path arranged to provide an optimal minimum fluid travel distance apart from each other, at least one pump for circulating fluid throughout the loop, the pump coupled to the at least one heat exchanger, and at least one heat rejector coupled to the pump and the heat exchanger, the heat rejector for cooling heated liquid output from the heat exchanger.

[0011] Other features and advantages of the present invention will become apparent after reviewing the detailed description of the preferred and alternative embodiments set forth below.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0012] FIG. 1A illustrates a side view of a conventional heat exchanger.

[0013] FIG. 1B illustrates a top view of the conventional heat exchanger.

[0014] FIG. 1C illustrates a side view diagram of a prior art multi-level heat exchanger.



[0015] **FIG. 2A** illustrates a schematic diagram of a closed loop cooling system incorporating a alternative embodiment of the flexible fluid delivery microchannel heat exchanger of the present invention.

[0016] **FIG. 2B** illustrates a schematic diagram of a closed loop cooling system incorporating an alternative embodiment of the flexible fluid delivery microchannel heat exchanger of the present invention.

[0017] **FIG. 3A** illustrates a top view of the alternative manifold layer of the heat exchanger in accordance with the present invention.

[0018] **FIG. 3B** illustrates an exploded view of the alternative heat exchanger with the alternative manifold layer in accordance with the present invention.

[0019] **FIG. 4** illustrates a perspective view of the an interwoven manifold layer in accordance with the present invention.

[0020] **FIG. 5** illustrates a top view of the interwoven manifold layer with interface layer in accordance with the present invention.

[0021] **FIG. 6A** illustrates a cross-sectional view of the interwoven manifold layer with interface layer of the present invention along lines A-A.

[0022] **FIG. 6B** illustrates a cross-sectional view of the interwoven manifold layer with interface layer of the present invention along lines B-B.

[0023] **FIG. 6C** illustrates a cross-sectional view of the interwoven manifold layer with interface layer of the present invention along lines C-C.

[0024] **FIG. 7A** illustrates an exploded view of the interwoven manifold layer with interface layer of the present invention.

[0025] **FIG. 7B** illustrates a perspective view of an alternative embodiment of the interface layer of the present invention.

[0026] **FIG. 8A** illustrates a top view diagram of an alternate manifold layer in accordance with the present invention.

[0027] **FIG. 8B** illustrates a top view diagram of the interface layer in accordance with the present invention.

[0028] **FIG. 8C** illustrates a top view diagram of the interface layer in accordance with the present invention.

[0029] **FIG. 9A** illustrates a side view diagram of the alternative embodiment of the three tier heat exchanger in accordance with the present invention.

[0030] **FIG. 9B** illustrates a side view diagram of the alternative embodiment of the two tier heat exchanger in accordance with the present invention.

[0031] **FIGS. 10A-10E** illustrate a perspective view of the interface layer having different micro-pin arrays in accordance with the present invention.

[0032] **FIG. 11** illustrates a cut-away perspective view diagram of the alternate heat exchanger in accordance with the present invention.

[0033] **FIG. 12A** illustrates an exploded view of a preferred heat exchanger in accordance with the present invention.

[0034] **FIG. 12B** illustrates an exploded view of an alternative heat exchanger in accordance with the present invention.

[0035] **FIG. 12C** illustrates a perspective view of the alternative circulation level in accordance with the present invention.

[0036] **FIG. 12D** illustrates a perspective view of the underside of the preferred inlet level in accordance with the present invention.

[0037] **FIG. 12E** illustrates a perspective view of the underside of an alternative inlet level in accordance with the present invention.

[0038] **FIG. 12F** illustrates a perspective view of the underside of the preferred outlet level in accordance with the present invention.

[0039] **FIG. 12G** illustrates a perspective view of the underside of an alternative outlet level in accordance with the present invention.

[0040] **FIG. 12H** illustrates a cross sectional view of the preferred heat exchanger in accordance with the present invention.

[0041] **FIG. 12I** illustrates a cross sectional view of the alternative heat exchanger in accordance with the present invention.

[0042] **FIG. 13** illustrates a top view of the circulation level having the preferred arrangement of inlet and outlet apertures for single phase fluid flow in accordance with the present invention.

[0043] **FIG. 14** illustrates a top view of the circulation level having the preferred arrangement of inlet and outlet apertures for two phase fluid flow in accordance with the present invention.

[0044] **FIG. 15** illustrates a side view diagram of the interface layer of the heat exchanger having a coating material applied thereon in accordance with the present invention.

[0045] **FIG. 16** illustrates a flow chart of an alternative method of manufacturing the heat exchanger in accordance with the present invention.

[0046] **FIG. 17** illustrates a schematic of an alternate embodiment of the present invention having two heat exchangers coupled to a heat source.

#### DETAILED DESCRIPTION OF THE PRESENT INVENTION

[0047] Generally, the heat exchanger captures thermal energy generated from a heat source by passing fluid through selective areas of the interface layer which is preferably coupled to the heat source. In particular, the fluid is directed to specific areas in the interface layer to cool the hot spots and areas around the hot spots to generally create temperature uniformity across the heat source while maintaining a small pressure drop within the heat exchanger. As discussed in the different embodiments below, the heat exchanger



utilizes a plurality of apertures, channels and/or fingers in the manifold layer as well as conduits in the intermediate layer to direct and circulate fluid to and from selected hot spot areas in the interface layer. Alternatively, the heat exchanger includes several ports which are specifically disposed in predetermined locations to directly deliver fluid to and remove fluid from the hot spots to effectively cool the heat source.

[0048] It is apparent to one skilled in the art that although the microchannel heat exchanger of the present invention is described and discussed in relation to cooling hot spot locations in a device, the heat exchanger is alternatively used for heating a cold spot location in a device. It should also be noted that although the present invention is preferably described as a microchannel heat exchanger, the present invention can be used in other applications and is not limited to the discussion herein.

[0049] FIG. 2A illustrates a schematic diagram of a closed loop hermetically sealed cooling system 30 which includes an alternative flexible fluid delivery microchannel heat exchanger 100 in accordance with the present invention. In addition, FIG. 2B illustrates a schematic diagram of a closed loop cooling system 30 which includes an alternative flexible fluid delivery microchannel heat exchanger 100 with multiple ports 108, 109 in accordance with the present invention. It should be noted that the system alternatively incorporates other heat exchanger embodiments herein and is not limited to the alternative heat exchanger 100.

[0050] As shown in FIG. 2A, the fluid ports 108, 109 are coupled to fluid lines 38 which are coupled to a pump 32 and heat condensor 30. The pump 32 pumps and circulates fluid within the closed loop 30. In one alternative, one fluid port 108 is used to supply fluid to the heat exchanger 100. In addition, one fluid port 109 is used to remove fluid from the heat exchanger 100. In one embodiment, a uniform, constant amount of fluid flow enters and exits the heat exchanger 100 via the respective fluid ports 108, 109. Alternatively, different amounts of fluid flow enter and exit through the inlet and outlet port(s) 108, 109 at a given time. Alternatively, as shown in FIG. 2B, one pump provides fluid to several designated inlet ports 108. Alternatively, multiple pumps (not shown), provide fluid to their respective inlet and outlet ports 108, 109. In addition, the dynamic sensing and control module 34 is alternatively employed in the system to vary and dynamically control the amount and flow rate of fluid entering and exiting the preferred or alternative heat exchanger in response to varying hot spots or changes in the amount of heat in a hot spot location as well as the locations of the hot spots.

[0051] FIG. 3B illustrates an exploded view of the alternative three tier heat exchanger 100 with the alternative manifold layer in accordance with the present invention. The alternative embodiment, as shown in FIG. 3B, is a three level heat exchanger 100 which includes an interface layer 102, at least one intermediate layer 104 and at least one manifold layer 106. Alternatively, as discussed below, the heat exchanger 100 is a two level apparatus which includes the interface layer 102 and the manifold layer 106. As shown in FIGS. 2A and 2B, the heat exchanger 100 is coupled to a heat source 99, such as an electronic device, including, but not limited to a microchip and integrated circuit, whereby a thermal interface material 98 is preferably disposed between

the heat source 99 and the heat exchanger 100. Alternatively, the heat exchanger 100 is directly coupled to the surface of the heat source 99. It is also apparent to one skilled in the art that the heat exchanger 100 is alternatively integrally formed into the heat source 99, whereby the heat exchanger 100 and the heat source 99 are formed as one piece. Thus, the interface layer 102 is integrally disposed with the heat source 99 and is formed as one piece with the heat source.

[0052] It is preferred that the microchannel heat exchanger of the present invention is configured to be directly or indirectly in contact with the heat source 99 which is rectangular in shape, as shown in the figures. However, it is apparent to one skilled in the art that the heat exchanger 100 can have any other shape conforming with the shape of the heat source 99. For example, the heat exchanger of the present invention can be configured to have an outer semi-circular shape which allows the heat exchanger (not shown) to be in direct or indirect contact with a corresponding semicircular shaped heat source (not shown). In addition, it is preferred that the heat exchanger is slightly larger in dimension than the heat source within the range of and including 0.5-5.0 millimeters.

[0053] FIG. 3A illustrates a top view of the alternate manifold layer 106 of the present invention. In particular, as shown in FIG. 3B, the manifold layer 106 includes four sides as well as a top surface 130 and a bottom surface 132. However, the top surface 130 is removed in FIG. 3A to adequately illustrate and describe the workings of the manifold layer 106. As shown in FIG. 3A, the manifold layer 106 has a series of channels or passages 116, 118, 120, 122 as well as ports 108, 109 formed therein. The fingers 118, 120 extend completely through the body of the manifold layer 106 in the Z-direction as shown in FIG. 3B. Alternatively, the fingers 118 and 120 extend partially through the manifold layer 106 in the Z-direction and have apertures as shown in FIG. 3A. In addition, passages 116 and 122 extend partially through the manifold layer 106. The remaining areas between the inlet and outlet passages 116, 120, designated as 107, extend from the top surface 130 to the bottom surface 132 and form the body of the manifold layer 106.

[0054] As shown in FIG. 3A, the fluid enters manifold layer 106 via the inlet port 108 and flows along the inlet channel 116 to several fingers 118 which branch out from the channel 116 in several directions in the X and/or Y directions to apply fluid to selected regions in the interface layer 102. The fingers 118 are arranged in different predetermined directions to deliver fluid to the locations in the interface layer 102 corresponding to the areas at or near the hot spots in the heat source. These locations in the interface layer 102 are hereinafter referred to as interface hot spot regions. The fingers are configured to cool stationary as well as temporally varying interface hot spot regions. As shown in FIG. 3A, the channels 116, 122 and fingers 118, 120 are disposed in the X and/or Y directions in the manifold layer 106. Thus, the various directions of the channels 116, 122 and fingers 118, 120 allow delivery of fluid to cool hot spots in the heat source 99 and/or minimize pressure drop within the heat exchanger 100. Alternatively, channels 116, 122 and fingers 118, 120 are periodically disposed in the manifold layer 106 and exhibit a pattern, as in the example shown in FIGS. 4 and 5.



[0055] The arrangement as well as the dimensions of the fingers **118**, **120** are determined in light of the hot spots in the heat source **99** that are desired to be cooled. The locations of the hot spots as well as the amount of heat produced near or at each hot spot are used to configure the manifold layer **106** such that the fingers **118**, **120** are placed above or proximal to the interface hot spot regions in the interface layer **102**. The manifold layer **106** preferably allows one phase and/or two-phase fluid to circulate to the interface layer **102** without allowing a substantial pressure drop from occurring within the heat exchanger **100** and the system **30** (**FIG. 2A**). The fluid delivery to the interface hot spot regions creates a uniform temperature at the interface hot spot region as well as areas in the heat source adjacent to the interface hot spot regions.

[0056] The dimensions as well as the number of channels **116** and fingers **118** depend on a number of factors. In one embodiment, the inlet and outlet fingers **118**, **120** have the same width dimensions. Alternatively, the inlet and outlet fingers **118**, **120** have different width dimensions. The width dimensions of the fingers **118**, **120** are within the range of and including 0.25-0.50 millimeters. In one embodiment, the inlet and outlet fingers **118**, **120** have the same length and depth dimensions. Alternatively, the inlet and outlet fingers **118**, **120** have different length and depth dimensions. In another embodiment, the inlet and outlet fingers **118**, **120** have varying width dimensions along the length of the fingers. The length dimensions of the inlet and outlet fingers **118**, **120** are within the range of and including 0.5 millimeters to three times the size of the heat source length. In addition, the fingers **118**, **120** have a height or depth dimension within the range and including 0.25-0.50 millimeters. In addition, less than 10 or more than 30 fingers per centimeter are alternatively disposed in the manifold layer **106**. However, it is apparent to one skilled in the art that between 10 and 30 fingers per centimeter in the manifold layer is also contemplated.

[0057] It is contemplated within the present invention to tailor the geometries of the fingers **118**, **120** and channels **116**, **122** to be in non-periodic arrangement to aid in optimizing hot spot cooling of the heat source. In order to achieve a uniform temperature across the heat source **99**, the spatial distribution of the heat transfer to the fluid is matched with the spatial distribution of the heat generation. As the fluid flows along the interface layer through the microchannels **110**, its temperature increases and as it begins to transform to vapor under two-phase conditions. Thus, the fluid undergoes a significant expansion which results in a large increase in velocity. Generally, the efficiency of the heat transfer from the interface layer to the fluid is improved for high velocity flow. Therefore, it is possible to tailor the efficiency of the heat transfer to the fluid by adjusting the cross-sectional dimensions of the fluid delivery and removal fingers **118**, **120** and channels **116**, **122** in the heat exchanger **100**.

[0058] For example, a particular finger can be designed for a heat source where there is higher heat generation near the inlet. In addition, it may be advantageous to design a larger cross section for the regions of the fingers **118**, **120** and channels **116**, **122** where a mixture of fluid and vapor is expected. Although not shown, a finger can be designed to start out with a small cross sectional area at the inlet to cause high velocity flow of fluid. The particular finger or channel

can also be configured to expand to a larger cross-section at a downstream outlet to cause a lower velocity flow. This design of the finger or channel allows the heat exchanger to minimize pressure drop and optimize hot spot cooling in areas where the fluid increases in volume, acceleration and velocity due to transformation from liquid to vapor in two-phase flow.

[0059] In addition, the fingers **118**, **120** and channels **116**, **122** can be designed to widen and then narrow again along their length to increase the velocity of the fluid at different places in the microchannel heat exchanger **100**. Alternatively, it is appropriate to vary the finger and channel dimensions from large to small and back again many times over in order to tailor the heat transfer efficiency to the expected heat dissipation distribution across the heat source **99**. It should be noted that the above discussion of the varying dimensions of the fingers and channels also apply to the other embodiments discussed and is not limited to this embodiment.

[0060] Alternatively, as shown in **FIG. 3A**, the manifold layer **106** includes one or more apertures **19** in the inlet fingers **118**. In the three tier heat exchanger **100**, the fluid flowing along the fingers **118** flows down the apertures **119** to the intermediate layer **104**. Alternatively, in the two-tier heat exchanger **100**, the fluid flowing along the fingers **118** flows down the apertures **119** directly to the interface layer **102**. In addition, as shown in **FIG. 3A** the manifold layer **106** includes apertures **121** in the outlet fingers **120**. In the three tier heat exchanger **100**, the fluid flowing from the intermediate layer **104** flows up the apertures **121** into the outlet fingers **120**. Alternatively, in the two-tier heat exchanger **100**, the fluid flowing from the interface layer **102** flows directly up the apertures **121** into the outlet fingers **120**.

[0061] In the alternative embodiment, the inlet and outlet fingers **118**, **120** are open channels which do not have apertures. The bottom surface **103** of the manifold layer **106** abuts against the top surface of the intermediate layer **104** in the three tier exchanger **100** or abuts against the interface layer **102** in the two tier exchanger. Thus, in the three-tier heat exchanger **100**, fluid flows freely to and from the intermediate layer **104** and the manifold layer **106**. The fluid is directed to and from the appropriate interface hot spot region by conduits **105** the intermediate layer **104**. It is apparent to one skilled in the art that the conduits **105** are directly aligned with the fingers, as described below or positioned elsewhere in the three tier system.

[0062] Although **FIG. 3B** shows the alternative three tier heat exchanger **100** with the alternative manifold layer, the heat exchanger **100** is alternatively a two layer structure which includes the manifold layer **106** and the interface layer **102**, whereby fluid passes directly between the manifold layer **106** and interface layer **102** without passing through the interface layer **104**. It is apparent to one skilled in the art that the configuration of the manifold, intermediate and interface layers are shown for exemplary purposes and is thereby not limited to the configuration shown.

[0063] As shown in **FIG. 3B**, the intermediate layer **104** includes a plurality of conduits **105** which extend through. The inflow conduits **105** direct fluid entering from the manifold layer **106** to the designated interface hot spot regions in the interface layer **102**. Similarly, the apertures



**105** also channel fluid flow from the interface layer **102** to the exit fluid port(s) **109**. Thus, the intermediate layer **104** also provides fluid delivery from the interface layer **102** to the exit fluid port **109** where the exit fluid port **108** is in communication with the manifold layer **106**.

[0064] The conduits **105** are positioned in the interface layer **104** in a predetermined pattern based on a number of factors including, but not limited to, the locations of the interface hot spot regions, the amount of fluid flow needed in the interface hot spot region to adequately cool the heat source **99** and the temperature of the fluid. The conduits have a width dimension of 100 microns, although other width dimensions are contemplated up to several millimeters. In addition, the conduits **105** have other dimensions dependent on at least the above mentioned factors. It is apparent to one skilled in the art that each conduit **105** in the intermediate layer **104** has the same shape and/or dimension, although it is not necessary. For instance, like the fingers described above, the conduits alternatively have a varying length and/or width dimension.

[0065] Additionally, the conduits **105** have a constant depth or height dimension through the intermediate layer **104**. Alternatively, the conduits **105** have a varying depth dimension, such as a trapezoidal or a nozzle-shape, through the intermediate layer **104**. Although the horizontal shape of the conduits **105** are shown to be rectangular in FIG. 2C, the conduits **105** alternatively have any other shape including, but not limited to, circular (FIG. 3A), curved, elliptical. Alternatively, one or more of the conduits **105** are shaped and contour with a portion of or all of the finger or fingers above.

[0066] The intermediate layer **104** is horizontally positioned within the heat exchanger **100** with the conduits **105** positioned vertically. Alternatively, the intermediate layer **104** is positioned in any other direction within the heat exchanger **100** including, but not limited to, diagonal and curved forms. Alternatively, the conduits **105** are positioned within the intermediate layer **104** in a horizontally, diagonally, curved or any other direction. In addition, the intermediate layer **104** extends horizontally along the entire length of the heat exchanger **100**, whereby the intermediate layer **104** completely separates the interface layer **102** from the manifold layer **106** to force the fluid to be channeled through the conduits **105**. Alternatively, a portion of the heat exchanger **100** does not include the intermediate layer **104** between the manifold layer **106** and the interface layer **102**, whereby fluid is free to flow therebetween. Further, the intermediate layer **104** alternatively extends vertically between the manifold layer **106** and the interface layer **102** to form separate, distinct intermediate layer regions. Alternatively, the intermediate layer **104** does not fully extend from the manifold layer **106** to interface layer **102**.

[0067] FIG. 10A illustrates a perspective view of the preferred embodiment of the interface layer **302** in accordance with the present invention. As shown in FIG. 10A, the interface layer **302** includes a series of pillars **303** which extend upwards from the bottom surface **301** of the interface layer **302**. In addition, FIG. 10A illustrates a microporous structure **301** disposed on the bottom surface of the interface layer **302**. It is apparent that the interface layer **302** can include only the microporous structure **301** as well as a combination of the microporous structure with any other interface layer feature (e.g. microchannels, pillars, etc.).

[0068] The preferred interface layer **302** includes the pillars **303** rather than microchannels due to the flow of the fluid from the inlet apertures to the surrounding outlet apertures in the preferred manifold layer **302** (FIG. 12A). As will be discussed in more detail below, the fluid travels down to the interface layer **302** via a series of inlet apertures, whereby the fluid then exits from the interface layer **302** via a series of outlet apertures which are spaced an optimal distance to the inlet apertures. In other words, the fluid travels away from each inlet aperture toward the closest outlet aperture. Preferably, each inlet aperture is surrounded by outlet apertures. Thus, fluid entering the interface layer **302** will flow in the direction toward the surrounding outlet apertures. Accordingly, the pillars **303** are preferred in the interface layer **302** to accommodate sufficient heat transfer to the fluid as well as allow the fluid to experience the least amount of pressure drop while flowing from the inlet apertures to the outlet apertures.

[0069] The interface layer **302** preferably includes a dense array of tall, narrow pillars **303** which extend perpendicular from the bottom surface **301** are in contact with the bottom surface of the manifold layer. Alternatively, the pillars **303** are not in contact with the bottom surface of the manifold layer. In addition, at least one of the pillars **303** alternatively extend at an angle with respect to the bottom surface **301** of the interface layer **302**. The pillars **303** are also preferably equidistantly spaced from one another along the interface layer **302** such that the heat transfer capabilities of the interface layer **302** are uniform across its bottom surface **301**. Alternatively, the pillars **303** are spaced apart non-equidistantly as shown in FIG. 10B, in which the pillars **303** in the middle of the interface layer **302** are spaced further apart than the pillars **303** at the edges. The pillars **303** are spaced apart depending on the dimensions of the heat source **99**, and the flow resistance to the fluid as well as the size and locations of the hot spots and the heat flux density from the heat source **99**. For instance, a lower density of pillars **303** will offer less resistance to the flow, but will also offer less surface area for heat transfer from the interface layer **302** to the fluid. It should be noted that the configuration of the non-periodically spaced pillars **303** shown in the embodiment in FIG. 10B are not limited thereto and are configured in any other arrangement depending on the conditions of the heat source as well as the desired operation of the cooling system **30** (FIG. 2A).

[0070] In addition, the pillars **303** are preferably circular cylinders as shown in FIG. 10A to allow the fluid to flow from the inlet apertures to the outlet apertures with least amount of resistance. However, the pillars **303** alternatively have shapes including, but not limited to squared **303B** (FIG. 10B), diamond, elliptical **303C** (FIG. 10C), hexagonal **303D** (FIG. 10D) or any other shape. In addition, the interface layer **302** alternatively has a combination of differently shaped pillars along the bottom surface **301**.

[0071] For instance, as shown in FIG. 10E, the interface layer **302** includes several sets of rectangular fins **303E** which are radially disposed with respect to one another in their respective set. In addition, the interface layer **302** includes several pillars **303B** disposed in between the sets of rectangular fins **303E**. In one embodiment, the open circular areas within the radially arranged rectangular fins **303E** are placed below each inlet aperture, whereby the fins **303E** assist in guiding the flow to the outlet apertures. Thus, the



radially distributed fins **303E** assist in minimizing the pressure drop while allowing nearly uniform distribution of cooling fluid throughout the interface layer **302**. Depending on the size and relative placement of the inlet and outlet apertures, there are many possible configurations of the pillars and/or fins, and the selection of the optimal arrangement of the interface layer **302** depends on whether the fluid undergoes single-phase flow or two-phase flow conditions. It is apparent to one skilled in the art that the various pin **303** configurations can be incorporated with any of the embodiments and variations thereof discussed herein.

[0072] It is preferred that the heat exchanger **100** of the present invention is larger in width than the heat source **99**. In the case where the heat exchanger **100** is larger than the heat source **99**, an overhang dimension exists. The overhang dimension is the farthest distance between one outer wall of the heat source **99** and the interior fluid channel wall of the heat exchanger **100**, such as the inner wall of the inlet port **316** (FIG. 12A). In the preferred embodiment, the overhang dimension is within the range of and including 0 to 5 millimeters for single phase and 0 to 15 millimeters for two phase fluid. In addition, the interface layer **302** of the present invention preferably has a thickness dimension within the range of and including 0.3 to 0.7 millimeters for single phase fluid and 0.3 to 1.0 millimeters for two phase fluid.

[0073] In the embodiment of the heat exchanger which utilizes a microporous structure **301** disposed upon the interface layer **302**, the microporous structure **301** has an average pore size within the range of and including 10 to 200 microns for single phase as well as two phase fluid. In addition, the microporous structure **301** has a porosity within the range and including 50 to 80 percent for single phase as well as two phase fluid. The height of the microporous structure **301** is within the range of and including 0.25 to 2.00 millimeters for single phase as well as two phase fluid.

[0074] In the embodiment which utilizes pillars and/or microchannels along the interface layer **302**, the interface layer **302** of the present invention has a thickness dimension in the range of and including 0.3 to 0.7 millimeters for single phase fluid and 0.3 to 1.0 millimeters for two phase fluid. In addition, the area of each pillar, or microchannel, is in the range of and including 100 microns<sup>2</sup> to 10 millimeters<sup>2</sup> for single phase as well as two phase fluid. In addition, the area of the separation distance between each of the pillars and/or microchannels is in the range of and including 100 microns<sup>2</sup> to 22.5 millimeters<sup>2</sup> for single phase as well as two phase fluid. The width dimension of the microchannels are in the range of and including 10 to 100 microns for single phase as well as two phase fluid. The height dimension of the microchannels and/or pillars is within the range of and including 50 to 800 microns for single phase fluid and 50 microns to 2 millimeters for two phase fluid. It is contemplated by one skilled in the art that other dimension are alternatively contemplated.

[0075] FIG. 3B illustrates a perspective view of another embodiment of the interface layer **102** in accordance with the present invention. As shown in FIG. 3B, the interface layer **102** includes a bottom surface **103** and a plurality of microchannel walls **110**, whereby the area in between the microchannel walls **110** channels or directs fluid along a fluid flow path. The bottom surface **103** is flat and has a high

thermal conductivity to allow sufficient heat transfer from the heat source **99**. Alternatively, the bottom surface **103** includes troughs and/or crests designed to collect or repel fluid from a particular location. The microchannel walls **110** are configured in a parallel configuration, as shown in FIG. 3B, whereby fluid flows between the microchannel walls **110** along a fluid path.

[0076] It is apparent to one skilled in the art that the microchannel walls **110** are alternatively configured in any other appropriate configuration depending on the factors discussed above. For instance, the interface layer **102** alternatively has grooves in between sections of microchannel walls **110**, as shown in FIG. 8C. In addition, the microchannel walls **110** have dimensions which minimize the pressure drop or differential within the interface layer **102**. It is also apparent that any other features, besides microchannel walls **110** are also contemplated, including, but not limited to roughed surfaces and a micro-porous structure, such as sintered metal and silicon foam. However, for exemplary purposes, the parallel microchannel walls **110** shown in FIG. 3B is used to describe the interface layer **102** in the present invention. Alternatively, the microchannel walls **110** have non-parallel configurations.

[0077] The microchannel walls **110** allow the fluid to undergo thermal exchange along the selected hot spot locations of the interface hot spot region to cool the heat source **99** in that location. The microchannel walls **110** have a width dimension within the range of 10-100 microns and a height dimension within the range of 50 microns to two millimeters, depending on the power of the heat source **99**. The microchannel walls **110** have a length dimension which ranges between 100 microns and several centimeters, depending on the dimensions of the heat source, as well as the size of the hot spots and the heat flux density from the heat source. Alternatively, any other microchannel wall dimensions are contemplated. The microchannel walls **110** are spaced apart by a separation dimension range of 50-500 microns, depending on the power of the heat source **99**, although any other separation dimension range is contemplated.

[0078] Referring back to the assembly in FIG. 3B, the top surface of the manifold layer **106** is cut away to illustrate the channels **116**, **122** and fingers **118**, **120** within the body of the manifold layer **106**. The locations in the heat source **99** that produce more heat are hereby designated as hot spots, whereby the locations in the heat source **99** which produce less heat are hereby designated as warm spots. As shown in FIG. 3B, the heat source **99** is shown to have a hot spot region, namely at location A, and a warm spot region, namely at location B. The areas of the interface layer **102** which abut the hot and warm spots are accordingly designated interface hot spot regions. As shown in FIG. 3B, the interface layer **102** includes interface hot spot region A, which is positioned above location A and interface hot spot region B, which is positioned above location B.

[0079] As shown in FIGS. 3A and 3B, fluid initially enters the heat exchanger **100** through one inlet port **108**. The fluid then flows to one inlet channel **116**. Alternatively, the heat exchanger **100** includes more than one inlet channel **116**. As shown in FIGS. 3A and 3B, fluid flowing along the inlet channel **116** from the inlet port **108** initially branches out to finger **118D**. In addition, the fluid which continues



along the rest of the inlet channel 116 flows to individual fingers 118B and 118C and so on.

[0080] In FIG. 3B, fluid is supplied to interface hot spot region A by flowing to the FIG. 118A, whereby fluid flows down through finger 118A to the intermediate layer 104. The fluid then flows through the inlet conduit 105A, positioned below the finger 118A, to the interface layer 102, whereby the fluid undergoes thermal exchange with the heat source 99. As described, the microchannels in the interface layer 102 are configurable in any direction. Thus, the microchannels 111 in interface region A are positioned perpendicular to the rest of the microchannels 110 in the interface layer 102. Thus, the fluid from conduit 105A travels along the microchannels 111 as shown in FIG. 3B, although the fluid travel in other directions along the remaining areas of the interface layer 102. The heated liquid then travels upward through the conduit 105B to the outlet finger 120A.

[0081] Similarly, fluid flows down in the Z-direction through fingers 118E and 118F to the intermediate layer 104. The fluid then flows through the inlet conduit 105C down in the Z-direction to the interface layer 102. The heated fluid then travels upward in the Z-direction from the interface layer 102 through the outlet conduit 105D to the outlet fingers 120E and 120F. The heat exchanger 100 removes the heated fluid in the manifold layer 106 via the outlet fingers 120, whereby the outlet fingers 120 are in communication with the outlet channel 122. The outlet channel 122 allows fluid to flow out of the heat exchanger through one outlet port 109.

[0082] It is preferred that the inflow and outflow conduits 105 are also positioned directly or nearly directly above the appropriate interface hot spot regions to directly apply fluid to hot spots in the heat source 99. In addition, each outlet finger 120 is configured to be positioned closest to a respective inlet finger 118 for a particular interface hot spot region to minimize pressure drop therebetween. Thus, fluid enters the interface layer 102 via the inlet finger 118A and travels the least amount of distance along the bottom surface 103 of the interface layer 102 before it exits the interface layer 102 to the outlet finger 120A. It is apparent that the amount of distance which the fluid travels along the bottom surface 103 adequately removes heat generated from the heat source 99 without generating an unnecessary amount of pressure drop. In addition, as shown in FIGS. 3A and 3B, the corners in the fingers 118, 120 are curved to reduce pressure drop of the fluid flowing along the fingers 118.

[0083] It is apparent to one skilled in the art that the configuration of the manifold layer 106 shown in FIGS. 3A and 3B is only for exemplary purposes. The configuration of the channels 116 and fingers 118 in the manifold layer 106 depend on a number of factors, including but not limited to, the locations of the interface hot spot regions, amount of flow to and from the interface hot spot regions as well as the amount of heat produced by the heat source in the interface hot spot regions. For instance, one possible configuration of the manifold layer 106 includes an interdigitated pattern of parallel inlet and outlet fingers that are alternatively arranged along the width of the manifold layer, as shown in FIGS. 4-7A and discussed below. Nonetheless, any other configuration of channels 116 and fingers 118 is contemplated.

[0084] FIG. 4 illustrates a perspective view of an alternative manifold layer 406 in accordance with the heat

exchanger of the present invention. The manifold layer 406 in FIG. 4 includes a plurality of interwoven or interdigitated parallel fluid fingers 411, 412 which allow one phase and/or two-phase fluid to circulate to the interface layer 402 without allowing a substantial pressure drop from occurring within the heat exchanger 400 and the system 30 (FIG. 2A). As shown in FIG. 8, the inlet fingers 411 are arranged alternately with the outlet fingers 412. However, it is contemplated by one skilled in the art that a certain number of inlet or outlet fingers can be arranged adjacent to one another and is thereby not limited to the alternating configuration shown in FIG. 4. In addition, the fingers are alternatively designed such that a parallel finger branches off from or is linked to another parallel finger. Thus, it is possible to have many more inlet fingers than outlet fingers and vice versa.

[0085] The inlet fingers or passages 411 supply the fluid entering the heat exchanger to the interface layer 402, and the outlet fingers or passages 412 remove the fluid from the interface layer 402 which then exits the heat exchanger 400. The shown configuration of the manifold layer 406 allows the fluid to enter the interface layer 402 and travel a very short distance in the interface layer 402 before it enters the outlet passage 412. The substantial decrease in the length that the fluid travels along the interface layer 402 substantially decreases the pressure drop in the heat exchanger 400 and the system 30 (FIG. 2A).

[0086] As shown in FIGS. 4-5, the alternative manifold layer 406 includes a passage 414 which is in communication with two inlet passages 411 and provides fluid thereto. As shown in FIGS. 8-9 the manifold layer 406 includes three outlet passages 412 which are in communication with passage 418. The passages 414 in the manifold layer 406 have a flat bottom surface which channels the fluid to the fingers 411, 412. Alternatively, the passage 414 has a slight slope which aids in channeling the fluid to selected fluid passages 411. Alternatively, the inlet passage 414 includes one or more apertures in its bottom surface which allows a portion of the fluid to flow down to the interface layer 402. Similarly, the passage 418 in the manifold layer has a flat bottom surface which contains the fluid and channels the fluid to the port 408. Alternatively, the passage 418 has a slight slope which aids in channeling the fluid to selected outlet ports 408. In addition, the passages 414, 418 have a dimension width of approximately 2 millimeters, although any other width dimensions are alternatively contemplated.

[0087] The passages 414, 418 are in communication with ports 408, 409 whereby the ports are coupled to the fluid lines 38 in the system 30 (FIG. 2A). The manifold layer 406 includes horizontally configured fluid ports 408, 409. Alternatively, the manifold layer 406 includes vertically and/or diagonally configured fluid ports 408, 409, as discussed below, although not shown in FIG. 4-7. Alternatively, the manifold layer 406 does not include passage 414. Thus, fluid is directly supplied to the fingers 411 from the ports 408. Again, the manifold layer 411 alternatively does not include passage 418, whereby fluid in the fingers 412 directly flows out of the heat exchanger 400 through ports 408. It is apparent that although two ports 408 are shown in communication with the passages 414, 418, any other number of ports are alternatively utilized.

[0088] The inlet passages 411 have dimensions which allow fluid to travel to the interface layer without generating



a large pressure drop along the passages **411** and the system **30** (**FIG. 2A**). The inlet passages **411** have a width dimension in the range of and including 0.25-5.00 millimeters, although any other width dimensions are alternatively contemplated. In addition, the inlet passages **411** have a length dimension in the range of and including 0.5 millimeters to three times the length of the heat source. Alternatively, other length dimensions are contemplated. In addition, as stated above, the inlet passages **411** extend down to or slightly above the height of the microchannels **410** such that the fluid is channeled directly to the microchannels **410**. The inlet passages **411** have a height dimension in the range of and including 0.25-5.00 millimeters. It is apparent to one skilled in the art that the passages **411** do not extend down to the microchannels **410** and that any other height dimensions are alternatively contemplated. It is apparent to one skilled in the art that although the inlet passages **411** have the same dimensions, it is contemplated that the inlet passages **411** alternatively have different dimensions. In addition, the inlet passages **411** alternatively have varying widths, cross sectional dimensions and/or distances between adjacent fingers. In particular, the passage **411** has areas with a larger width or depths as well as areas with narrower widths and depths along its length. The varied dimensions allow more fluid to be delivered to predetermined interface hot spot regions in the interface layer **402** through wider portions while restricting flow to warm spot interface hot spot regions through the narrow portions.

[0089] In addition, the outlet passages **412** have dimensions which allow fluid to travel to the interface layer without generating a large pressure drop along the passages **412** as well as the system **30** (**FIG. 2A**). The outlet passages **412** have a width dimension in the range of and including 0.25-5.00 millimeters, although any other width dimensions are alternatively contemplated. In addition, the outlet passages **412** have a length dimension in the range of and including 0.5 millimeters to three times the length of the heat source. In addition, the outlet passages **412** extend down to the height of the microchannels **410** such that the fluid easily flows upward in the outlet passages **412** after horizontally flowing along the microchannels **410**. The inlet passages **411** have a height dimension in the range of and including 0.25-5.00 millimeters, although any other height dimensions are alternatively contemplated. It is apparent to one skilled in the art that although outlet passages **412** have the same dimensions, it is contemplated that the outlet passages **412** alternatively have different dimensions. Again, the inlet passage **412** alternatively have varying widths, cross sectional dimensions and/or distances between adjacent fingers.

[0090] The inlet and outlet passages **411**, **412** are segmented and distinct from one another, as shown in **FIGS. 4 and 5**, whereby fluid among the passages do not mix together. In particular, as shown in **FIG. 8**, two outlet passages are located along the outside edges of the manifold layer **406**, and one outlet passage **412** is located in the middle of the manifold layer **406**. In addition, two inlet passages **411** are configured on adjacent sides of the middle outlet passage **412**. This particular configuration causes fluid entering the interface layer **402** to travel a short distance in the interface layer **402** before it flows out of the interface layer **402** through the outlet passage **412**. However, it is apparent to one skilled in the art that the inlet passages and outlet passages are positioned in any other appropriate configuration and is thereby not limited to the configuration

shown and described in the present disclosure. The number of inlet and outlet fingers **411**, **412** are more than three within the manifold layer **406** but less than 10 per centimeter across the manifold layer **406**. It is also apparent to one skilled in the art that any other number of inlet passages and outlet passages are used and thereby is not limited to the number shown and described in the present disclosure.

[0091] The manifold layer **406** is coupled to the intermediate layer (not shown), whereby the intermediate layer (not shown) is coupled to the interface layer **402** to form a three-tier heat exchanger **400**. The intermediate layer discussed herein is referred to above in the embodiment shown in **FIG. 3B**. The manifold layer **406** is alternatively coupled to the interface layer **402** and positioned above the interface layer **402** to form a two-tier heat exchanger **400**, as shown in **FIG. 7A**. **FIGS. 6A-6C** illustrate cross-sectional schematics of the alternative manifold layer **406** coupled to the interface layer **402** in the two tier heat exchanger. Specifically, **FIG. 6A** illustrates the cross section of the heat exchanger **400** along line A-A in **FIG. 5**. In addition, **FIG. 6B** illustrates the cross section of the heat exchanger **400** along line B-B and **FIG. 6C** illustrates the cross section of the heat exchanger **400** along line C-C in **FIG. 5**. As stated above, the inlet and outlet passages **411**, **412** extend from the top surface to the bottom surface of the manifold layer **406**. When the manifold layer **406** and the interface layer **402** are coupled to one another, the inlet and outlet passages **411**, **412** are at or slightly above the height of the microchannels **410** in the interface layer **402**. This configuration causes the fluid from the inlet passages **411** to easily flow from the passages **411** through the microchannels **410**. In addition, this configuration causes fluid flowing through the microchannels to easily flow upward through the outlet passages **412** after flowing through the microchannels **410**.

[0092] In the alternative embodiment, the intermediate layer **104** (**FIG. 3B**) is positioned between the manifold layer **406** and the interface layer **402**, although not shown in the figures. The intermediate layer **104** (**FIG. 3B**) channels fluid flow to designated interface hot spot regions in the interface layer **402**. In addition, the intermediate layer **104** (**FIG. 3B**) can be utilized to provide a uniform flow of fluid entering the interface layer **402**. Also, the intermediate layer **104** is utilized to provide fluid to interface hot spot regions in the interface layer **402** to adequately cool hot spots and create temperature uniformity in the heat source **99**. The inlet and outlet passages **411**, **412** are positioned near or above hot spots in the heat source **99** to adequately cool the hot spots, although it is not necessary.

[0093] **FIG. 7A** illustrates an exploded view of the alternate manifold layer **406** with the an alternative interface layer **102** of the present invention. The interface layer **102** includes continuous arrangements of microchannel walls **110**, as shown in **FIG. 3B**. In general operation, similar to the preferred manifold layer **106** shown in **FIG. 3B**, fluid enters the manifold layer **406** at fluid port **408** and travels through the passage **414** and towards the fluid fingers or passages **411**. The fluid enters the opening of the inlet fingers **411** and flows the length of the fingers **411** in the X-direction, as shown by the arrows. In addition, the fluid flows downward in the Z direction to the interface layer **402** which is positioned below to the manifold layer **406**. As shown in **FIG. 7A**, the fluid in the interface layer **402** traverses along the bottom surface in the X and Y directions of the interface



layer **402** and performs thermal exchange with the heat source **99**. The heated fluid exits the interface layer **402** by flowing upward in the Z-direction via the outlet fingers **412**, whereby the outlet fingers **412** channel the heated fluid to the passage **418** in the manifold layer **406** in the X-direction. The fluid then flows along the passage **418** and exits the heat exchanger by flowing out through the port **409**.

[0094] The interface layer, as shown in **FIG. 7A**, includes a series of grooves **416** disposed in between sets of microchannels **410** which aid in channeling fluid to and from the passages **411**, **412**. In particular, the grooves **416A** are located directly beneath the inlet passages **411** of the alternate manifold layer **406**, whereby fluid entering the interface layer **402** via the inlet passages **411** is directly channeled to the microchannels adjacent to the groove **416A**. Thus, the grooves **416A** allow fluid to be directly channeled into specific designated flow paths from the inlet passages **411**, as shown in **FIG. 5**. Similarly, the interface layer **402** includes grooves **416B** which are located directly beneath the outlet passages **412** in the Z-direction. Thus, fluid flowing horizontally along the microchannels **410** toward the outlet passages are channeled horizontally to the grooves **416B** and vertically to the outlet passage **412** above the grooves **416B**.

[0095] **FIG. 6A** illustrates the cross section of the heat exchanger **400** with manifold layer **406** and interface layer **402**. In particular, **FIG. 6A** shows the inlet passages **411** interwoven with the outlet passages **412**, whereby fluid flows down the inlet passages **411** and up the outlet passages **412**. In addition, as shown in **FIG. 6A**, the fluid flows horizontally through the microchannel walls **410** which are disposed between the inlet passages and outlet passages and separated by the grooves **416A**, **416B**. Alternatively, the microchannel walls are continuous (**FIG. 3B**) and are not separated by the microchannels **410**. As shown in **FIG. 6A**, either or both of the inlet and outlet passages **411**, **412** have a curved surface **420** at their ends at the location near the grooves **416**. The curved surface **420** directs fluid flowing down the passage **411** towards the microchannels **410** which are located adjacent to the passage **411**. Thus, fluid entering the interface layer **102** is more easily directed toward the microchannels **410** instead of flowing directly to the groove **416A**. Similarly, the curved surface **420** in the outlet passages **412** assists in directing fluid from the microchannels **410** to the outer passage **412**.

[0096] In an alternative embodiment, as shown in **FIG. 7B**, the interface layer **402'** includes the inlet passages **411'** and outlet passages **412'** discussed above with respect to the manifold layer **406** (**FIGS. 8-9**). In the alternative embodiment, the fluid is supplied directly to the interface layer **402'** from the port **408'**. The fluid flows along the passage **414'** towards the inlet passages **411'**. The fluid then traverses laterally along the sets of microchannels **410'** and undergoes heat exchange with the heat source (not shown) and flows to the outlet passages **412'**. The fluid then flows along the outlet passages **412'** to passage **418'**, whereby the fluid exits the interface layer **402'** by via the port **409'**. The ports **408'**, **409'** are configured in the interface layer **402'** and are alternatively configured in the manifold layer **406** (**FIG. 7A**).

[0097] It is apparent to one skilled in the art that although all of the heat exchangers in the present application are shown to operate horizontally, the heat exchanger alterna-

tively operates in a vertical position. While operating in the vertical position, the heat exchangers are alternatively configured such that each inlet passage is located above an adjacent outlet passage. Therefore, fluid enters the interface layer through the inlet passages and is naturally channeled to an outlet passage. It is also apparent that any other configuration of the manifold layer and interface layer is alternatively used to allow the heat exchanger to operate in a vertical position.

[0098] **FIGS. 8A-8C** illustrate top view diagrams of another alternate embodiment of the heat exchanger in accordance with the present invention. In particular, **FIG. 8A** illustrates a top view diagram of an alternate manifold layer **206** in accordance with the present invention. **FIGS. 8B and 8C** illustrate a top view of an intermediate layer **204** and interface layer **202**. In addition, **FIG. 9A** illustrates a three tier heat exchanger utilizing the alternate manifold layer **206**, whereas **FIG. 9B** illustrates a two-tier heat exchanger utilizing the alternate manifold layer **206**.

[0099] As shown in **FIGS. 8A and 9A**, the manifold layer **206** includes a plurality of fluid ports **208** configured horizontally and vertically. Alternatively, the fluid ports **208** are positioned diagonally or in any other direction with respect to the manifold layer **206**. The fluid ports **208** are placed in selected locations in the manifold layer **206** to effectively deliver fluid to the predetermined interface hot spot regions in the heat exchanger **200**. The multiple fluid ports **208** provide a significant advantage, because fluid can be directly delivered from a fluid port to a particular interface hot spot region without significantly adding to the pressure drop to the heat exchanger **200**. In addition, the fluid ports **208** are also positioned in the manifold layer **206** to allow fluid in the interface hot spot regions to travel the least amount of distance to the exit port **208** such that the fluid achieves temperature uniformity while maintaining a minimal pressure drop between the inlet and outlet ports **208**. Additionally, the use of the manifold layer **206** aids in stabilizing two phase flow within the heat exchanger **200** while evenly distributing uniform flow across the interface layer **202**. It should be noted that more than one manifold layer **206** is alternatively included in the heat exchanger **200**, whereby one manifold layer **206** routes the fluid into and out-of the heat exchanger **200** and another manifold layer (not shown) controls the rate of fluid circulation to the heat exchanger **200**. Alternatively, all of the plurality of manifold layers **206** circulate fluid to selected corresponding interface hot spot regions in the interface layer **202**.

[0100] The alternate manifold layer **206** has lateral dimensions which closely match the dimensions of the interface layer **202**. In addition, the manifold layer **206** has the same dimensions of the heat source **99**. Alternatively, the manifold layer **206** is larger than the heat source **99**. The vertical dimensions of the manifold layer **206** are within the range of 0.1 and 10 millimeters. In addition, the apertures in the manifold layer **206** which receive the fluid ports **208** are within the range between 1 millimeter and the entire width or length of the heat source **99**.

[0101] **FIG. 11** illustrates a broken-perspective view of a three tier heat exchanger **200** having the alternate manifold layer **200** in accordance with the present invention. As shown in **FIG. 11**, the heat exchanger **200** is divided into separate regions dependent on the amount of heat produced



along the body of the heat source **99**. The divided regions are separated by the vertical intermediate layer **204** and/or microchannel wall features **210** in the interface layer **202**. However, it is apparent to one skilled in the art that the assembly shown in **FIG. 11** is not limited to the configuration shown and is for exemplary purposes. The heat exchanger **200** is coupled to one or more pumps, whereby by one pump is coupled to the inlets **208A** and another pump is coupled to the inlet **208B**.

[0102] As shown in **FIG. 3**, the heat source **99** has a hot spot in location A and a warm spot, location B, whereby the hot spot in location A produces more heat than the warm spot in location B. It is apparent that the heat source **99** alternatively has more than one hot spot and warm spot at any location at any given time. In the example, since location A is a hot spot and more heat in location A transfers to the interface layer **202** above location A (designated in **FIG. 11** as interface hot spot region A), more fluid and/or a higher rate of liquid flow is provided to interface hot spot region A in the heat exchanger **200** to adequately cool location A. It is apparent that although interface hot spot region B is shown to be larger than interface hot spot region A, interface hot spot regions A and B, as well as any other interface hot spot regions in the heat exchanger **200**, can be any size and/or configuration with respect to one another.

[0103] Alternatively, as shown in **FIG. 11**, the fluid enters the heat exchanger via fluid ports **208A** is directed to interface hot spot region A by flowing along the intermediate layer **204** to the inflow conduits **205A**. The fluid then flows down the inflow conduits **205A** in the Z-direction into interface hot spot region A of the interface layer **202**. The fluid flows in between the microchannels **210A** whereby heat from location A transfers to the fluid by conduction through the interface layer **202**. The heated fluid flows along the interface layer **202** in interface hot spot region A toward exit port **209A** where the fluid exits the heat exchanger **200**. It is apparent to one skilled in the art that any number of inlet ports **208** and exit ports **209** are utilized for a particular interface hot spot region or a set of interface hot spot regions. In addition, although the exit port **209A** is shown near the interface layer **202A**, the exit port **209A** is alternatively positioned in any other location vertically, including but not limited to the manifold layer **209B**.

[0104] Similarly, in the example shown in **FIG. 1**, the heat source **99** has a warm spot in location B which produces less heat than location A of the heat source **99**. Fluid entering through the port **208B** is directed to interface hot spot region B by flowing along the intermediate layer **204B** to the inflow conduits **205B**. The fluid then flows down the inflow conduits **205B** in the Z-direction into interface hot spot region B of the interface layer **202**. The fluid flows in between the microchannels **210** in the X and Y directions, whereby heat generated by the heat source in location B is transferred into the fluid. The heated fluid flows along the entire interface layer **202B** in interface hot spot region B upward to exit ports **209B** in the Z-direction via the outflow conduits **205B** in the intermediate layer **204** whereby the fluid exits the heat exchanger **200**.

[0105] Alternatively, as shown in **FIG. 9A**, the heat exchanger **200** alternatively includes a vapor permeable membrane **214** positioned above the interface layer **202**. The vapor permeable membrane **214** is in sealable contact with

the inner side walls of the heat exchanger **200**. The membrane is configured to have several small apertures which allow vapor produced along the interface layer **202** to pass therethrough to the port **209**. The membrane **214** is also configured to be hydrophobic to prevent liquid fluid flowing along the interface layer **202** from passing through the apertures of the membrane **214**. More details of the vapor permeable membrane **114** is discussed in co-pending U.S. application Ser. No. 10/366,128, filed Feb. 12, 2003 and entitled, "VAPOR ESCAPE MICROCHANNEL HEAT EXCHANGER" which is hereby incorporated by reference.

[0106] **FIG. 12A** illustrates an exploded view of a preferred heat exchanger **300** in accordance with the present invention. **FIG. 12B** illustrates an exploded view of an alternative heat exchanger **300'** in accordance with the present invention. As shown in **FIGS. 12A and 12B**, the heat exchanger **300, 300'** includes the interface layer **302, 302'** and the manifold layer **306, 306'** coupled thereto. As stated above, the heat exchanger **300, 300'** is coupled to the heat source (not shown) or alternatively fully integrated within the heat source (e.g. embedded in a microprocessor). It is apparent to one skilled in the art that the interface layer **302, 302'** is substantially enclosed, and is only shown exposed in **FIG. 12A** for exemplary purposes only. It is preferred that the interface layer **302, 302'** includes a plurality of pillars **303** disposed along the bottom surface **301**. In addition, the pillars **303** alternatively has any shape, as discussed in relation to **FIGS. 10A-10E** and/or radially distributed fins **303E**. Again, the interface layer **302** alternatively has any other features as discussed above (e.g. microchannels, roughened surfaces). The interface layer **302** as well as the features within the layer **302** also preferably has the same thermal conductivity characteristics as discussed above and will not be discussed again with respect to the preferred embodiment. Although the interface layer **302** is shown as smaller compared to the manifold layer **306**, it is apparent to one skilled in the art that the interface layer **302** and manifold layer **306** can be any other size with respect to each other and the heat source **99**. The remaining features of the interface layer **302, 302'** has the same characteristics as the interface layers described above and will not be discussed in any more detail.

[0107] Generally, the preferred heat exchanger **300** minimizes the pressure drop within the heat exchanger using the delivery channels **322** in the manifold layer **306**. The delivery channels **322** are vertically positioned within the manifold layer **306** and vertically provide fluid to the interface layer **302** to reduce the pressure drop in the heat exchanger **300**. As stated above, pressure drop is created or increased in the heat exchanger **300** due to fluid flowing along the interface layer in the X and Y directions for a substantial amount of time and/or distance. The manifold layer **306** minimizes the flow in the X and Y directions by vertically forcing the fluid onto the interface layer **302** by the several delivery channels **322**. In other words, several individual jets of fluid are applied directly onto the interface layer **302** from above. The delivery channels **322** are positioned an optimal distance from one another to allow fluid to flow minimally in the X and Y directions and vertically upward out of the interface layer **302**. Therefore, the force of individual fluid paths from the optimally positioned channels **322** naturally cause the fluid to flow in an upward fluid path away from the interface layer **302**. In addition, the individual channels **322** maximize the division of fluid flow among the several



channels **322** in the interface layer **302**, thereby reducing the pressure drop in the heat exchanger **300** while effectively cooling the heat source **99**. In addition, the configuration of the preferred heat exchanger **300** allows the heat exchanger **300** to be smaller in size than other heat exchangers, because fluid does not need to travel a large amount of distance in the lateral X and Y directions to adequately cool the heat source **99**.

[0108] The preferred manifold layer **306** shown in **FIG. 12A** includes two individual levels. In particular, the manifold layer **306** includes a level **308** and a level **312**. The level **308** is coupled to the interface layer **302** and the level **312**. Although **FIG. 12A** illustrates that the level **312** is positioned above the level **308**, it is contemplated by one skilled in the art that the level **308** is alternatively positioned above the level **312**. It is also apparent to one skilled in the art that any number of levels are alternatively implemented in accordance with the present invention.

[0109] The alternative manifold layer **306'** shown in **FIG. 12B** includes three individual levels. In particular, the manifold layer **306'** includes a circulation level **304'**, a level **308'** and a level **312'**. The circulation level **304'** is coupled to the interface layer **302'** as well as the level **308'**. The level **308'** is coupled to the circulation level **304'** and the level **312'**. Although **FIG. 12B** illustrates that the level **312'** is positioned above the level **308'**, it is contemplated by one skilled in the art that the level **308'** is alternatively positioned above the level **312'**. It is also apparent to one skilled in the art that any number of levels are alternatively implemented in accordance with the present invention.

[0110] **FIG. 12C** illustrates a perspective view of the circulation level **304'** in accordance with the present invention. The circulation level **304'** includes a top surface **304A'** and a bottom surface **304B'**. As shown in **FIGS. 12B and 12C**, the circulation level **304'** includes several apertures **322'** which extend therethrough. In one embodiment, the openings of the apertures **322'** are flush with the bottom surface **304B'**. Alternatively, the apertures **322'** extend beyond the bottom surface **304B'** to apply fluid closer to the interface layer **302'**. In addition, the circulation level **304'** includes several apertures **324'** which extend therethrough from the top surface **304A'** to the bottom surface **304B'** as well as protrude vertically as cylindrical protrusions in the Z-direction a predetermined distance. It is apparent to one skilled in the art that the apertures **322'**, **324'** alternatively extend at an angle through the circulation level and do not need to be completely vertical. As stated above, in one embodiment, the interface layer **302'** (**FIG. 12B**) is coupled to the bottom surface **304B'** of the circulation level **304'**. Thus, fluid enters the interface layer **302'** by flowing only through the apertures **322'** in the Z-direction and exits the interface layer **302'** by flowing only through the apertures **324'** in the Z-direction. As discussed below, fluid entering the interface layer **302'** via the apertures **322'** is kept separate from fluid exiting the interface layer **302'** via the apertures **324'** through the circulation level **304'**.

[0111] As shown in **FIG. 12C**, a portion of the apertures **324'** preferably have cylindrical members extending from the top surface **304A'** in the Z-direction from the circulation level **304'**, such that fluid flows through the apertures **324'** directly to the corridor **326'** in the level **312'** (**FIG. 12F and 12G**). Preferably, the cylindrical protrusions are circular as

in **FIG. 12C**, but alternatively has any other other shape. Along the interface layer **302'**, however, the fluid flows from each aperture **322'** to the adjacent apertures **324'** in the lateral and vertical directions. It is preferred that the apertures **322'** and the apertures **324'** are thermally insulated from one another so that heat from the heated fluid exiting the interface layer **302'** through the manifold layer **306'** does not propagate to the cooled fluid flowing to the interface layer **302'** through the manifold layer **306'**.

[0112] **FIG. 12D** illustrates a preferred embodiment of the level **308** in accordance with the present invention. As shown in **FIG. 12D**, the level **308** includes a top surface **308A** and a bottom surface **308B**. Preferably, the bottom surface **308B** of the level **308** is coupled directly to the interface layer **302**, as shown in **FIG. 12A**. The level **308** includes a recessed corridor **320** which includes several fluid delivery channels **322** which preferably deliver fluid to the interface layer **302**. The recessed corridor **320** is in sealable contact with the interface layer **302**, wherein fluid exiting the interface layer **302** flows around and between the channels **322** in the corridor **320** and out through the port **314**. It should be noted that fluid exiting the interface layer **302** does not enter the delivery channels **322**.

[0113] **FIG. 12E** illustrates a perspective view of the underside of alternative embodiment of the level **308'** in accordance with the present invention. The level **308'** includes a top surface **308A'** and a bottom surface **308B'**, whereby the bottom surface of the level **308B'** is coupled directly to the circulation level **304'** (**FIG. 12C**). The level **308'** preferably includes a port **314'**, a corridor **320'** and a plurality of apertures **322'**, **324'** in the bottom surface **308B'**. It is apparent to one skilled in the art that the level **308'** includes any number of ports and corridors. The apertures **322'**, **324'** in **FIG. 12E** are configured to face the circulation level **304'**. In particular, as shown in **FIG. 12E**, the apertures **322'** direct fluid entering the corridor **320'** to flow into the interface layer **302'**, whereas the apertures **324'** direct fluid from the interface layer **302'** to flow to the level **312'**. The apertures **324'** extend completely through the corridor **320'** in the level **308'**. The apertures **324'** are individualized and separated, such that fluid flowing through the apertures **324'** does not mix or come into contact with the fluid flowing through the cylinders associated with the apertures **324'**. The apertures **324'** are also individualized to ensure that fluid entering through each aperture **324'** flows along the fluid path provided by the aperture **324'**. Preferably, the apertures **324'** are vertically configured. Therefore, the fluid is channeled vertically through a substantial portion of the manifold layer **306'**. It is apparent that the same applies to the apertures **322'**, especially in the case in which the level is positioned between the interface layer and the level.

[0114] Although the apertures or holes **322** are shown as having the same size, the apertures **322** can have different or varying diameters along a length. For instance, the holes **322** closer to the port **314** can have a smaller diameter to restrict fluid flow therethrough. The smaller holes **322** thus force the fluid to flow down the apertures **322** which are further away from the port **314**. This variation in the diameters in the holes **322** allow a more uniform distribution of fluid into the interface layer **302**. It is apparent to one skilled in the art that the hole **322** diameters are alternatively varied to address cooling in known interface hot spot regions in the interface layer **302**. It is apparent to one skilled in the art that the



above discussion is applicable to the apertures 324', whereby the dimensions of the apertures 324' vary or are different to accommodate uniform outflow from the interface layer 302.

[0115] In the preferred embodiment, the port 314 provides fluid to the level 308 and to the interface layer 302. The port 314 in FIG. 12D preferably extends from the top surface 308A through a portion of the body of the level 308 to the corridor 320. Alternatively, the port 314 extends to the corridor 320 from the side or the bottom of the level 308. It is preferred that the port 314 is coupled to the port 315 in the level 312 (FIGS. 12A-12B). The port 314 leads to the corridor 320 which is enclosed, as shown in FIG. 12C, or recessed, as in FIG. 12D. The corridor 320 preferably serves to channel fluid to the port 314 from the interface layer 302. The corridor 320 alternatively channels fluid from the port 314 to the interface layer 302.

[0116] As shown in FIGS. 12F and 12G, the port 315 in the level 312 is preferably aligned with and in communication with the port 314. In relation to FIG. 12A, fluid preferably enters the heat exchanger 300 via port 316 and flows through the corridor 328 down to the delivery channels 322 in the level 308 eventually to the interface layer 302. In relation to FIG. 12B, fluid alternatively enters the heat exchanger 300' preferably enters via the port 315' and flows through the port 314' in the level 308' and eventually to the interface layer 302'. The port 315 in FIG. 12F preferably extends from the top surface 312A through the body of the level 312. Alternatively, the port 315 extends from a side of the level 312. Alternatively, the level 312 does not include the port 315, whereby the fluid enters the heat exchanger 300 via the port 314 (FIGS. 12D and 12E). In addition, the level 312 includes a port 316 which preferably channels the fluid to the corridor 328'. It is apparent to one skilled in the art that the level includes any number of ports and corridors. The corridor 328 preferably channels fluid to the delivery channels 322 and eventually to the interface layer 302.

[0117] FIG. 12G illustrates a perspective underside view of an alternative embodiment of the level 312' in accordance with the present invention. The level 312' is preferably coupled to the level 308' in FIG. 12E. As shown in FIG. 12F, the level 312' includes a recessed corridor area 328' within the body which is exposed along the bottom surface 312B'. The recessed corridor 328' is in communication with the port 316', whereby fluid travels directly from the recessed corridor 328' to the port 316'. The recessed corridor 328' is positioned above the top surface 308A' of the level 308' to allow fluid to freely travel upward from the apertures 324' to the corridor 328'. The perimeter of the recessed corridor 320' and bottom surface 312B' is sealed against the top surface 308A' of the level 312' such that all of the fluid from the apertures 324' flows to the port 316' via the corridor 328'. Each of the apertures 330' in the bottom surface 312B' is aligned with and in communication with a corresponding aperture 321' in the level 308' (FIG. 12E), whereby the apertures 330' are positioned flush with the top surface 308A' of the level 308' (FIG. 12E). Alternatively, the apertures 330 have a diameter slightly larger than the diameter of the corresponding aperture 324', whereby the apertures 324' extend through the apertures 330' into the corridor 328'.

[0118] FIG. 12H illustrates a cross sectional view of the preferred heat exchanger in FIG. 12A along lines H-H in

accordance with the present invention. As shown in FIG. 12H, the interface layer 302 is coupled to a heat source 99. As stated above, the heat exchanger 300 is alternatively integrally formed with the heat source 99 as one component. The interface layer 302 is coupled to the bottom surface 308B of the level 308. In addition, the level 312 is preferably coupled to the level 308, whereby the top surface 308A of the level 308 is sealed against the bottom surface 312B of the level 312. The perimeter of the corridor 320 of the level 308 is in communication with the interface layer 302. In addition, the corridor 328 in the level 312 is in communication with the apertures 322 in the level 308. The bottom surface 312B of the level 312 is sealed against the top surface 308A of the level 308 such that fluid does not leak between the two levels 308, 312.

[0119] FIG. 12I illustrates a cross sectional view of the alternative heat exchanger in FIG. 12B along lines I-I in accordance with the present invention. As shown in FIG. 12I, the interface layer 302' is coupled to a heat source 99'. The interface layer 302' is coupled to the bottom surface 304B' of the circulation level 304'. Also, the circulation level 304 is coupled to the level 308', whereby the top surface 304A' of the circulation level 304' is sealed against the bottom surface 308B' of the level 308'. In addition, the level 312' is preferably coupled to the level 308', whereby the top surface 308A' of the level 308' is sealed against the bottom surface 312B' of the level 312'. The perimeter of the corridor 320' of the level 308' is in communication with the apertures in the top surface 304A' of the circulation level 304' such that fluid does not leak between the two levels. In addition, the perimeter of the corridor 328' in the level 312' is in communication with the apertures in the top surface 308A' of the circulation level 308' such that fluid does not leak between the two levels.

[0120] In the preferred operation, as shown by the arrows in FIGS. 12A and 12H, cooled fluid enters the heat exchanger 300 through the port 316 in the level 312'. The cooled fluid travels down the port 316 to the corridor 328 and flows downward to the interface layer 302 via the delivery channels 322. The cooled fluid in the corridor 320 does not mix or come into contact with any heated fluid exiting the heat exchanger 300. The fluid entering the interface layer 302 undergoes thermal exchange with and absorbs the heat produced in the heat source 99. The apertures 322 are optimally arranged such that the fluid travels the least amount of distance in the X and Y direction in the interface layer 302 to minimize the pressure drop in the heat exchanger 300 while effectively cooling the heat source 99. The heated fluid then travels upward in the Z-direction from the interface layer 302 to the corridor 320 in the level 308. The heated fluid exiting the manifold layer 306 does not mix or come into contact with any cooled fluid entering the manifold layer 306. The heated fluid, upon entering the corridor 320 flows to the ports 314 and 315 and exits the heat exchanger 300. It is apparent to one skilled in the art that the fluid alternatively flows opposite the way shown in FIGS. 12A and 12H without departing from the scope of the present invention.

[0121] In the alternative operation, as shown by the arrows in FIGS. 12B and 12I, cooled fluid enters the heat exchanger 300' through the port 316' in the level 312'. The cooled fluid travels down the port 315' to the port 314' in the level 308'. The fluid then flows into the corridor 320' and



flows downward to the interface layer **302'** via the apertures **322'** in the circulation level **304'**. However, the cooled fluid in the corridor **320'** does not mix or come into contact with any heated fluid exiting the heat exchanger **300'**. The fluid entering the interface layer **302'** undergoes thermal exchange with and absorbs the heat produced in the heat source **99**. As discussed below, the apertures **322'** and apertures **324'** are arranged such that the fluid travels the optimal closest distance along the interface layer **302'** from each aperture **322'** to an adjacent aperture **324'** to reduce the pressure drop therebetween while effectively cooling the heat source **99**. The heated fluid then travels upward in the Z-direction from the interface layer **302'** through the level **308'** via the several apertures **324'** to the corridor **328'** in the level **312'**. The heated fluid does not mix or come into contact with any cooled fluid entering the manifold layer **306'** as it travels up the apertures **324'**. The heated fluid, upon entering the corridor **328'** in the level **312'** flows to the port **316'** and exits the heat exchanger **300'**. It is apparent to one skilled in the art that the fluid alternatively flows opposite the way shown in **FIGS. 12B and 121** without departing from the scope of the present invention.

[0122] In the preferred manifold layer **306**, the apertures **322** are arranged such that the distance which the fluid flows in the interface layer **302** is minimized while adequately cooling the heat source **99**. In the alternative manifold layer **306'**, the apertures **322'** and apertures **324'** are arranged such that the distance which the fluid flows in the interface layer **302'** is minimized while adequately cooling the heat source **99**. Specifically, the and apertures **322'**, **324'** provide substantially vertical fluid paths, such that the flow is minimize in the X and Y lateral directions in the heat exchanger **300'**. Thus, the heat exchanger **300, 300'** greatly reduces the distance that the fluid must flow to adequately cool the heat source **99**, which in turn, greatly reduces the pressure drop generated within the heat exchanger **300, 300'** and system **30, 30'** (**FIGS. 2A-2B**).

[0123] The specific arrangement and cross-sectional sizes of the apertures **322** and/or apertures **324** depend on a variety of factors, including, but not limited to, flow conditions, temperature, heat generated by the heat source **99** and fluid flow-rate. It is noted that although the following discussion relates to apertures **322** and **324**, it is apparent that the discussion also applies to only apertures **322** or apertures **324**.

[0124] The apertures **322, 324** are spaced apart from each other an optimal distance whereby the pressure drop is minimized as the heat source **99** is adequately cooled to a desired temperature. The arrangement and optimal distance of the apertures **322** and/or apertures **324** in the preferred embodiment also allows independent optimization of the apertures **322, 324** and fluid paths, in general, through the interface layer **302** by changing the dimensions and locations of the individual apertures. In addition, the arrangement of the apertures in the preferred embodiment also significantly increases the division of total flow entering the interface layer as well as the amount of area cooled by the fluid entering through each aperture **322**.

[0125] In one embodiment, the apertures **322, 324** are disposed in an alternating configuration or a 'checkerboard' pattern in the manifold layer **306**, as shown in **FIGS. 13 and 14**. Each of the apertures **322, 324** are separated by the least

amount of distance that the fluid must travel in the checkerboard pattern. However, the apertures **322, 324** must be separated a distance large enough from each other to provide the cooling liquid to the interface layer **302** for a sufficient amount of time. As shown in **FIGS. 13 and 14**, it is preferred that one or more of the apertures **322** are disposed adjacent to a corresponding number of apertures or vice versa such that the fluid entering the interface layer **302** travels the least amount of distance along the interface layer **302** before exiting the interface layer **302**. Thus, as shown in the figures, it is preferred that the apertures **322, 324** are radially distributed around each other to assist the fluid in traveling the least amount of distance from any aperture **322** to the closest aperture **324**. For example, as shown in **FIG. 13**, fluid entering the interface layer **302** via one specific aperture **322** experiences the path of least resistance to an adjacent aperture **324**. In addition, the apertures **322, 324** are preferably circular in shape, although the apertures can have any other shape.

[0126] In addition, as stated above, although the apertures **324** shown in the figures protrude from the circulation level **304** or level **308, 312** as a cylindrical member, the apertures alternatively do not protrude from any of the levels in the manifold layer **306**. It is also preferred that the manifold layer **306** has rounded surfaces around the areas where fluid changes direction to aid in reducing the pressure drop in the heat exchanger **300**.

[0127] The optimal distance configuration as well as the dimensions of the apertures **322, 324** depend on the amount of temperature that the fluid is exposed to along the interface layer **302**. It is also important that the cross sectional dimensions for the fluid paths in the apertures **322, 324** are large enough to reduce pressure drop in the heat exchanger **300**. For the case in which fluid experiences only single-phase flow along the interface layer **302**, each aperture **322** is preferably surrounded by several adjacent apertures **324** in a symmetrical hexagonal arrangement, as shown in **FIG. 13**. In addition, for single-phase flow, it is preferred that the number of apertures are approximately equal in the circulation level **304**. Additionally, for single-phase flow, the apertures **322, 324** are preferably the same diameter. It is apparent to one skilled in the art that other arrangements as well as any ratio of apertures **322, 324** are alternatively contemplated.

[0128] For the case in which the fluid experiences two-phase flow along the interface layer **302**, non-symmetric arrangements of the apertures **322, 324** are preferred to accommodate acceleration of the two-phase fluid. However, symmetric arrangements of the apertures **322, 324** are also contemplated for two-phase flow. For instance, the apertures **322, 324** can be symmetrically arranged in the circulation level **304**, whereby the apertures **324** have larger openings than the apertures **322**. Alternatively, the hexagonal symmetrical arrangement shown in **FIG. 13** are used in the circulation level **304** for two-phase flow, whereby more apertures **324** are present in the circulation level **304** than apertures **322**.

[0129] It should be noted that the apertures **322, 324** in the circulation level can alternatively be arranged to cool hot spots in the heat source **99**. Thus, for example, two apertures **322** are alternatively positioned immediately next to each other in the circulation level **304**, whereby both apertures



**322** are positioned near or above an interface hot spot region. It is apparent that the appropriate number of apertures **324** are positioned adjacent to both apertures **322** to reduce the pressure drop in the interface layer **302**. Therefore, the two apertures **322** supply cool fluid to the interface hot spot region to compel the interface hot spot region, discussed above, to be a uniform, substantially equal temperature.

[0130] As stated above, the preferred heat exchanger **300** has significant advantages over other heat exchangers. The configuration of the preferred heat exchanger **300** is alternatively utilized with a modest-performance pump due to the reduction of pressure drop caused by the vertical fluid paths. In addition, the configuration of the preferred heat exchanger **300** allows independent optimization of the inlet, and fluid paths along the interface layer **302**. Additionally, the separate levels allow a customizable design foundation to optimize the uniformity of heat transfer, reduction of pressure drop and dimensions of the individual components therein. The configuration of the preferred heat exchanger **300** also reduces the pressure drop in systems in which the fluid undergoes two phase flow and thereby can be used in single phase and two phase systems. Further, as discussed below, the preferred heat exchanger accommodates many different manufacturing methods and allows adjustment of component geometry for tolerance purposes.

[0131] The details of how the heat exchanger **100** as well as the individual layers in the heat exchanger **100** are fabricated and manufactured are discussed below. The following discussion applies to the preferred and alternative heat exchangers of the present invention, although the heat exchanger **100** in FIG. 3B and individual layers therein are expressly referred to for simplicity. It is also apparent to one skilled in the art that although the fabrication/manufacturing details are described in relation to the present invention, the fabrication and manufacturing details also alternatively apply to conventional heat exchangers as well as two and three-tier heat exchangers utilizing one fluid inlet port and one fluid port as shown in FIGS. 1A-1C.

[0132] Preferably, the interface layer has a coefficient of thermal expansion (CTE) which is approximate or equal to that of the heat source **99**. Thus, the interface layer preferably expands and contracts accordingly with the heat source **99**. Alternatively, the material of the interface layer **302** has a CTE which is different than the CTE of the heat source material. An interface layer **302** made from a material such as Silicon has a CTE that matches that of the heat source **99** and has sufficient thermal conductivity to adequately transfer heat from the heat source **99** to the fluid. However, other materials are alternatively used in the interface layer **302** which have CTEs that match the heat source **99**.

[0133] The interface layer preferably has a high thermal conductivity for allowing sufficient conduction to pass between the heat source **99** and fluid flowing along the interface layer **302** such that the heat source **99** does not overheat. The interface layer is preferably made from a material having a high thermal conductivity of 100 W/m-K. However, it is apparent to one skilled in the art that the interface layer **302** has a thermal conductivity of more or less than 100 W/m-K and is not limited thereto.

[0134] To achieve the preferred high thermal conductivity, the interface layer is preferably made from a semiconductor

substrate, such as Silicon. Alternatively, the interface layer is made from any other material including, but not limited to single-crystalline dielectric materials, metals, aluminum, nickel and copper, Kovar, graphite, diamond, composites and any appropriate alloys. An alternative material of the interface layer **302** is a patterned or molded organic mesh.

[0135] As shown in FIG. 15, it is preferred that the interface layer is coated with a coating layer **112** to protect the material of the interface layer as well as enhance the thermal exchange properties of the interface layer. In particular, the coating **112** provides chemical protection that eliminates certain chemical interactions between the fluid and the interface layer **302**. For example, an interface layer **302** made from aluminum is etched by the fluid coming into contact with it, whereby the interface layer **102** would deteriorate over time. The coating **112** of a thin layer of Nickel, approximately 25 microns, is thus electroplated over the surface of the interface layer **302** to chemically pacify any potential reactions without significantly altering the thermal properties of the interface layer **302**. It is apparent that any other coating material with appropriate layer thickness is contemplated depending on the material(s) in the interface layer **302**.

[0136] The interface layer **302** is formed by an etching process using a Copper material coated with a thin layer of Nickel to protect the interface layer **302**. Alternatively, the interface layer **302** is made from Aluminum, Silicon substrate, plastic or any other appropriate material. The interface layer **302** being made of materials having poor thermal conductivity are also coated with the appropriate coating material to enhance the thermal conductivity of the interface layer **302**. One method of electroforming the interface layer is by applying a seed layer of chromium or other appropriate material along the bottom surface of the interface layer **302** and applying electrical connection of appropriate voltage to the seed layer. The electrical connection thereby forms a layer of the thermally conductive coating material **112** on top of the interface layer **302**. The electroforming process also forms feature dimensions in a range of 10-100 microns. The interface layer **302** is formed by an electroforming process, such as patterned electroplating. In addition, the interface layer is alternatively processed by photochemical etching or chemical milling, alone or in combination, with the electroforming process. Standard lithography sets for chemical milling are used to process features in the interface layer **302**. Additionally, the aspect ratios and tolerances are enhanceable using laser assisted chemical milling processes.

[0137] The pillars **303** discussed above are manufactured a variety of methods. However, it should be noted that the pillars **303** are manufactured to have a high thermal conductivity. It is preferred that the pillars **303** are made with a highly conductive material such as Copper. However, other materials, such as Silicon are contemplated by one skilled in the art. The pillars **303** are manufactured by various means including, but not limited to, electroforming, EDM wire manufacturing, stamping, MIM and machining. In addition, cross-cutting with saws and/or milling tools can also produce the desired configuration in the interface layer **302**. For an interface layer **302** made of Silicon, the pillars **303** would be manufactured by methods such as plasma etching, sawing, lithographic patterning and various wet etching depending on the desired aspect ratio of pillars **303** in the interface layer **302**. The radially distributed rectangular fins **303E**



(FIG. 10E) can be manufactured by lithographic patterning whereby plasma etching or electroplating methods are employed within the lithographically defined molds.

[0138] In the alternative embodiment, microchannel walls 110 used in the interface layer 102 are made of Silicon. The microchannel walls 110 are alternatively made of any other materials including, but not limited to, patterned glass, polymer, and a molded polymer mesh. Although the microchannel walls 110 are made from the same material as that of the bottom surface 103 of the interface layer 102, the microchannel walls 110 are alternatively made from a different material than that of the rest of the interface layer 102.

[0139] In the alternative embodiment, the microchannel walls 110 have thermal conductivity characteristics of at least 10 W/m-K. Alternatively, the microchannel walls 110 have thermal conductivity characteristics of more than 10 W/m-K. It is apparent to one skilled in the art that the microchannel walls 110 alternatively have thermal conductivity characteristics of less than 10 W/m-K, whereby coating material 112 is applied to the microchannel walls 110, as shown in FIG. 15, to increase the thermal conductivity of the wall features 110. For microchannel walls 110 made from materials already having a good thermal conductivity, the coating 112 applied has a thickness of at least 25 microns which also protects the surface of the microchannel walls 110. For microchannel walls 110 made from material having poor thermal conductivity characteristics, the coating 112 has a thermal conductivity of at least 50 W/m-K and is more than 25 microns thick. It is apparent to one skilled in the art that other types of coating materials as well as thickness dimensions are contemplated.

[0140] To configure the microchannel walls 110 to have an adequate thermal conductivity of at least 10 W/m-K, the walls 110 are electroformed with the coating material 112 (FIG. 15), such as Nickel or other metal, as discussed above. To configure the microchannel walls 110 to have an adequate thermal conductivity of at least 50 W/m-K, the walls 110 are electroplated with Copper on a thin metal film seed layer. Alternatively, the microchannel walls 110 are not coated with the coating material. It is understood that the thermal conductivity characteristics of the microchannel walls 110 and the coating 112, when appropriate, also apply to the pillars 303 (FIG. 10A) and any appropriate coating applied thereon.

[0141] The microchannel walls 110 are formed by a hot embossing technique to achieve a high aspect ratio of channel walls 110 along the bottom surface 103 of the interface layer 102. The microchannel wall features 110 are alternatively fabricated as Silicon structures deposited on a glass surface, whereby the features are etched on the glass in the desired configuration. The microchannel walls 110 are alternatively formed by a standard lithography techniques, stamping or forging processes, or any other appropriate method. The microchannel walls 110 are alternatively made separately from the interface layer 102 and coupled to the interface layer 102 by anodic or epoxy bonding. Alternatively, the microchannel features 110 are coupled to the interface layer 102 by conventional electroforming techniques, such as electroplating.

[0142] There are a variety of methods that can be used to fabricate the intermediate layer 104. The intermediate layer is made from Silicon. It is apparent to one skilled in the art

that any other appropriate material is contemplated including, but not limited to glass, laser-patterned glass, polymers, metals, glass, plastic, molded organic material or any composites thereof. Alternatively, the intermediate layer 104 is formed using plasma etching techniques. Alternatively, the intermediate layer 104 is formed using a chemical etching technique. Other alternative methods include machining, etching, extruding and/or forging a metal into the desired configuration. The intermediate layer 104 is alternatively formed by injection molding of a plastic mesh into the desired configuration. Alternatively, the intermediate layer 104 is formed by laser-drilling a glass plate into the desired configuration.

[0143] The manifold layer 306 is manufactured by a variety of methods. The preferred manifold layer 306 is manufactured as one entire piece. Alternatively, the preferred manifold layer 306 is manufactured as separate components shown in FIG. 12 which are then coupled together. The manifold layer 306 can be fabricated is an injection molding process utilizing plastic, metal, polymer composite or any other appropriate material, whereby each layer is made from the same material. Alternatively, as discussed above, each layer is made from a different material. The manifold layer 306 is alternatively generated using a machined or etched metal technique. It is apparent to one skilled in the art that the manifold layer 306 is manufactured utilizing any other appropriate method.

[0144] The intermediate layer 104 is coupled to the interface layer 102 and manifold layer 106 to form the heat exchanger 100 using a variety of methods. The interface layer 102, intermediate layer 104 and manifold layer 106 are coupled to one another by an anodic, adhesive or eutectic bonding process. The intermediate layer 104 is alternatively integrated within features of the manifold layer 106 and interface layer 102. The intermediate layer 104 is coupled to the interface layer 102 by a chemical bonding process. The intermediate layer 104 is alternatively manufactured by a hot embossing or soft lithography technique, whereby a wire EDM or Silicon master is utilized to stamp the intermediate layer 104. The intermediate layer 104 is then alternatively electroplated with metal or another appropriate material to enhance the thermal conductivity of the intermediate layer 104, if needed.

[0145] Alternatively, the intermediate layer 104 is formed along with the fabrication of the 10 microchannel walls 110 in the interface layer 102 by an injection molding process. Alternatively, the intermediate layer 104 is formed with the fabrication of the microchannel walls 110 by any other appropriate method. Other methods of forming the heat exchanger include, but are not limited to soldering, fusion bonding, eutectic Bonding, intermetallic bonding, and any other appropriate technique, depending on the types of materials used in each layer.

[0146] Another alternative method of manufacturing the heat exchanger of the present invention is described in FIG. 16. As discussed in relation to FIG. 16, an alternative method of manufacturing the heat exchanger includes building a hard mask formed from a silicon substrate as the interface layer (step 500). The hard mask is made from silicon dioxide or alternatively spin-on-glass. Once the hard mask is formed, a plurality of under-channels are formed in the hard mask, wherein the under-channels form the fluid



paths between the microchannel walls **110** (step **502**). The under-channels are formed by any appropriate method, including but not limited to HF etching techniques, chemical milling, soft lithography and xenon difluoride etch. In addition, enough space between each under-channel must be ensured such that under-channels next to one another do not bridge together. Thereafter, spin-on-glass is then applied by any conventional method over the top surface of the hard mask to form the intermediate and manifold layers (step **504**). Following, the intermediate and manifold layers are hardened by a curing method (step **506**). Once the intermediate and manifold layers are fully formed and hardened, one or more fluid ports are formed into the hardened layer (step **508**). The fluid ports are etched or alternatively drilled into the manifold layer. Although specific methods of fabricating the interface layer **102**, the intermediate layer **104** and manifold layer **106** are discussed herein, other known methods known in art to manufacture the heat exchanger **100** are alternatively contemplated.

[0147] **FIG. 17** illustrates an alternative embodiment of the heat exchanger of the present invention. As shown in **FIG. 6**, two heat exchangers **200, 200'** are coupled to one heat source **99**. In particular, the heat source **99**, such as an electronic device, is coupled to a circuit board **96** and is positioned upright, whereby each side of the heat source **99** is potentially exposed. A heat exchanger of the present invention is coupled to one exposed side of the heat source **99**, whereby both heat exchangers **200, 200'** provide maximum cooling of the heat source **99**. Alternatively, the heat source is coupled to the circuit board horizontally, whereby more than one heat exchanger is stacked on top of the heat source **99** (not shown), whereby each heat exchanger is electrically coupled to the heat source **99**. More details regarding this embodiment are shown and described in co-pending U.S. patent application Ser. No. 10/072,137, filed Feb. 7, 2002, entitled "POWER CONDITIONING MODULE" which is hereby incorporated by reference.

[0148] As shown in **FIG. 17**, the heat exchanger **200** having two layers is coupled to the left side of the heat source **99** and the heat exchanger **200'** having three layers is coupled to the right side of the heat source **99**. It is apparent to one skilled in the art that the heat exchangers are coupled to the sides of the heat source **99**. It is also apparent to one skilled in the art that the alternative embodiments of the heat exchanger **200'** are alternatively coupled to the sides of the heat source **99**. The alternative embodiment shown in **FIG. 17** allows more precise hot spot cooling of the heat source **99** by applying fluid to cool hot spots which exist along the thickness of the heat source **99**. Thus, the embodiment in **FIG. 17** applies adequate cooling to hot spots in the center of the heat source **99** by exchanging heat from both sides of the heat source **99**. It is apparent to one skilled in the art that the embodiment shown in **FIG. 17** is used with the cooling system **30** in **FIGS. 2A-2B**, although other closed loop systems are contemplated.

[0149] As stated above, the heat source **99** alternatively has characteristics in which the locations of one or more of the hot spots change due to different tasks required to be performed by the heat source **99**. To adequately cool the heat source **99**, the system **30** alternatively includes a sensing and control module **34** (**FIGS. 2A-2B**) which dynamically

changes the amount of flow and/or flow rate of fluid entering the heat exchanger **100** in response to a change in location of the hot spots.

[0150] In particular, as shown in **FIG. 17**, one or more sensors **124** are placed in each interface hot spot region in the heat exchanger **200** and/or alternatively the heat source **99** at each potential hot spot location. Alternatively, a plurality of heat sources are uniformly placed in between the heat source and heat exchanger and/or in the heat exchanger itself. The control module **38** (**FIG. 2A-2B**) is also coupled to one or more valves in the loop **30** which control the flow of fluid to the heat exchanger **100**. The one or more valves are positioned within the fluid lines, but are alternatively positioned elsewhere. The plurality of sensors **124** are coupled to the control module **34**, whereby the control module **34** is preferably placed upstream from heat exchanger **100**, as shown in **FIG. 2**. Alternatively, the control module **34** is placed at any other location in the closed loop system **30**.

[0151] The sensors **124** provide information to the control module **34** including, but not limited to, the flow rate of fluid flowing in the interface hot spot region, temperature of the interface layer **102** in the interface hot spot region and/or heat source **99** and temperature of the fluid. For example, referring to the schematic in **FIG. 17**, sensors positioned on the interface **124** provide information to the control module **34** that the temperature in a particular interface hot spot region in heat exchanger **200** is increasing whereas the temperature in a particular interface hot spot region in heat exchanger **200'** is decreasing. In response, the control module **34** increases the amount of flow to heat exchanger **200** and decreases the amount of flow provided to heat exchanger **200'**. Alternatively, the control module **34** alternatively changes the amount of flow to one or more interface hot spot regions in one or more heat exchangers in response to the information received from the sensors **118**. Although the sensors **118** are shown with the two heat exchangers **200, 200'** in **FIG. 17**, it is apparent that the sensors **118** are alternatively coupled with only one heat exchanger.

[0152] The present invention has been described in terms of specific embodiments incorporating details to facilitate the understanding of the principles of construction and operation of the invention. Such reference herein to specific embodiments and details thereof is not intended to limit the scope of the claims appended hereto. It will be apparent to those skilled in the art that modifications may be made in the embodiment chosen for illustration without departing from the spirit and scope of the invention.

What is claimed is:

1. A heat exchanger comprising:

- a. an interface layer in contact with the heat source and configured to pass fluid therethrough to cool the heat source, the interface layer includes a thickness within a range of about 0.3 to about 1.0 millimeters; and
- b. a manifold layer coupled to the interface layer, the manifold layer further comprising a first set of individualized fluid paths for channeling fluid to the interface layer, the individual fluid paths in the first set positioned to minimize pressure drop within the heat exchanger.



**2.** The heat exchanger according to claim 1 wherein the manifold layer further comprises a second set of individualized fluid paths for channeling fluid from the interface layer.

**3.** The heat exchanger according to claim 2 wherein the manifold layer further comprises a first port for providing fluid to the first set of individualized fluid paths and a second port for removing fluid channeled from the second set of individualized fluid paths.

**4.** The heat exchanger according to claim 1 wherein the first set of fluid paths are arranged to provide a minimized fluid path distance along the interface layer to cool a predetermined region of the heat source to a desired temperature.

**5.** The heat exchanger according to claim 3 wherein the first set and second set of fluid paths are arranged to provide a minimized fluid path distance between the first and second ports to cool a predetermined region of the heat source to a desired temperature.

**6.** The heat exchanger according to claim 1 wherein the fluid is in single phase flow conditions.

**7.** The heat exchanger according to claim 1 wherein at least a portion of the fluid is in two phase flow conditions.

**8.** The heat exchanger according to claim 1 wherein at least a portion of the fluid undergoes a transition between single and two phase flow conditions in the heat exchanger.

**9.** The heat exchanger according to claim 2 wherein the manifold layer further comprises a circulation level having the first and second fluid paths extending therethrough, the circulation level coupled to the interface layer and configured to separably channel fluid to and from the interface layer via the first and second set of fluid paths.

**10.** The heat exchanger according to claim 9 wherein each of the fluid paths in the first set include a cylindrical protrusion in communication therewith, each cylindrical protrusion extending from the circulation level at a predetermined height.

**11.** The heat exchanger according to claim 3 wherein the manifold layer further comprises

- a. a first level configured to channel fluid between the first port and the first set of fluid paths; and
- b. a second level coupled to the first level and configured to channel fluid between the second port and the second set of fluid paths wherein fluid channeled via the first level is kept separate from the fluid channeled via the second level in the manifold layer.

**12.** The heat exchanger according to claim 11 wherein the first level further comprises a first corridor in communication with the first port and the first set of fluid paths, wherein fluid in the first corridor flows directly to the first set of fluid paths.

**13.** The heat exchanger according to claim 11 wherein the second level further comprises a second corridor in communication with the second port and the second set of fluid paths wherein fluid in the second set flows directly to the second corridor.

**14.** The heat exchanger according to claim 2 wherein the first set of fluid paths are thermally insulated from the second set of fluid paths to prevent heat transfer therebetween.

**15.** The heat exchanger according to claim 2 wherein the first set and the second set of fluid paths are arranged in a uniform manner along at least one dimension.

**16.** The heat exchanger according to claim 2 wherein the first set and second set of fluid paths are arranged in a non-uniform manner along at least one dimension.

**17.** The heat exchanger according to claim 1 wherein each fluid paths in the first set is positioned a closest optimal distance to one another.

**18.** The heat exchanger according to claim 2 wherein the first set and second set of fluid paths are positioned to cool at least one interface hot spot region in the heat source.

**19.** The heat exchanger according to claim 2 wherein at least one of the first fluid paths flows via a plurality of first holes, wherein at least one first hole in the plurality has a first dimension substantially equivalent to a second dimension of at least one hole in the second set of fluid paths.

**20.** The heat exchanger according to claim 2 wherein at least one of the first fluid paths flows via a plurality of first holes, wherein at least one first hole in the plurality has a first dimension different than a second dimension of at least one second hole in the second set of fluid paths.

**21.** The heat exchanger according to claim 1 wherein the interface layer is made of a material having a thermal conductivity of at least 100 W/mk.

**22.** The heat exchanger according to claim 1 wherein the interface layer includes a coating thereupon, wherein the coating provides an appropriate thermal conductivity of at least 10 W/m-K.

**23.** The heat exchanger according to claim 1 wherein the interface layer further comprises a plurality of pillars configured in a predetermined pattern along the interface layer.

**24.** The heat exchanger according to claim 23 wherein at least one of the plurality of pillars has an area dimension within the range of and including  $(10 \text{ micron})^2$  and  $(100 \text{ micron})^2$ .

**25.** The heat exchanger according to claim 23 wherein at least one of the plurality of pillars has a height dimension within the range of and including 50 microns and 2 millimeters.

**26.** The heat exchanger according to claim 23 wherein at least two of the plurality of pillars are separate from each other by a spacing dimension within the range of and including 10 to 150 microns.

**27.** The heat exchanger according to claim 23 wherein the plurality of pillars include a coating thereupon, wherein the coating has an appropriate thermal conductivity of at least 10 W/m-K.

**28.** The heat exchanger according to claim 23 wherein at least one of the plurality of pillars includes at least varying dimension along a predetermined direction.

**29.** The heat exchanger according to claim 23 wherein an appropriate number of pillars are disposed in a predetermined area along the interface layer.

**30.** The heat exchanger according to claim 1 wherein at least a portion of the interface layer has a roughened surface.

**31.** The heat exchanger according to claim 23 wherein the plurality of pillars include a coating thereupon, wherein the coating has an appropriate thermal conductivity of at least 10 W/m-K.

**32.** The heat exchanger according to claim 1 further comprising a porous microstructure disposed along the interface layer.

**33.** The heat exchanger according to claim 32 wherein the porous microstructure has a porosity within the range of and including 50 to 80 percent.



**34.** The heat exchanger according to claim 32 wherein the porous microstructure has an average pore size within the range of and including 10 to 200 microns.

**35.** The heat exchanger according to claim 32 wherein the porous microstructure has a height dimension within the range of and including 0.25 to 2.00 millimeters.

**36.** The heat exchanger according to claim 32 wherein the porous microstructure includes at least one pore having a varying dimension along a predetermined direction.

**37.** The heat exchanger according to claim 1 further comprising a plurality of microchannels disposed in a predetermined configuration along the interface layer.

**38.** The heat exchanger according to claim 37 wherein at least one of the plurality of microchannels has an area dimension within the range of and including  $(10 \text{ micron})^2$  and  $(100 \text{ micron})^2$ .

**39.** The heat exchanger according to claim 37 wherein at least one of the plurality of microchannels has a height dimension within the range of and including 50 microns and 2 millimeters.

**40.** The heat exchanger according to claim 37 wherein at least two of the plurality of microchannels are separate from each other by a spacing dimension within the range of and including 10 to 150 microns.

**41.** The heat exchanger according to claim 37 wherein at least one of the plurality of microchannels has a width dimension within the range of and including 10 to 100 microns.

**42.** The heat exchanger according to claim 37 wherein the plurality of microchannels include a coating thereupon, wherein the coating has an appropriate thermal conductivity of at least 10 W/m-K.

**43.** The heat exchanger according to claim 1 wherein the interface layer is coupled to the heat source.

**44.** The heat exchanger according to claim 1 wherein the interface layer is integrally formed to the heat source.

**45.** The heat exchanger according to claim 1 wherein the heat source is an integrated circuit.

**46.** The heat exchanger according to claim 1 wherein an overhang dimension is within the range of and including 0 to 15 millimeters.

**47.** A heat exchanger configured to cool a heat source comprising:

- a. an interface layer in contact with the heat source and configured to pass fluid therethrough, the interface layer includes a thickness within a range of about 0.3 to about 1.0 millimeters; and
- b. a manifold layer coupled to the interface layer, the manifold layer further comprising:
  - i. a first level having a plurality of substantially vertical inlet paths for delivering fluid to the interface layer, wherein the inlet paths are arranged an optimal fluid travel distance from one another other; and
  - ii. a second level having at least one outlet path for removing fluid from the interface layer.

**48.** The heat exchanger according to claim 47 wherein the first level further comprises at least one first port configured to channel fluid to the inlet paths.

**49.** The heat exchanger according to claim 48 wherein the second level further comprises at least one second port

configured to channel fluid from the at least one outlet path, wherein fluid in the second level flows separately from the fluid in the first level.

**50.** The heat exchanger according to claim 49 wherein the second level further comprises a plurality of substantially vertical outlet paths for removing fluid from the interface layer, the plurality of inlet and outlet paths arranged an optimal fluid travel distance apart from each other.

**51.** The heat exchanger according to claim 50 wherein the manifold layer further comprises a circulation level coupled to the interface layer and having a plurality of first apertures extending vertically therethrough for channeling fluid along the inlet paths to the interface layer and a plurality of second apertures extending vertically therethrough for channeling fluid along the at least outlet path from the interface layer.

**52.** The heat exchanger according to claim 51 wherein the first level further comprises an inlet fluid corridor within for horizontally channeling fluid from the first port to the first apertures.

**53.** The heat exchanger according to claim 52 wherein the second level further comprises an outlet fluid corridor for horizontally channeling fluid from the second apertures to the second port.

**54.** The heat exchanger according to claim 51 wherein the first and second apertures are individually arranged in a uniform manner along at least one dimension.

**55.** The heat exchanger according to claim 51 wherein the first and second fluid apertures are individually arranged in a non-uniform manner along at least one dimension.

**56.** The heat exchanger according to claim 47 wherein the inlet paths and the at least one outlet paths are separately sealed from one another in the manifold layer.

**57.** The heat exchanger according to claim 47 wherein the interface layer is coupled to the heat source.

**58.** The heat exchanger according to claim 47 wherein the interface layer is integrally formed to the heat source.

**59.** The heat exchanger according to claim 47 wherein the heat source is an integrated circuit.

**60.** The heat exchanger according to claim 51 wherein the first and second apertures are arranged to cool at least one interface hot spot cooling region in the heat source.

**61.** The heat exchanger according to claim 51 wherein at least one of the first apertures has an inlet dimension substantially equivalent to an outlet dimension of at least one second apertures in the plurality.

**62.** The heat exchanger according to claim 51 wherein at least one of the first apertures has an inlet dimension different than an outlet dimension of at least one of the second apertures in the plurality.

**63.** The heat exchanger according to claim 47 wherein the interface layer is made of a material having a thermal conductivity of at least 100 W/mk.

**64.** The heat exchanger according to claim 47 wherein the interface layer includes a coating thereupon, wherein the coating provides an appropriate thermal conductivity of at least 10 W/m-K.

**65.** The heat exchanger according to claim 47 wherein the interface layer further comprises a plurality of pillars disposed thereon in an appropriate pattern.

**66.** The heat exchanger according to claim 65 wherein at least one of the plurality of pillars has an area dimension within the range of and including  $(10 \text{ micron})^2$  and  $(100 \text{ micron})^2$ .



**67.** The heat exchanger according to claim 65 wherein at least one of the plurality of pillars has a height dimension within the range of and including 50 microns and 2 millimeters.

**68.** The heat exchanger according to claim 65 wherein at least two of the plurality of pillars are separate from each other by a spacing dimension within the range of and including 10 to 150 microns.

**69.** The heat exchanger according to claim 65 wherein the plurality of pillars include a coating thereupon, wherein the coating has an appropriate thermal conductivity of at least 10 W/m-K.

**70.** The heat exchanger according to claim 65 wherein at least one of the plurality of pillars includes at least varying dimension along a predetermined direction.

**71.** The heat exchanger according to claim 65 wherein an appropriate number of pillars are disposed in a predetermined area along the interface layer.

**72.** The heat exchanger according to claim 47 wherein at least a portion of the interface layer has a roughened surface.

**73.** The heat exchanger according to claim 65 wherein the plurality of pillars include a coating thereupon, wherein the coating has an appropriate thermal conductivity of at least 10 W/m-K.

**74.** The heat exchanger according to claim 47 further comprising a porous microstructure disposed along the interface layer.

**75.** The heat exchanger according to claim 74 wherein the porous microstructure has a height dimension within the range of and including 0.25 to 2.00 millimeters.

**76.** The heat exchanger according to claim 74 wherein the porous microstructure includes at least one pore having a varying dimension along a predetermined direction.

**77.** The heat exchanger according to claim 74 wherein an average pore size in the porous microstructure is within the range and including 10 microns and 200 microns.

**78.** The heat exchanger according to claim 74 wherein the porous microstructure has a porosity in the range and including 50 to 80 percent.

**79.** The heat exchanger according to claim 47 wherein the interface layer further comprises a plurality of microchannels disposed thereon in an appropriate pattern.

**80.** The heat exchanger according to claim 79 wherein at least one of the plurality of microchannels has an area dimension within the range of and including  $(10 \text{ micron})^2$  and  $(100 \text{ micron})^2$ .

**81.** The heat exchanger according to claim 79 wherein at least one of the plurality of microchannels has a height dimension within the range of and including 50 microns and 2 millimeters.

**82.** The heat exchanger according to claim 79 wherein at least two of the plurality of microchannels are separate from each other by a spacing dimension within the range of and including 10 to 150 microns.

**83.** The heat exchanger according to claim 79 wherein at least one of the plurality of microchannels has a width dimension within the range of and including 10 to 100 microns.

**84.** The heat exchanger according to claim 79 wherein the plurality of microchannels include a coating thereupon, wherein the coating has an appropriate thermal conductivity of at least 10 W/m-K.

**85.** The heat exchanger according to claim 47 wherein an overhang dimension is within the range of and including 0 to 15 millimeters.

**86.** The heat exchanger according to claim 51 further comprising a plurality of cylindrical protrusions extending an appropriate height from the circulation level, each protrusion in communication with the first apertures.

**87.** An electronic device which produces heat comprising:

a. an integrated circuit;

b. an interface layer for cooling heat produced by the electronic device, wherein the interface layer includes a thickness within a range of about 0.3 to about 1.0 millimeters, the interface layer integrally formed with the integrated circuit and configured to pass fluid therethrough; and

c. a manifold layer for circulating fluid with the interface layer, the manifold layer having at least one inlet fluid path for delivering fluid to the interface layer and at least one outlet fluid path for removing fluid from the interface layer, the at least one inlet fluid path and the at least one outlet fluid path arranged to provide an optimal minimum fluid travel distance apart from each other.

**88.** A closed loop system for cooling at least one integrated circuit comprising:

a. at least one heat exchanger for absorbing heat generated by the integrated circuit, the heat exchanger further comprising:

i. an interface layer in contact with the integrated circuit and configured to pass fluid therethrough, the interface layer includes a thickness within a range of about 0.3 to about 1.0 millimeters; and

ii. a manifold layer coupled to the interface layer, the manifold layer having at least one inlet fluid path for delivering fluid to the interface layer and at least one outlet fluid path for removing fluid from the interface layer, the at least inlet fluid path and the at least one outlet fluid path arranged to provide an optimal minimum fluid travel distance apart from each other;

b. at least one pump for circulating fluid throughout the loop, the pump coupled to the at least one heat exchanger; and

c. at least one heat rejector coupled to the pump and the heat exchanger, the heat rejector for cooling heated liquid output from the heat exchanger.

\* \* \* \* \*