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(54) **SURFACE MICROMACHINED  
MECHANICAL MICROPUMPS AND FLUID  
SHEAR MIXING, LYSING, AND  
SEPARATION MICROSYSTEMS**

**Related U.S. Application Data**

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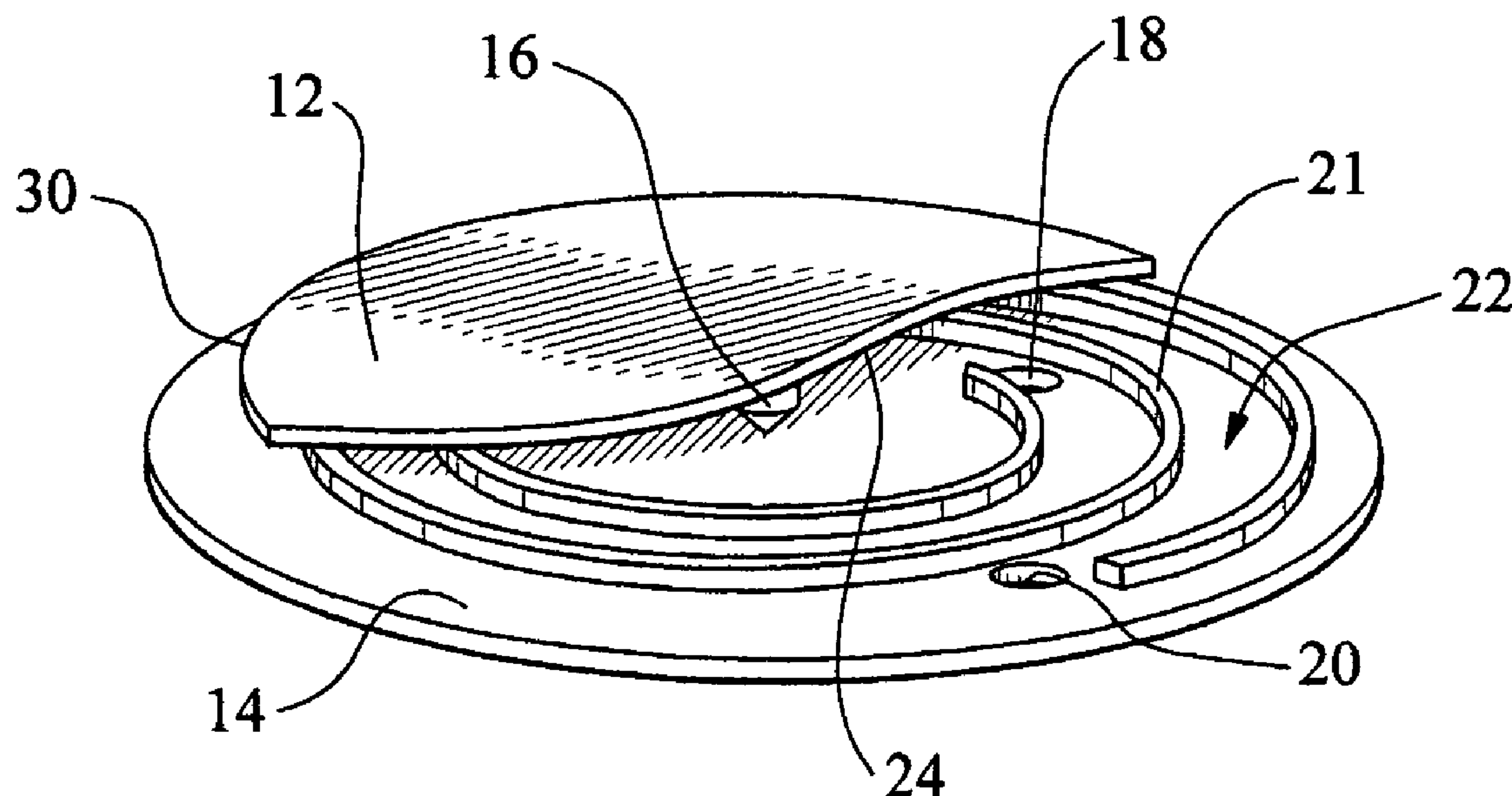
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**ABSTRACT**

A micropump formed from a monolithic body and rotatable disc contained within the body. The rotatable disc may include one or more protrusions for drawing a fluid through an inlet and expelling it through an outlet. The protrusions may be formed in a spiral formation, extend as radial vanes from a central point, or have another configuration. The micropump may have a thickness no more than about 12 microns. In other embodiments, the rotatable disk includes one or more gears that utilize positive displacement to pump fluids. The micropump may be used with other microelectromechanical systems and devices.

(21) Appl. No.: **10/697,412**

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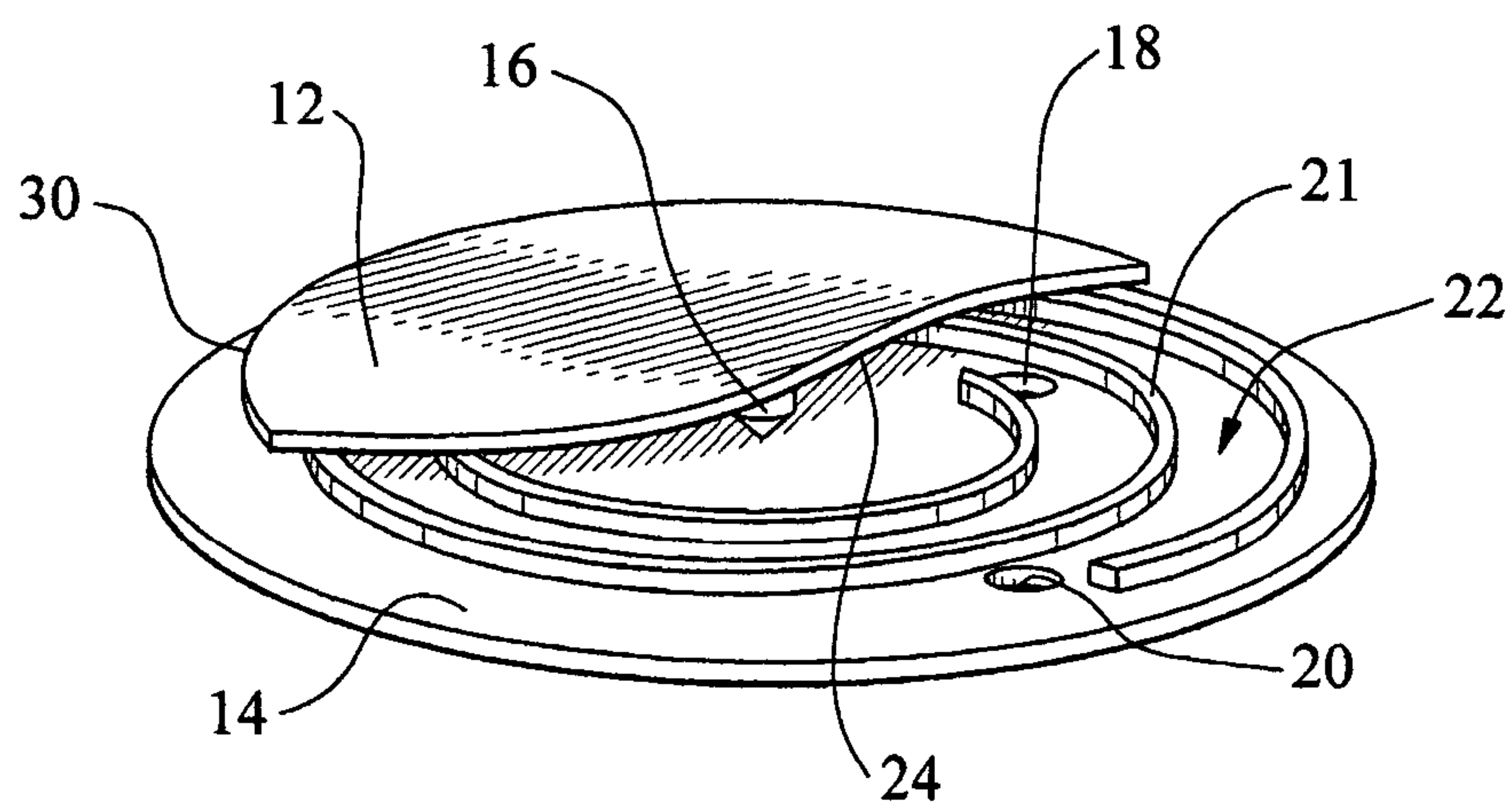


FIG. 1

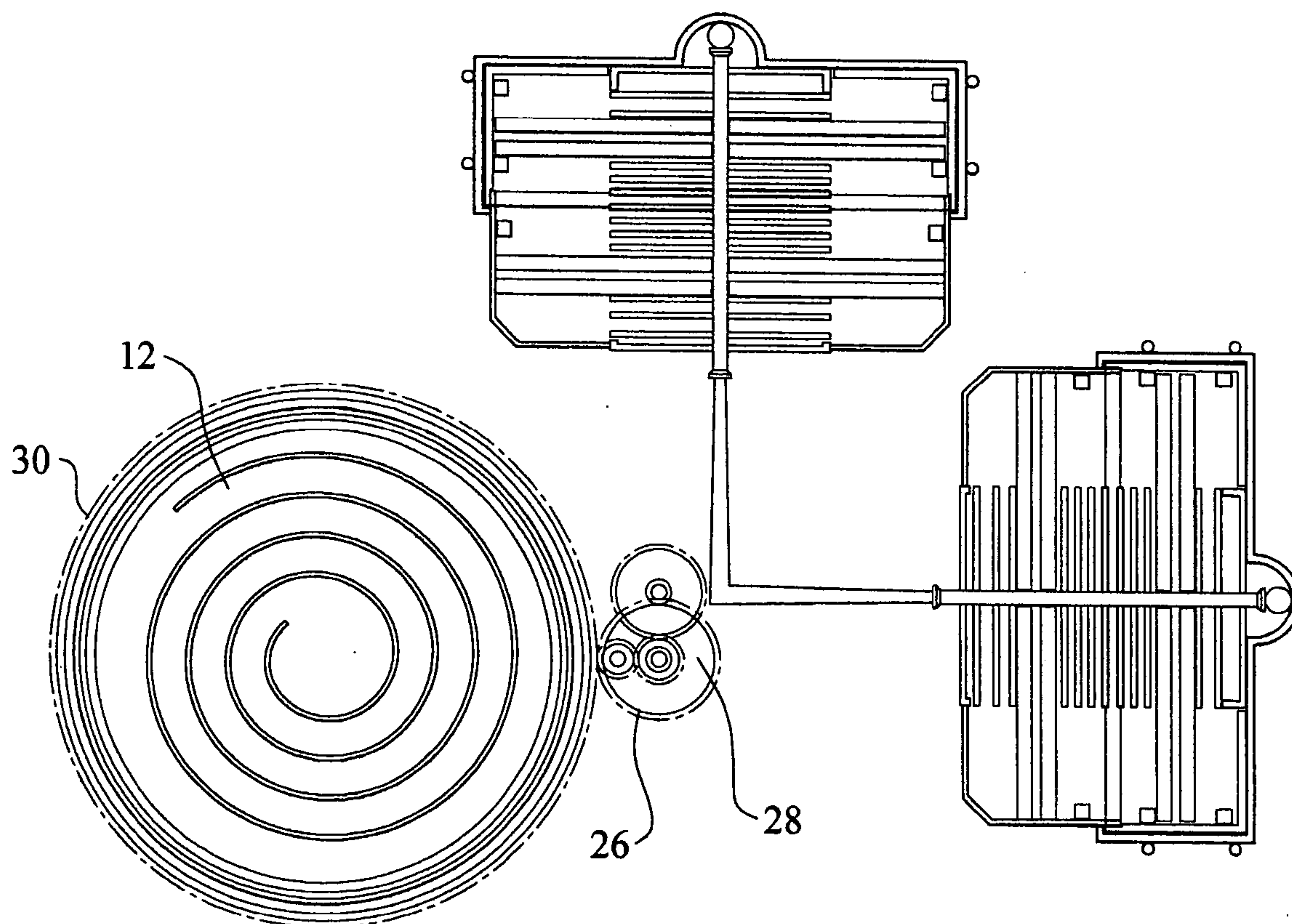


FIG. 2

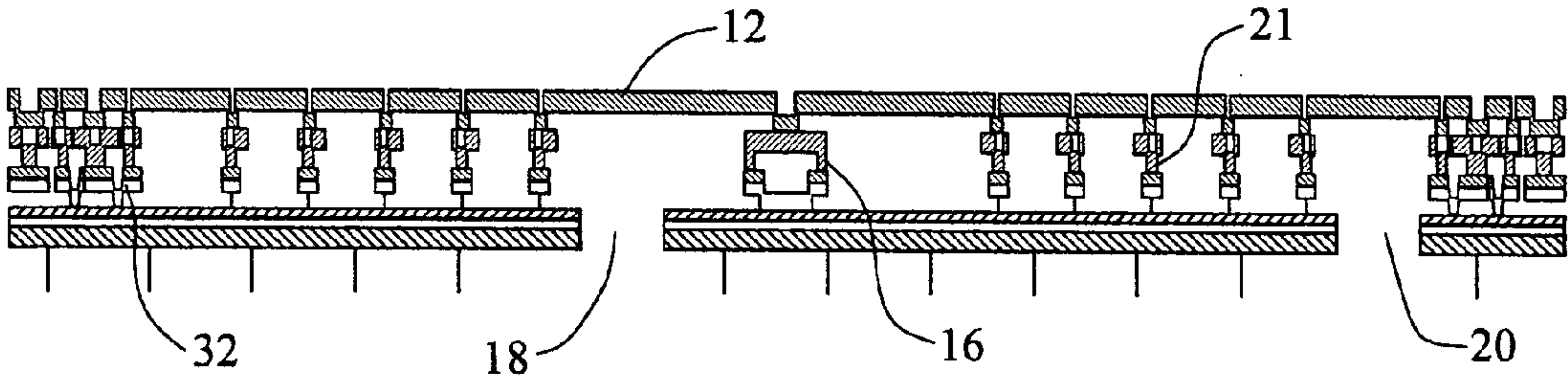


FIG. 3

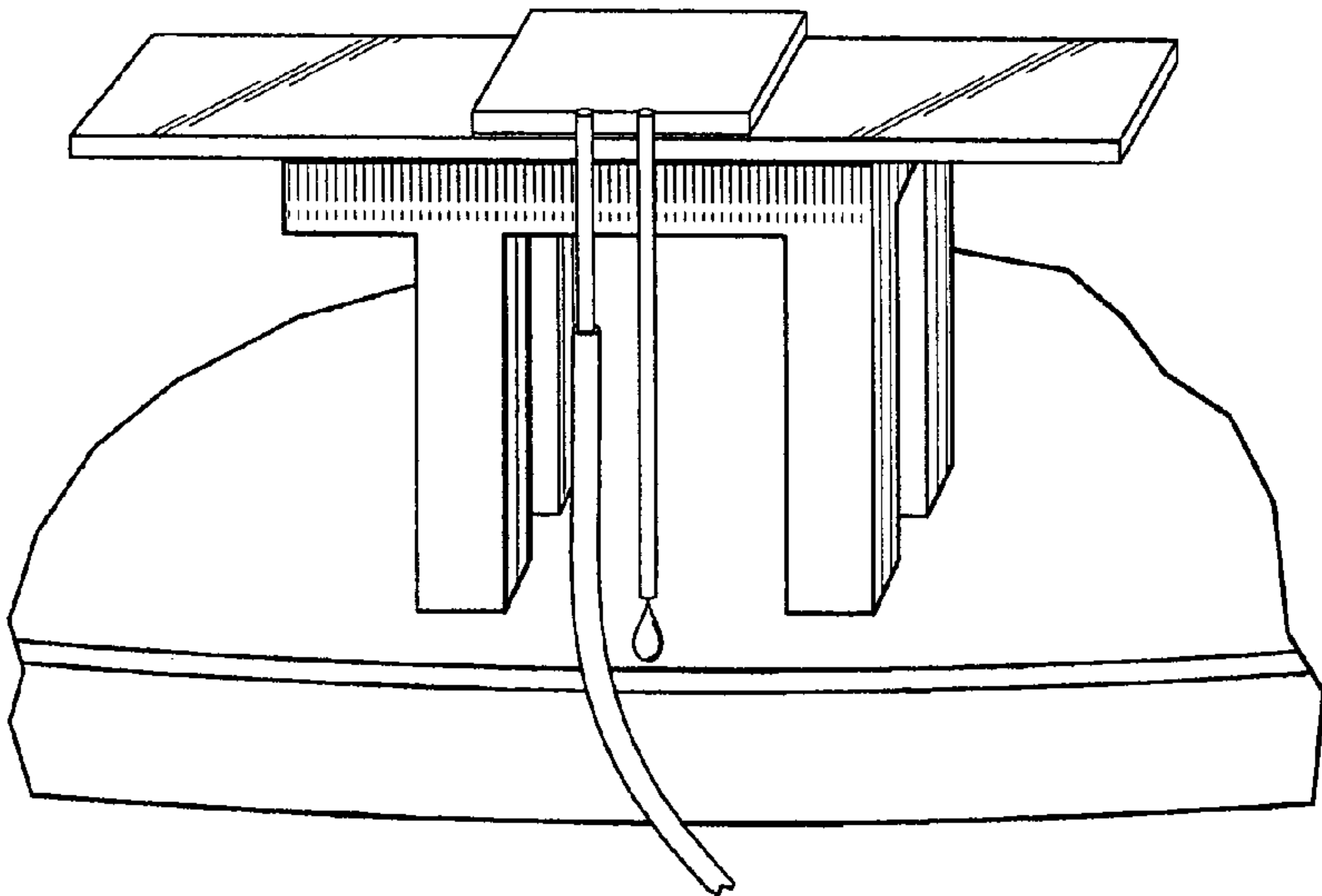


FIG. 4

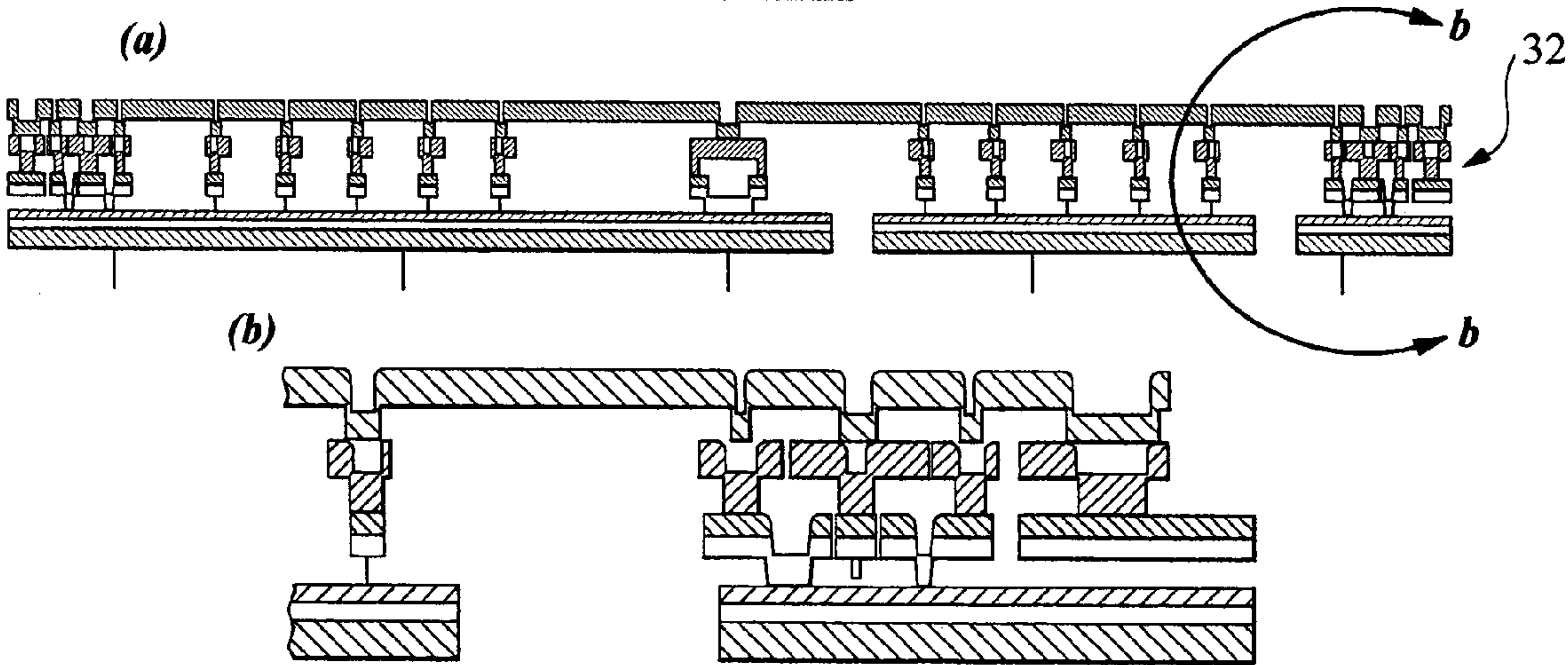


FIG. 5



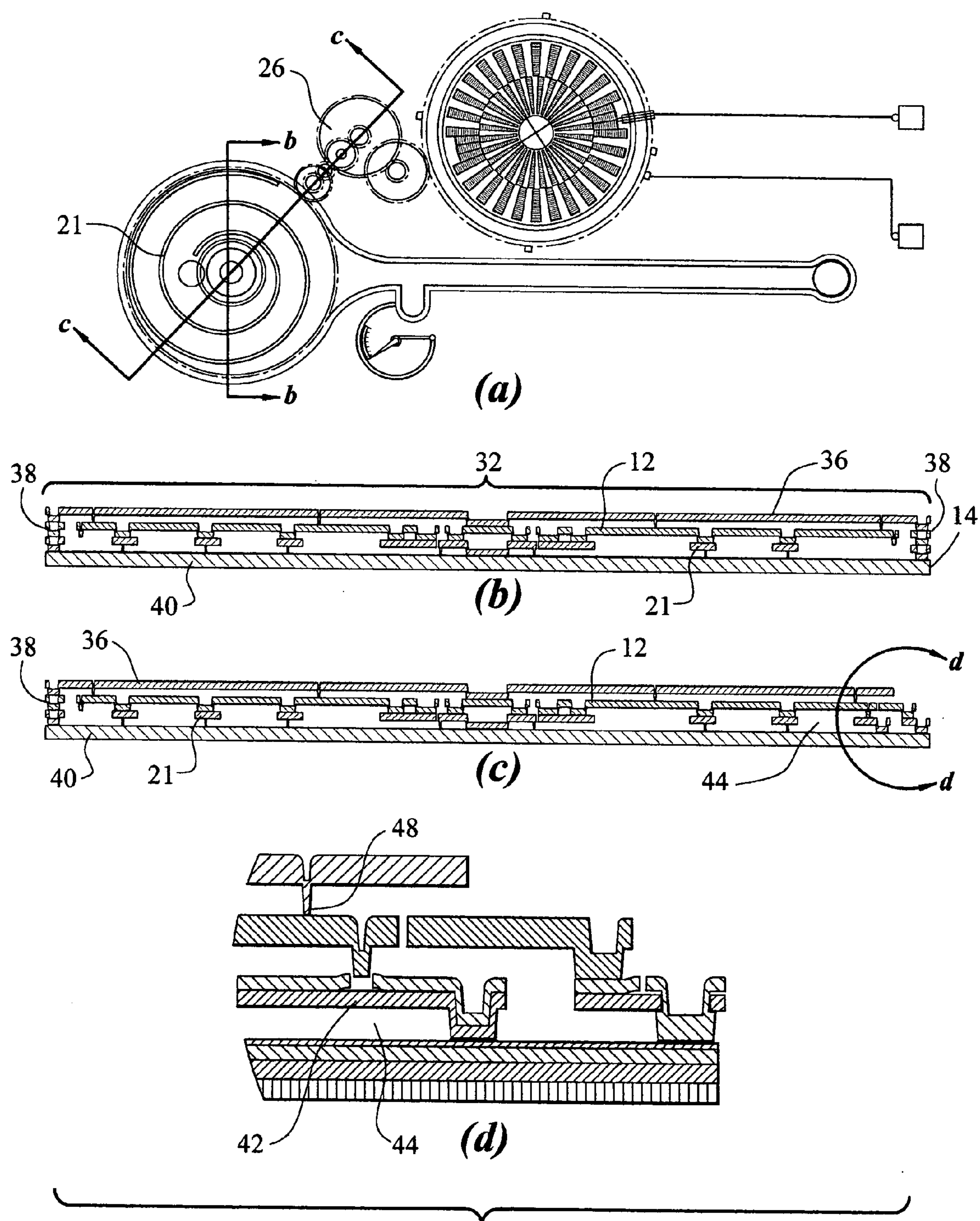


FIG. 6

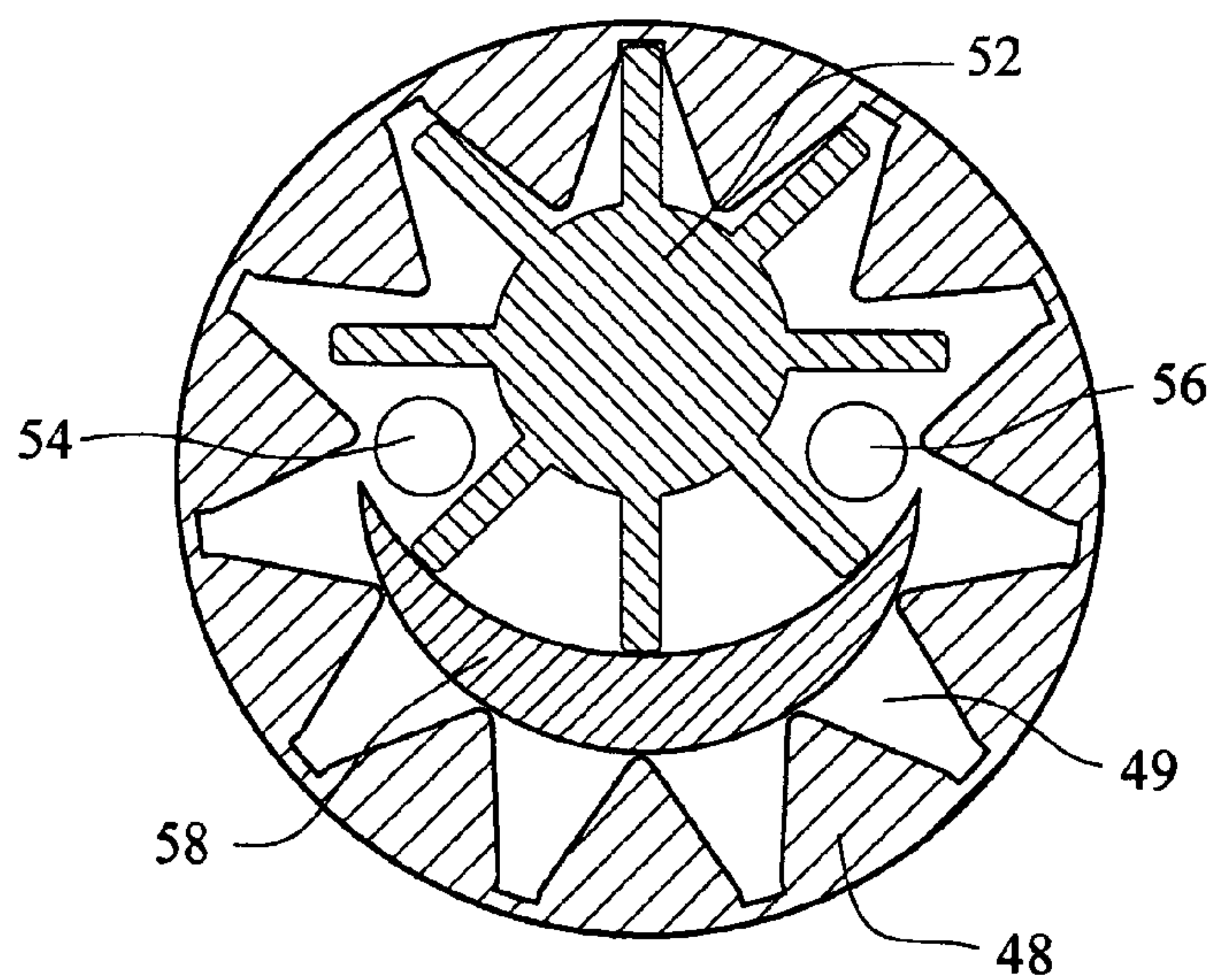


FIG. 7

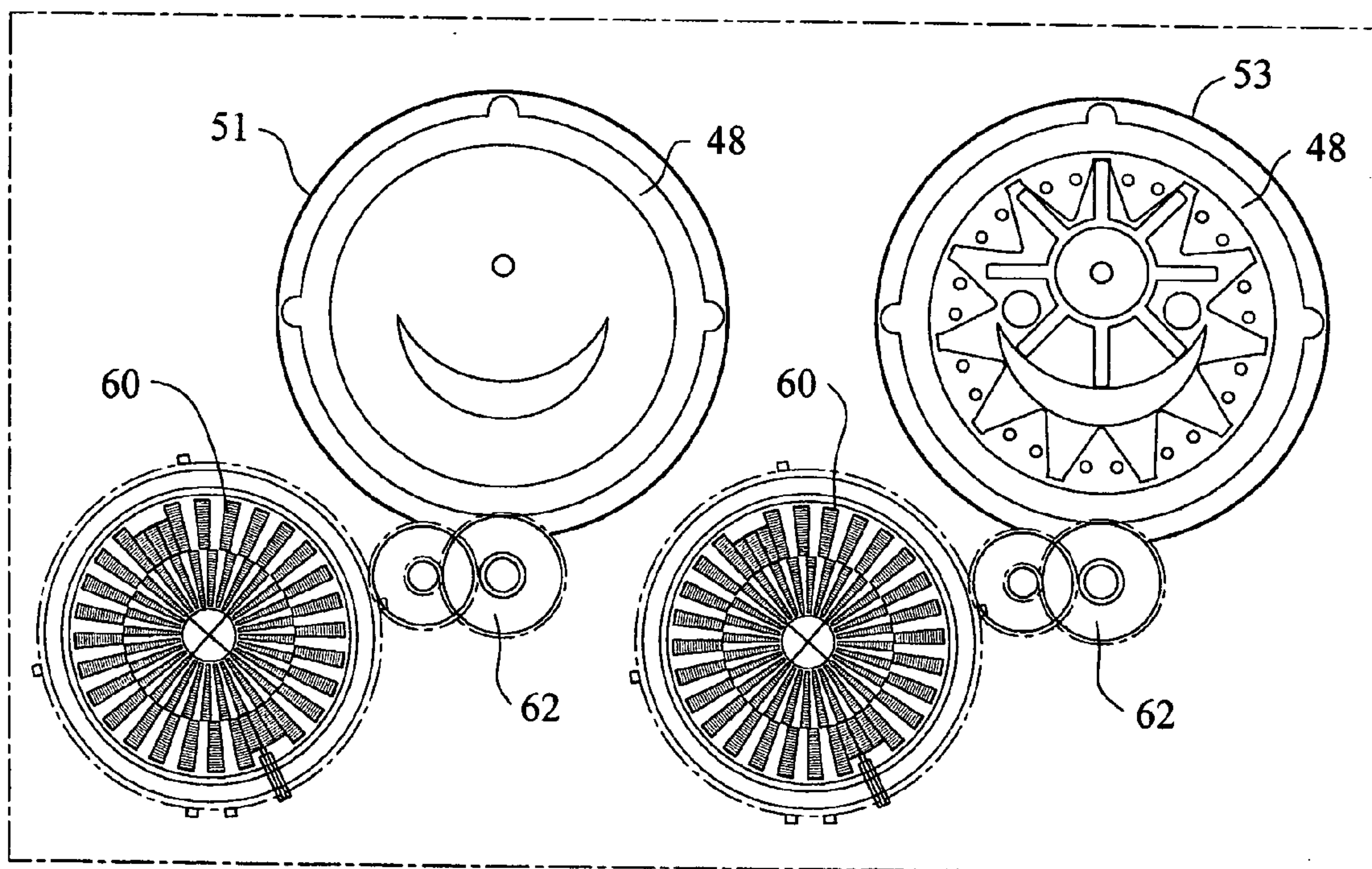


FIG. 8



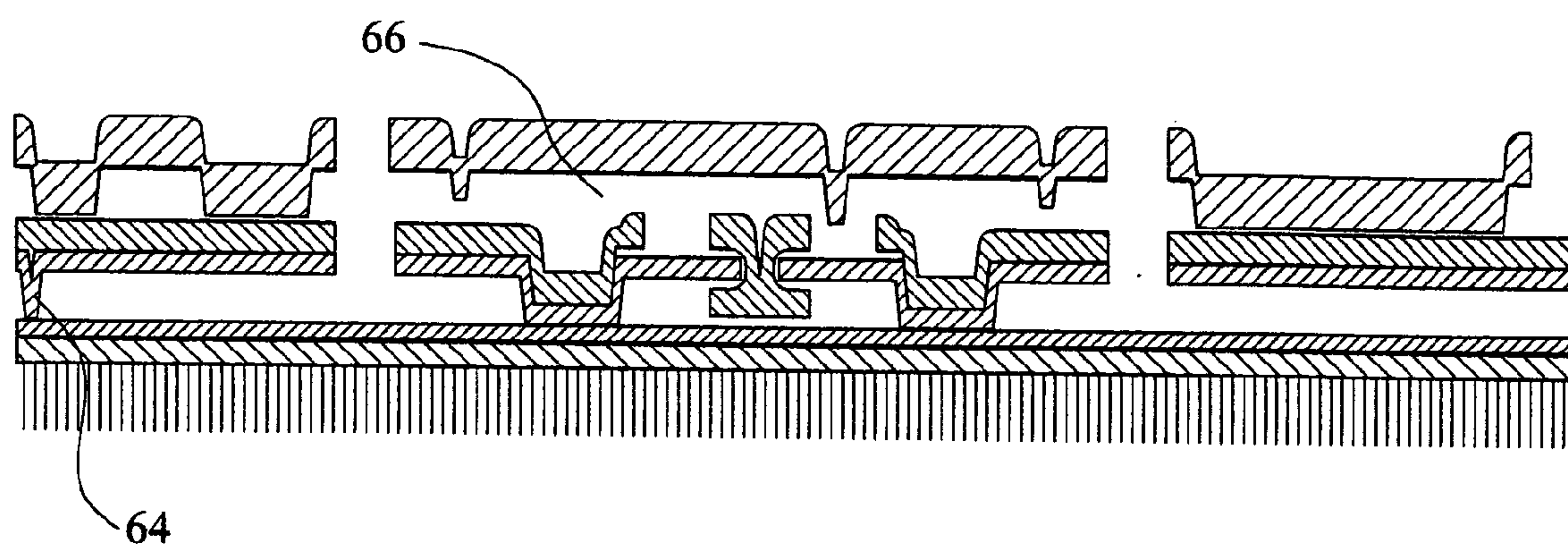


FIG. 9

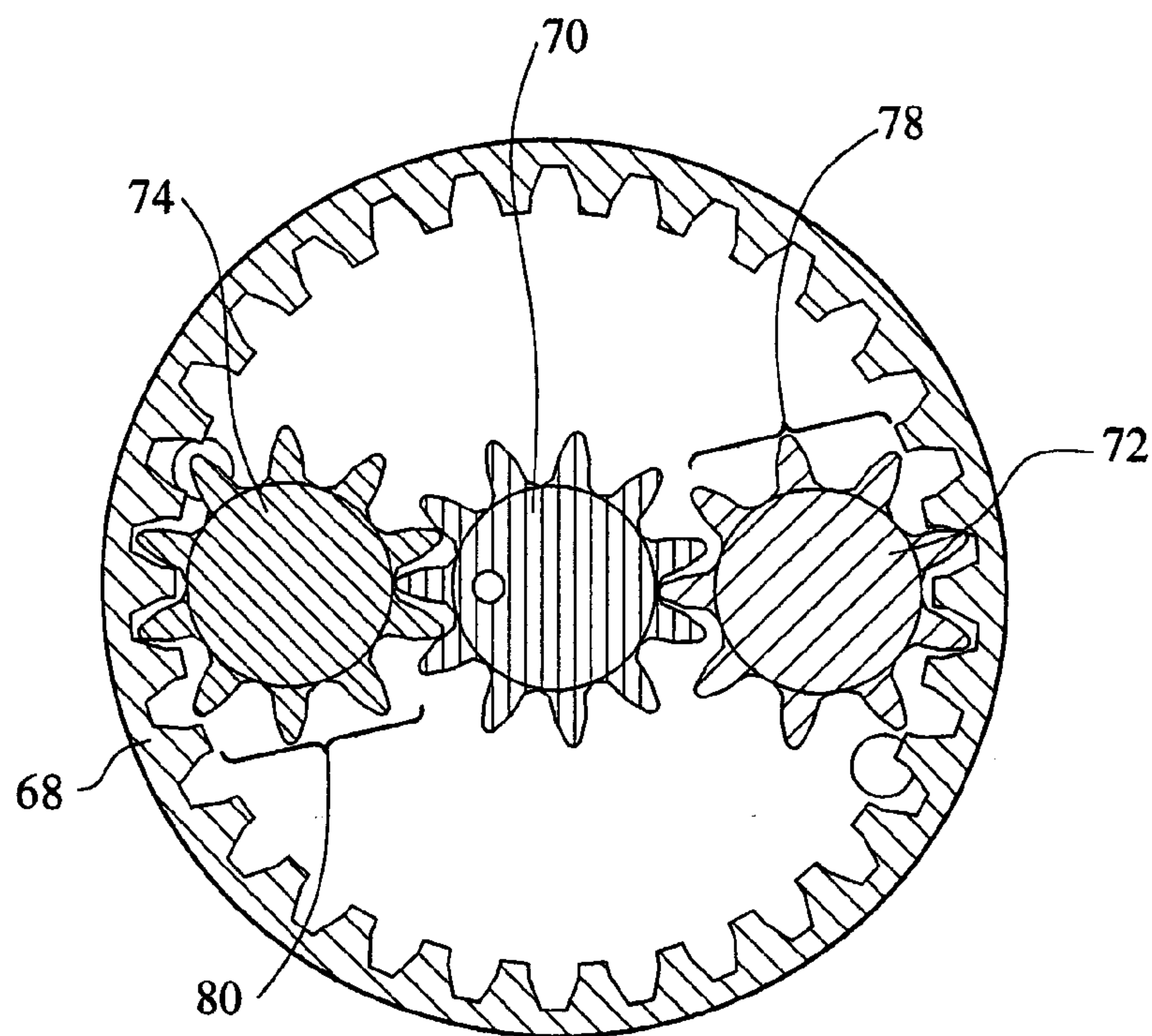
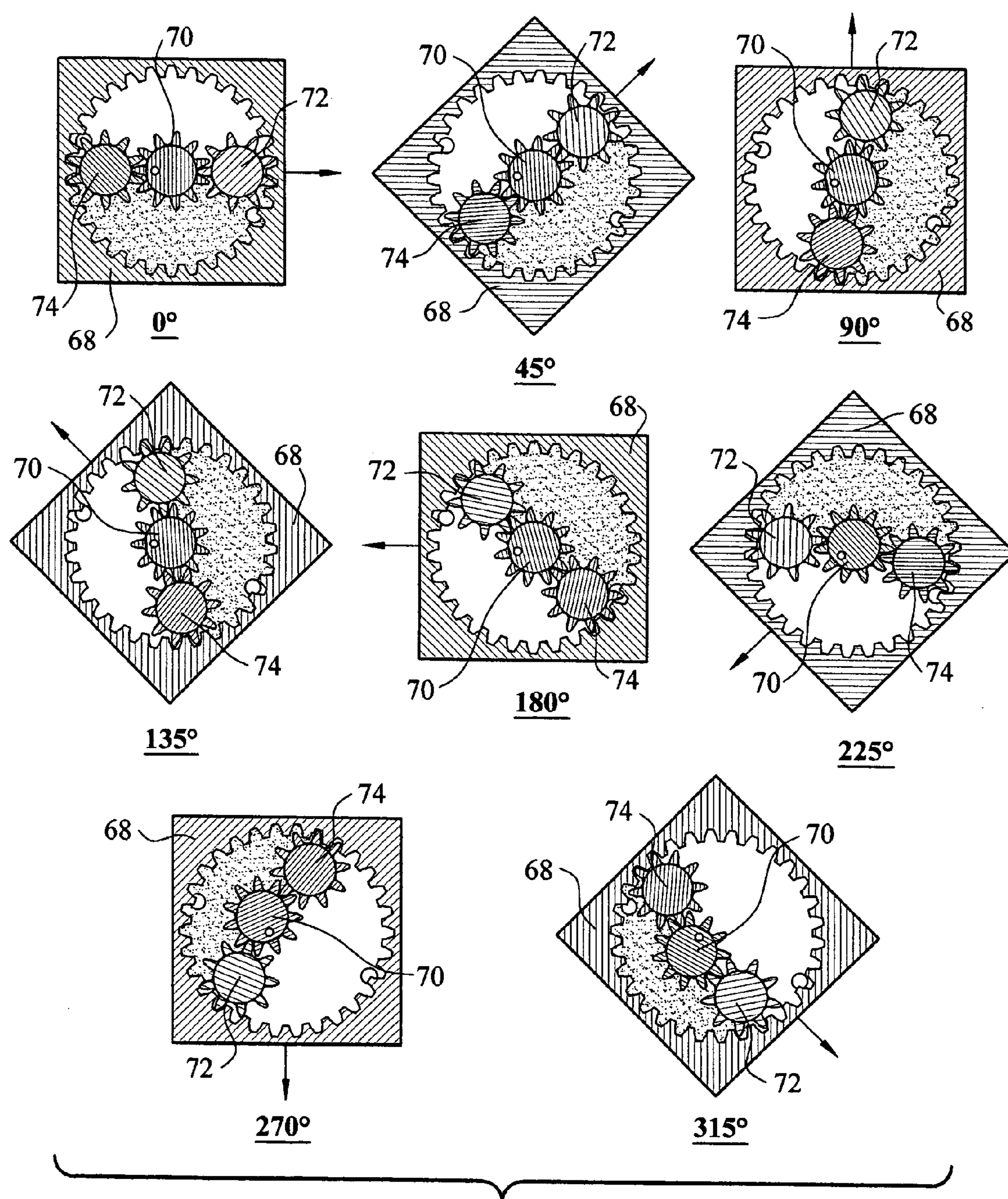
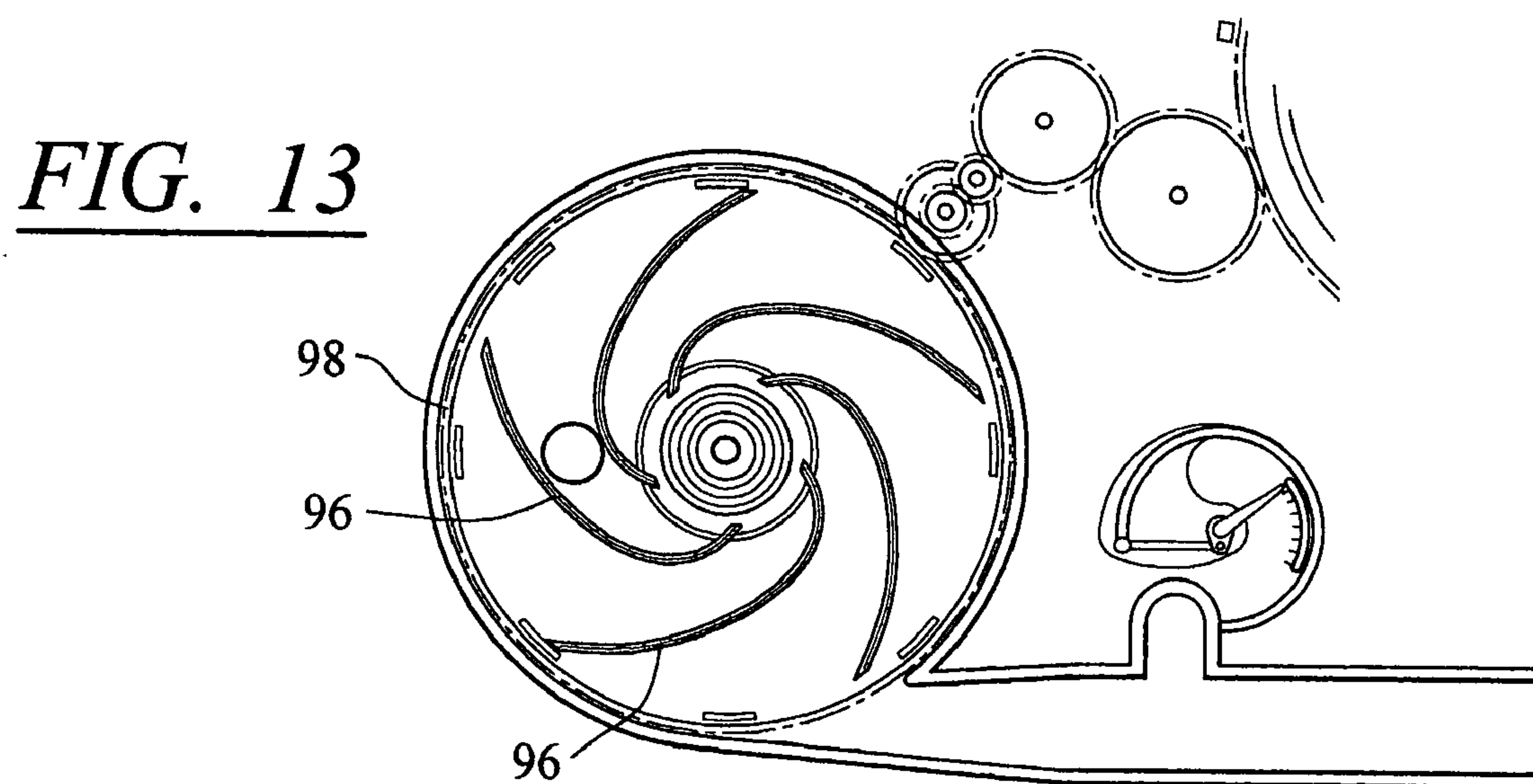
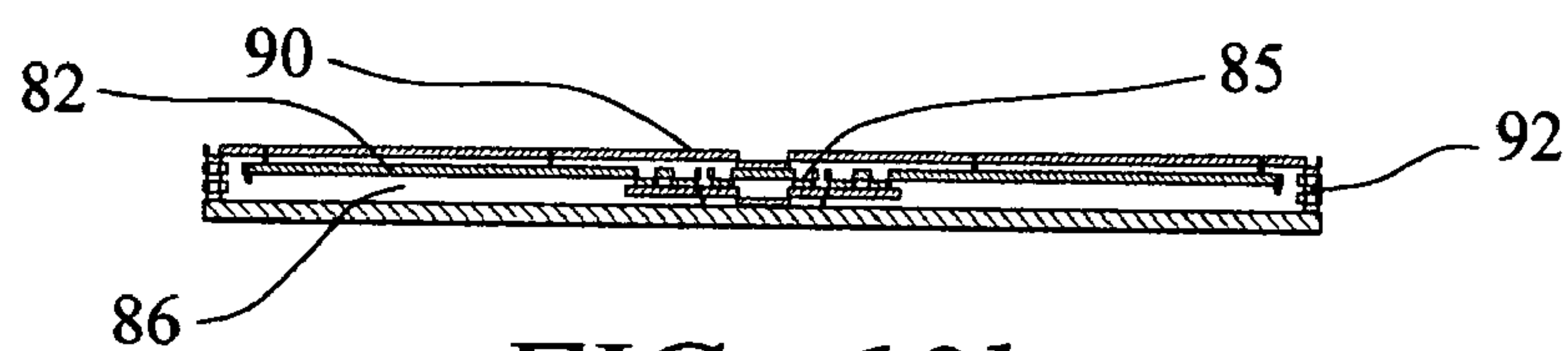
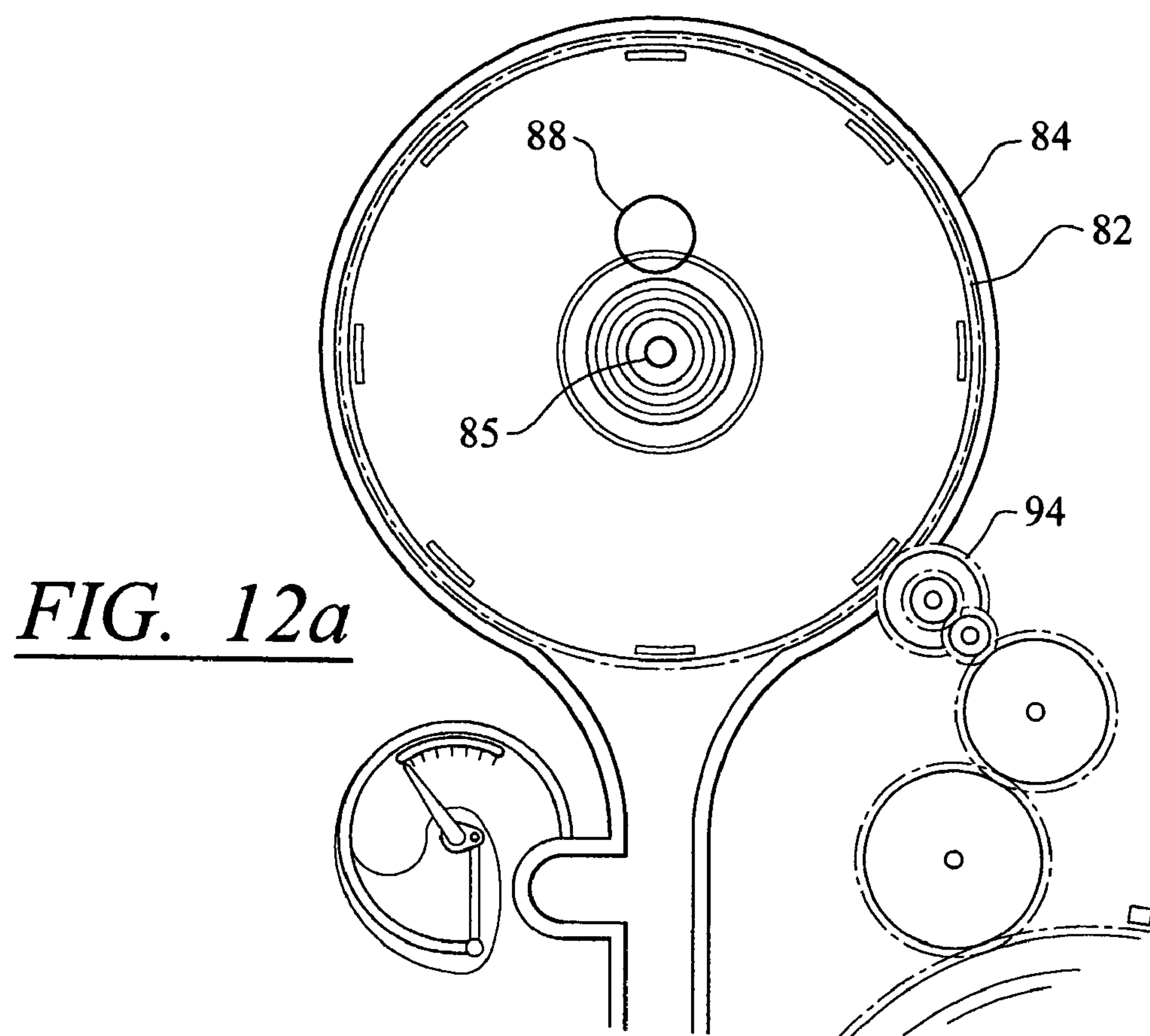


FIG. 10









# **SURFACE MICROMACHINED MECHANICAL MICROPUMPS AND FLUID SHEAR MIXING, LYSING, AND SEPARATION MICROSYSTEMS**

## **CROSS REFERENCE TO RELATED APPLICATIONS**

[0001] This application claims the benefit of U.S. Provisional Application No. 60/422,548 entitled "SURFACE MICROMACHINED MICROPUMPS AND FLUID SHEAR MIXING, LYSING, AND SEPARATION MICROSYSTEMS", filed on Oct. 31, 2002, which is incorporated by reference into the current application in its entirety.

## **STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT**

[0002] Development for this invention was supported in part by U.S. Department of Energy Contract No. DE-AO385. Accordingly, the United States Government may have certain rights in this invention.

## **FIELD OF THE INVENTION**

[0003] The invention is directed generally to micromachined mechanical devices, and more particularly, to micromachined pumps capable of pumping fluids at micro and nano scales and related shear driven mixing, lysing, and separation devices.

## **BACKGROUND**

[0004] Miniature pumps, hereafter referred to as micropumps, are in great demand for environmental, biomedical, medical, biotechnical, printing, analytical instrumentation, and miniature cooling applications. Other typical applications include use of micropumps in drug delivery systems, including both transdermal and implantable systems, micro total analysis systems, and electronic cooling devices. Just as in larger-scale applications, various pump designs are required for different micropump systems. For certain applications in which space is at a premium and in which fluid volumes are small, pumps with minimal dimensions, particularly pump cavity dimensions, are of interest.

[0005] Currently available micropumps typically are fabricated using etched silicon or glass substrates that are bonded together and utilize an actuation mechanism that most often is a piezo-electric bimorph, or in the case of electrokinetic micropumps, embedded electrodes. Typically, each component is individually bonded to other components to form a pump. As a result, this process is labor intensive and expensive. The resulting high price of the micropumps may preclude profitable commercialization of these micropumps. Moreover, the bonding of a plurality of components renders these pumps susceptible to reliability problems, such as separation of the bonds.

[0006] Thus, a need exists for an efficient, inexpensive micropump that is capable of being produced in mass quantities with little or no assembly required.

[0007] In addition, many fluids of interest in microfluidic applications are biological or contain complex chemical mixtures. Such solutions often must be analyzed or manipulated to separate a constituent of interest or to mix in chemical reagents. Because the flow in microfluidic devices essentially is laminar having a low Reynolds number, it is

difficult to complete these tasks using the turbulence and inertia based methods effective at larger scales.

[0008] Also, in certain applications it can be necessary to lyse cells in order to access cellular constituents (e.g. DNA or RNA). Typically, cell lysis is accomplished using a centrifuge or sonication in a bead solution. However, neither method is readily scaleable to microdevices. Therefore, a need exists for microfluidic cell lysis, mixing and separation devices.

## **SUMMARY OF THE INVENTION**

[0009] This invention is directed to micropumps formed from monolithic structures having thicknesses of no more than about 12 microns and include pumping chambers with inlets and outlets, and structures for mechanically urging fluid from the inlet to the outlet. The micropumps may be capable of pumping fluids on the micro and nano scales. Each of these pumps may be capable of being produced complete with the actuation and transmission mechanisms in batches of hundreds to thousands per batch using surface micromachining. Consequently, pumps according to this invention can provide increased reliability and can be produced with little, if any, costs associated with manual assembly.

[0010] Micropumps embodiments include viscous micropumps and ring gear micropumps. The viscous micropumps include spiral micropumps, centrifugal micropumps, and micropumps without spiral protrusions, which are referred to as Von Karman micropumps. The ring gear micropumps include crescent micropumps and planetary gear micropumps.

[0011] According to one aspect of this invention, a micropump, referred to as a spiral micropump, includes a rotatable disk and a stationary plate. A spiral protrusion is attached to the rotatable disk and draws a fluid through an inlet port in the micropump. The fluid passes through a spiral channel formed by the spiral protrusion and between the rotatable disk and stationary plate. The fluid is expelled through an outlet port. The rotatable disk and stationary plate may be sealed with a variety of seals, which may include, but are not limited to, a seal resembling a labyrinth or a housing.

[0012] In another embodiment of this invention, a micropump is configured identically to the spiral micropump, but does not include the spiral protrusion. This micropump is referred to as the Von-Karman pump and operates using the viscous drag that develops in the fluid in the micropump as the rotatable disk rotates. This embodiment is advantageous because this micropump is not limited by the small aspect ratio that characterizes surface micromachined devices.

[0013] In yet another embodiment of this invention, a micropump is configured to include a radial array of vanes attached to a gear disk that defines an impeller of the micropump. This micropump is referred to as the centrifugal micropump.

[0014] Certain pumping devices described herein can generate a shear field. Such a field can be used to lyse cells at the microscale where centrifugation and sonication are less effective. Also, by positioning different solution constituents at different streamlines in the shear field, cells can be separated and eluted at the end of the micropump according to their position in the shear field. Those constituents closest



to the moving plate will be eluted first and those constituents closest to the stationary plate will be eluted last. This type of constituent separation can be enhanced by operating the shear pump against a pressure gradient. Methods of manipulating constituents as to their location in different layers of a varying cross-stream shear field include but are not limited to electrical fields (AC and DC), hydrodynamic forces, sedimentation forces, thermal gradients and diffusion.

**[0015]** Other embodiments of this invention include ring gear micropumps. One type of ring gear micropump is a crescent micropump that is formed from a ring gear having a plurality of teeth on its inner and outer surfaces. The teeth on the inner surface are configured to mesh with an idler positioned within the inner aspects of the ring gear, and the teeth on the outer surface are configured to mesh with teeth on a transmission gear used to drive the ring gear. The micropump includes an inlet port and an outlet port in the inner aspects of the ring gear. The crescent micropump further includes a crescent shaped component for positioning the idler and the ring gear relative to each other. The crescent micropump operates by rotating the ring gear using, for instance, a transmission gear, which in turn causes the idler to rotate. The rotating idler draws a fluid from the inlet port and expels the fluid through the outlet port.

**[0016]** In yet another embodiment of a ring gear micropump, the micropump, referred to as a planetary gear micropump, is composed of a ring gear having a sun gear and first and second planetary gears positioned in interior aspects of the ring gear. The ring gear has a plurality of teeth positioned on an inner surface of the ring gear that mesh with the planetary gears. The sun gear is coupled to a pivot positioned eccentrically within the sun gear, and the diameter of the first planetary gear may be larger than the diameter of the second planetary gear.

**[0017]** This micropump is operable by rotating the ring gear, which causes the planetary and sun gears to rotate. The eccentric pivot causes the sun gear to rotate around the pivot and oscillate. This oscillation creates successive increasing and decreasing volumes on either side of the sun gear and the first and second gears, which draws fluid into the micropump through an inlet port and expels fluid out of the micropump through an outlet port.

**[0018]** The various gearing systems and mechanisms of the ring gear micropumps can be used to move fluids continuously through the micropump using positive displacement. The gears may also act to lyse cells, which is also referred to as cell lysis, when a cellular solution is pumped by the gears.

**[0019]** An advantage of micropumps according to the invention is that the micropumps have a monolithic body. For example, these pumps may be constructed using Sandia National Laboratories' Ultraplanner Multi-level MEMS Technology (SUMMIT™) process or similar process. As the micropumps formed by this process are monolithic, the micropumps do not require additional assembly. The SUMMIT™ process uses three or four movable polysilicon layers together with one stationary polysilicon layer. The polysilicon layers are separated from adjacent layers by sacrificial oxide layers.

**[0020]** Another advantage of these pumps is their ability to operate in micro and nano scales.

**[0021]** Yet another advantage of this invention is that the micropumps can operate without valves, thereby making the micropumps more reliable and having less components as compared to micropumps having valve requirements. Furthermore, because the pump is continuous flow rather than pulsatile flow, a continuously and smoothly varying flow rate may be generated without use of microfluidic capacitors to dampen the oscillations.

**[0022]** These and other features and advantages of the present invention will become apparent after review of the following drawings and detailed description of the disclosed embodiments.

#### BRIEF DESCRIPTION OF THE DRAWINGS

**[0023]** The accompanying drawings, which are incorporated in and form a part of the specification, illustrate preferred embodiments of the presently disclosed invention(s) and, together with the description, disclose the principles of the invention(s). These several illustrative figures include the following:

**[0024]** FIG. 1 is a schematic perspective illustration of a partial cutaway of a spiral micropump;

**[0025]** FIG. 2 is an exemplary spiral micropump coupled to a typical electrostatic comb drive system for supplying rotational motion to the micropump;

**[0026]** FIG. 3 is a cross-sectional view of the spiral micropump of FIG. 2;

**[0027]** FIG. 4 is a picture of a spiral micropump expelling a droplet of fluid under experimental conditions;

**[0028]** FIG. 5(a) is a cross-sectional view of spiral micropump of FIG. 2;

**[0029]** FIG. 5(b) is a detail view of a portion of the spiral micropump of FIG. 5(a);

**[0030]** FIG. 6(a) is a top view of the spiral micropump of FIG. 2 including a housing seal;

**[0031]** FIG. 6(b) is a cross-sectional view taken at section line A-A in FIG. 6(a);

**[0032]** FIG. 6(c) is a cross-sectional view taken at section line B-B in FIG. 6(b);

**[0033]** FIG. 6(d) is a detail view of a portion of the spiral micropump shown in FIG. 6(a);

**[0034]** FIG. 7 is a schematic illustration of a crescent micropump;

**[0035]** FIG. 8 is a picture of two exemplary crescent micropumps, the micropump on the left side having a top cover and the micropump on the right side without a top cover;

**[0036]** FIG. 9 is a cross section of the crescent micropump of FIG. 7;

**[0037]** FIG. 10 is a schematic illustration of a planetary gear micropump;

**[0038]** FIG. 11 is a collection of schematic illustrations of the micropump of FIG. 10 in various orientations during operation;



[0039] FIG. 12(a) is a cross-sectional top view of a Von Karman micropump;

[0040] FIG. 12(b) is a cross-sectional front view of the Von Karman micropump of FIG. 12(a); and

[0041] FIG. 13 is a cross-sectional top view of a centrifugal micropump.

#### DETAILED DESCRIPTION OF THE INVENTION

[0042] This invention includes numerous embodiments of monolithic micropumps that are capable of pumping fluids and are configured for use in microelectromechanical systems (MEMSs). These micropumps are monolithic structures having thicknesses of no more than about 12 microns and include pumping chambers with inlets and outlets, and structures for mechanically urging fluid from the inlet to the outlet. As used herein, the term monolithic refers to the resulting structure obtained from an integrated circuit formation process, which generally comprises a plurality of lithography, etching, and deposition steps. Thus, no assembly steps, such as bonding steps, are needed as the various layers are inherently self-assembled. Although the micropumps according to the invention are fully monolithic, use of this term does not preclude substantially free movement of one layer relative to another layer, such as in the case of a spinning rotatable disk.

[0043] Micropumps according to the invention have a total thickness of no more than about 12 microns. Thicknesses of the micropumps described herein are less than the thicknesses of conventional piezoelectric driven membrane pumps having, which have thicknesses of between about 80 microns and about 100 microns. The relatively high efficiency of pumps having thicknesses of 12 microns or less is an unexpected result because as the thickness is reduced to no more than 12 microns, the Reynolds number decreases and the effective viscosity increases. Therefore, it would be expected that the low Reynolds number would render pumps according to the invention ineffective. However, it has been found for thickness of no more than about 12 microns, that viscous effects actually begin aiding pumping as the mechanism for pumping is based on viscous drag and not on inertial effects.

[0044] Embodiments of these micropumps, which are described in detail below, include viscous micropumps formed from rotatable discs and ring gear micropumps. The viscous micropumps include a spiral micropump, a Von Karman micropump, which is a spiral micropump without a spiral protrusion, and a centrifugal micropump. The ring gear micropumps include a crescent micropump and a planetary gear micropump. The micropumps may be actuated electrostatically using on-chip micro-engines. Slightly larger meso-scale versions of these pumps can be fabricated using more conventional machining techniques and powered using small electric motors.

[0045] These micropumps may be used in a variety of applications. For instance, these micropumps may be included as a component of an integrated circuit system and be placed in communication with microprocessors, amplifiers, actuators, voltage controllers for the actuators, sensors and other appropriate devices. These micropumps may be used as a component in microlabs, which may also be

referred to as a lab-on-a-chip, in medical devices, such as insulin pumps, chemical synthesis, for cooling systems in integrated circuits, and other applications.

[0046] Each of these embodiments is preferably formed using surface machining processes capable of fabricating hundreds or thousands of devices together with no part assembly being required. Surface micromachined devices are planar in nature, and are characterized by very shallow depths, such as, but not limited to, no more than about 12 microns. The micropumps may be fabricated using Sandia National Laboratories' Ultraplanar Multi-level MEMs Technology (SUMMIT™) process or similar process. The SUMMIT™ process uses three or four movable polysilicon layers together with one stationary polysilicon layer ("Poly"). The polysilicon layers are separated from adjacent layers by sacrificial oxide layers that are removed during the final etch release process step. See e.g. *I-C Compatible Polysilicon Surface Micromachining* by J. J. Sniegowski and M. P. de Boer, Annu. Rev. Mater. Sci. 2000, 30:299-333.

#### [0047] 1. Monolithic Viscous Micropumps

##### [0048] A. Spiral Micropump

[0049] One embodiment of this invention, as shown in FIG. 1 and referred to hereinafter as the spiral micropump, includes a rotatable disk 12 coupled to a stationary plate 14 using a pin joint 16, which is positioned generally within the center of stationary plate 14. Rotatable disk 12 includes a spiral protrusion 21 that directs fluids from an inlet port 18 to an outlet port 20. Stationary plate 14 is a generally flat shaped component and includes two generally flat surfaces. One of these flat surfaces is positioned in close proximity to spiral protrusion 21. In one embodiment, the combined thickness of rotatable disk 12, stationary plate 14, and spiral protrusion 21 is no more than about 12 microns. In at least one embodiment, the spiral micropump may be formed from as few as 2 silicon layers. However, the spiral micropump may be formed from between 3 and 5 silicon layers as well.

[0050] In another embodiment, the micropump contains the components described above; however, spiral protrusion 21 is not included. Rather, this embodiment, which is referred to as a viscous micropump, pumps fluids using viscous phenomena as the driving mechanism.

[0051] During operation, a fluid enters inlet port 18 and flows through spiral channel 22 to outlet port 20. Spiral channel 22 is formed by spiral protrusion 21 that is bounded by stationary plate 14 on one side and rotatable disk 12 on the other side. Fluids, with or without suspended particles, are drawn through spiral channel 22 as a result of a velocity profile created by rotatable disk 12 rotating around pin joint 16. The velocity profile consists of fluids having velocities that vary between about zero at the surface of stationary plate 14 and a velocity approximately equal to the rotational velocity of the rotatable disk at a location proximate to the inner surface 24 of rotatable disk 12. Viscous stresses on upper surfaces of the spiral channel 22 allow fluids to be transported against an imposed pressure difference. The spiral micropump is capable of expelling a sufficient amount of fluids to produce droplets of fluid visible to the unassisted human eye, as shown in FIG. 4.

[0052] Rotatable disk 12 may be rotated through numerous methods. In one embodiment, rotatable disk 12 is rotated using an electrostatic comb drive microengine, as shown in



**FIG. 2**, that provides continuous mechanical power transmitted to rotatable disk **12** through a transmission **26**, which may be a torque amplification gear mechanism operating at 12:1. Transmission **26** includes an output gear **28** that includes a plurality of teeth positioned on a perimeter **30** of output gear **28**. The teeth on output gear **28** mesh with the teeth located on the perimeter **30** of rotatable disk **12**.

[0053] **FIG. 3** is a cross-sectional view of the spiral micropump taken through the centerline to illustrate the relationships between the layers forming the spiral micropump. Rotatable disk **12** is formed from a polysilicon layer, which is identified as Poly 4, and stationary plate **14** is formed from another polysilicon layer, which is identified as Poly 0. Spiral protrusion **21** is formed from three polysilicon layers, which are identified as Poly 1, Poly 2, and Poly 3, and is anchored to rotatable disk **12**. This configuration leaves a small gap between spiral protrusion **21** and stationary plate **14**.

[0054] The spiral micropump may be contained using a variety of seals or components for preventing fluids from leaking out. In one embodiment, seal **32** resembles a labyrinth seal positioned around the periphery of the spiral micropump, as shown in **FIG. 5**. The seal **32** can be formed from three polysilicon layers. In one embodiment, the three layers may be concentric and cylindrical. However, the layers are not limited to this shape or number. Rather, seal **32** may be formed from any other number of layers or alternative shapes.

[0055] The three layers are positioned between the rotatable disk and the fixed plate. The inner and outer layers form protrusion extending from the stationary plate **14** and Poly 0, and the middle layer forms a protrusion extending from the rotatable disk **12** and Poly 4 and positioned between the protrusions extending from the stationary plate **14**. The middle layer rotates with the rotatable disk **12**. A small clearance gap is located between adjacent layers. As shown in **FIG. 5**, the three cylindrical layers are defined by interconnected layers designated as Poly 1, Poly 2, and Poly 3.

[0056] In another embodiment, as shown in **FIG. 6**, seal **32** may be a housing that nearly entirely encloses rotatable disk **12**, stationary plate **14**, and spiral protrusion **21**, except for a small opening through which transmission **26** contacts rotatable disk **12**. **FIG. 6(b)** is a cross-sectional view of the spiral micropump and shows seal **32** formed from a top cover **36** that is formed from a Poly 4 layer, a side wall **38** that is formed from Poly 1, Poly 2 and Poly 3 layers, and a bottom cover **40** that is formed from a Poly 0 layer. Top cover **36** and side wall **38** form a closed chamber that surrounds rotatable disk **12** and stationary plate **14**. In this embodiment, spiral protrusion **21** is defined by the Poly 1 and 2 layer and is attached to rotatable disk **12**. The Poly 1 layer may also include dimples that create protrusions below the spiral protrusion **21** to improve the seal between the poly layers forming spiral protrusion **21**. Seal **32** may further include a cantilever seal **42**, as shown in **FIG. 6(d)**, for reducing leakage from the bottom of pumping chamber **44** through an opening. Seal **32** may also include a dimple **48**, which may be formed by a dimple cut in the Poly 3 layer, for minimizing leakage from the top of pumping chamber **44** through a window.

[0057] Micropumps according to the invention may also be used to lyse cells by pumping a cellular solution at a shear

rate sufficient to destroy the cell membrane. In addition, the shear field created in the spiral or viscous micropumps can be used to spatially separate constituents as the constituents are eluted from the micropump.

[0058] In operation, a liquid containing cells is introduced at the inlet **18** of the spiral or viscous micropump. As the rotatable disk **12** is turned rapidly, the solution is pumped towards outlet **20**, and a shear field is developed between rotatable disk **12** and stationary plate **14** that is proportional to the velocity of the rotating disk. If the resulting shear stress induced in the cells in solution is high enough, the cell membrane of the cells will rupture, which results in lysis of the cells. After the cells rupture, the fluid stream will continue to be pumped out of spiral channel **22** through outlet **20**. Cellular constituents, such as DNA and cell membrane material, may be separated while flowing through spiral channel **22**, as described in detail below.

[0059] The shear field developed by a viscous micropump may be used to separate constituents in a fluid stream flowing through a channel fed by the pump. Separation of the constituents is possible due to a variation in velocity of the fluid across the fluid stream. In the simplest case, the fluid near rotatable disk **12** is moving at approximately the velocity of the rotatable disk **12**, and the fluid near the stationary plate **14** has a velocity approximately equal to zero, which is the velocity of stationary plate **14**. The velocity varies linearly between zero and the moving disk velocity as the fluid stream is traversed from the stationary plate to the rotatable disk. Because the flow field through channel **22** is essentially laminar, constituents stay in layers, or lanes, as the constituents move through the micropump. The constituents closest to rotatable disk **12** are expelled from the micropump ahead of the slower moving constituents that are located closer to stationary plate **14**. Because of this phenomena, constituents are separated in space and time in an exit channel as a result of the constituents occupying different layers within the fluid flow. The separation between constituents may be increased by increasing the speed of the micropump. For best operation, different constituents should be positioned at different locations across channel **22** in the flow stream. In some cases, such a constituent configuration occurs naturally because of the shear field. Different constituents occupy different lamina because of the way the constituents respond to the shear field.

[0060] Constituents may also be positioned in different fluid lamina using other methods.

[0061] For instance, an electrode or an array of electrodes can be incorporated in stationary plate **14** to apply an electric field consisting of alternating or direct current (AC or DC, respectively), to the electrode or electrodes while rotatable disk **12** is grounded. Rotatable disk **12** may be grounded through the drive mechanism. This configuration produces an electric field that is generally perpendicular to the direction of fluid flow. The solution constituents are positioned differently within the cross-stream field and are therefore, in different fluid lamina. The position of the solution constituents is dictated by the constituents' electrophoretic or dielectrophoretic properties. The electrophoretic properties determine the DC signal response, and the dielectrophoretic properties determine the AC signal response. Constituents positioned in lamina nearest rotating disk **12**, which is the ground, travel further through the micropump in a particular time period than other fluids.



[0062] Other methods of establishing cross-stream fields include sedimentation processes in which different specific gravity constituents are positioned at different locations in a cross-stream gravity field, and chemical affinity processes, whereby a wall of a micropump, whether stationary or rotating, is coated which causes chemical constituents to be adsorbed and removed from the fluids at different rates. Differences in diffusion coefficients correlating with different constituents causes some separation of constituents but also leads to broadening of the bands of eluted constituents as the fluids are expelled from the micropump, thereby reducing resolution.

[0063] These separation effects can be enhanced when the pump is operated against a pressure gradient, such as where the pressure at outlet 20 is greater than the pressure at inlet 18. This pressure gradient forces the fluids against the flow induced by rotatable disk 12. The fluid near stationary plate 14 is more affected by the pressure gradient than the fluid in streamlines located near rotatable disk 12. If the pressure gradient is sufficient, the fluid near stationary plate 14 will be pushed backward against the shear driven flow. This causes the solution constituents to be separated more widely because while the fluid near the stationary wall is pushed back towards inlet 18 by the pressure gradient, solution constituents near rotatable disk 12 are pulled in the usual flow direction.

[0064] While these processes produce constituent separation, the same processes may also be used for constituent mixing. Enhanced diffusion (dispersion) in the shear field occurs when the constituent concentration gradient across the stream due to along stream convection reduces the mixing time required. Another method of mixing constituents is to stop the flow at outlet 20. In this embodiment, a re-circulation system is established in which the fluids first travel through the micropump in the forward direction along rotatable disk 12 and then travel back along stationary plate 14 due to the pressure driven flow in the low velocity streamlines positioned closely to stationary plate 14. This re-circulation region is an effective microfluidic mixer.

#### [0065] B. Von Karman Micropump.

[0066] In another embodiment of this invention, a micropump, which is referred to as a Von Karman micropump is shown in FIGS. 12a and 12b. The Von Karman micropump is composed of a rotatable plate 82 that rotates on top of a parallel fixed plate 84 about pin joint 85. A cavity 86 is formed between the disk 82 and the plate 84 and for pumping the fluid. The fixed plate 84 has an inlet port 88 and an outlet port (not shown). The viscous forces caused by the rotating flat disk 82 carry the fluid from the inlet port 88 to the outlet port.

[0067] FIG. 12b illustrates a Von Karman micropump that may be formed using the SUMMIT-V™ process and may have a thickness no more than about 12 microns. In at least one embodiment, the Von Karman micropump may be formed from as few as 2 silicon layers. However, the Von Karman micropump may be formed from between 3 and 5 silicon layers as well. The fixed plate 84 may be formed in Poly 0 and the inlet port 88 and may be created by a Bosch etch through the wafer. The rotatable plate 82 may be formed in the Poly 3 and may create a cavity 86 whereby the rotatable plate 82 is about six microns from the fixed plate 84. The rotatable plate 82 may be driven using gear teeth on

the outer surface of the rotatable plate 82. The Poly 4 layer may form a top cover 90 that may be connected seamlessly to the housing walls 92, which may be anchored to the ground. The housing walls 92 and the Poly 4 top cover 90 provide a continuous seal around the entire micropump, except for the area proximate to the driving gears 94. Surface tension forces prevent the fluid in the micropump from leaking through the very small gap proximate to the drive gears 94.

#### [0068] C. Centrifugal Micropump

[0069] FIG. 13 shows yet another embodiment of a viscous drag micropump and is referred to as a centrifugal micropump. The centrifugal micropump may have a thickness no more than about 12 microns. In at least one embodiment, the centrifugal micropump may be formed from as few as 2 silicon layers. However, the centrifugal micropump may be formed from between 3 and 5 silicon layers as well. The configuration of the centrifugal micropump resembles the spiral micropump; however, the centrifugal micropump does not include a spiral protrusion. Rather, the centrifugal micropump includes a radial array of vanes 96 attached to a rotatable disk 98. The rotatable disk 98 functions as an impeller of the centrifugal micropump.

#### [0070] 2. Monolithic Ring Gear Micropumps

##### [0071] A. Crescent Micropump

[0072] The invention also includes planar gear pumps, such as the crescent micropump and the planetary gear micropump, for pumping fluids and for lysing cells. The planar gear micropumps may have thicknesses no more than about 12 microns. In at least one embodiment, the planar gear micropump may be formed from as few as 2 silicon layers. However, the planar gear micropump may be formed from between 3 and 5 silicon layers as well. The planar gears may be used to lyse cells, as described in detail above, by pumping a cellular solution through the micropump. The crescent micropump, as shown in FIG. 7, includes a ring gear 48 having a plurality of teeth on its outer and inner surfaces. In at least one embodiment, the ring gear 48 may be formed from three or four layers of silicon and a base layer 49 may be formed from one or more layers of silicon. The teeth on the outer surface mesh with teeth on a drive gear, and the teeth on the inner surface mesh with an idler 52. In this configuration, a drive gear rotates and causes ring gear 48 to rotate, which in turn causes idler 52 to rotate. This action causes a fluid to be drawn into interior aspects of ring gear 48 from inlet 54 and expelled through outlet 56. Idler 52 and ring gear 50 are kept in position with a crescent diverter 58.

[0073] FIG. 8 depicts two crescent micropumps 51 and 53, micropump 51 having a top cover in place and micropump 55 having the top cover removed. The crescent micropumps can be driven with torsional ratchet actuators 60, or other structure for providing rotational motion to micropumps. Torsional ratchet actuators are independently attached to transmissions 62 for applying rotational motion to ring gears 48. The crescent micropump on the right may have a cover installed using a post fabrication technique such as, but not limited to, anodic bonding.

[0074] FIG. 9 depicts a cross-section of ring gear 48 including a seal 64 positioned around pumping chamber 66, which is formed as an integral part of ring gear 48. Seal 64



resembles a labyrinth seal and is formed from a dimple in the Poly 1 layer. In addition, seal **64** includes a plurality of rollers that are created using a pin joint process and act as axial bearings that support the walls of the seal during rotation and thus minimize friction.

**[0075]** B. Planetary Gear Micropump

**[0076]** Yet another embodiment of this invention, as shown in **FIG. 10** and referred to hereinafter as a planetary gear micropump, may be used to pump fluids or lyse cells. The planetary gear micropump may have a thickness no more than about 12 microns. In at least one embodiment, the planetary gear micropump may be formed from as few as 2 silicon layers. However, the planetary gear micropump may be formed from between 3 and 5 silicon layers as well. The micropump includes a ring gear **68** mechanically coupled to a sun gear **70** using first and second planetary gears, **72** and **74** respectively. Sun gear **70** pivots eccentrically around pivot **76** that is not in the center point of sun gear **70**. Ring gear **68** drives the rotation of first and second planetary gears **72** and **74** and sun gear **70**. The diameter of the first planetary gear **72** is larger than the diameter of the second planetary gear **74**, or vice versa, and the sum of the diameters of sun gear **70** and first and second planetary gears **72** and **74** is approximately equal to the pitch diameter of ring gear **68**. The ring gear **68** may be formed from three or more layers of silicon. A base layer may be formed from one or more layers of silicon.

**[0077]** Operation of the planetary gear micropump is shown in **FIG. 11**. As ring gear **68** rotates, first and second planetary gears **72** and **74** rotate around sun gear **70**. Rotation of first and second planetary gears **72** and **74** around sun gear **70** causes sun gear **70** to rotate because the gap **78** between the right side of sun gear **70** and the inner wall of ring gear **68** is smaller than the gap **80** between the left side of sun gear **70** and the inner wall of ring gear **68**. As sun gear **70** rotates around pivot **76**, gap **78** continues to shrink in size and sun gear is forced to make a full revolution around pivot **76**. This eccentric rotation of sun gear **70** produces successive increasing and decreasing volumes on either side of sun gear **70** and the first and second gears **72** and **74**. Such action provides pumping action necessary for the pump to operate.

**[0078]** The foregoing is provided for purposes of illustrating, explaining, and describing embodiments of this invention. Modifications and adaptations to these embodiments will be apparent to those skilled in the art and may be made without departing from the scope or spirit of this invention.

We claim:

1. A micropump, comprising:
  - a pumping chamber, wherein said pumping chamber includes an inlet for drawing fluid therein and an outlet for expelling said fluid out of said chamber, and
  - structure for mechanically urging said fluid from said inlet to said outlet, wherein said micropump is fully monolithic forming a monolithic body, said pump having a total thickness of no more than about 12 microns.
2. The micropump of claim 1, wherein said pumping chamber includes at least one rotatable disc in fluid communication with said fluid, said structure for mechanically urging comprising said rotatable disc.

3. The micropump of claim 2, wherein the at least one rotatable disc comprises at least one protrusion extending from the disc.

4. The micropump of claim 3, wherein the at least one protrusion forms a spiral shaped fluid pathway concentric with the at least one rotatable disc.

5. The micropump of claim 3, wherein the at least one protrusion forms a plurality of radial vanes extending from an axis of rotation of the rotatable disc.

6. The micropump of claim 2, wherein at least one rotatable disc further comprises a plurality of gear teeth on a side surface of the rotatable disc.

7. The micropump of claim 6, further comprising at least one crescent shaped diverter positioned in the pumping chamber proximate to the at least one rotatable disc, and wherein an inner surface of the monolithic body includes a plurality of gear teeth for meshing with the at least one rotatable disc.

8. The micropump of claim 2, further comprising at least one cap forming a portion of the monolithic body and having an opening enabling a driving gear to contact the at least one rotatable disc contained in the monolithic body.

9. The micropump of claim 2, further comprising a labyrinth seal formed from a first protrusion forming a ring extending generally vertically from a base layer and surrounding the rotatable disc, a second protrusion forming a ring extending generally vertically from the base layer and positioned inside the first protrusion, and a third protrusion forming a ring extending generally vertically from the at least one rotatable disc and positioned between the first and second protrusions.

10. The micropump of claim 2, further comprising at least one electrostatic comb drive for rotating the at least one rotatable disc.

11. The micropump of claim 10, further comprising at least one gear in contact with the electrostatic comb drive and in contact with the at least one rotatable disc.

12. The micropump of claim 11, wherein the at least one gear comprises a 12:1 torque amplification gear train.

13. The micropump of claim 1, wherein said pumping chamber includes at least two rotatable gears therein, said structure for mechanically urging comprising said rotating gears.)

14. The micropump of claim 13, wherein the at least two rotatable gears comprises at least three rotatable gears, wherein a first rotatable gear is rotatably attached to a pin substantially at a center point of the base layer and includes a plurality of gear teeth, a second rotatable gear including a plurality of teeth on a side surface is positioned between the first rotatable disc and a side wall of the monolithic body, and a third rotatable gear including a plurality of teeth on a side surface and having a diameter larger than the second rotatable gear is positioned between the first rotatable gear and a side wall of the monolithic body.

15. A micropump, comprising:

a monolithic body formed from between about two layers of silicon and about five layers of silicon and having a thickness no more than about 12 microns, wherein the monolithic body comprises a base layer and side walls forming an pumping chamber containing at least one rotatable disc; wherein said pumping chamber includes an inlet for drawing fluid therein and an outlet for expelling said fluid out of said cavity; and



at least one rotatable disc positioned in the pumping chamber for drawing a fluid through the inlet and expelling the fluid out of the outlet.

**16.** The micropump of claim 15, wherein the at least one rotatable disc comprises at least one protrusion extending from the disc.

**17.** The micropump of claim 15, wherein the at least one protrusion forms a spiral shaped fluid pathway concentric with the at least one rotatable disc.

**18.** The micropump of claim 15, wherein the at least one protrusion forms a plurality of radial vanes extending from an axis of rotation of the rotatable disc.

**19.** The micropump of claim 15, wherein at least one rotatable disc further comprises a plurality of gear teeth on a side surface of the rotatable disc.

**20.** The micropump of claim 19, further comprising at least one crescent shaped diverter positioned in the pumping chamber proximate to the at least one rotatable disc, and wherein an inner surface of the monolithic body includes a plurality of gear teeth for meshing with the at least one rotatable disc.

**21.** The micropump of claim 15, wherein the at least one rotatable disc comprises at least three rotatable discs, wherein a first rotatable disc is rotatably attached to a pin substantially at a center point of the base layer and includes a plurality of gear teeth, a second rotatable disc including a plurality of teeth on a side surface is positioned between the first rotatable disc and a side wall of the monolithic body, and a third rotatable disc including a plurality of teeth on a side surface and having a diameter larger than the second rotatable disc is positioned between the first rotatable disc and a side wall of the monolithic body.

**22.** The micropump of claim 15, further comprising at least one cap forming a portion of the monolithic body and having an opening enabling a driving gear to contact the at least one rotatable disc contained in the monolithic body.

**23.** The micropump of claim 15, further comprising a labyrinth seal formed from a first protrusion forming a ring extending generally vertically from the base layer and surrounding the rotatable disc, a second protrusion forming a ring extending generally vertically from the base layer and positioned inside the first protrusion, and a third protrusion

forming a ring extending generally vertically from the at least one rotatable disc and positioned between the first and second protrusions.

**24.** The micropump of claim 15, further comprising at least one electrostatic comb drive for rotating the at least one rotatable disc.

**25.** The micropump of claim 24, further comprising at least one gear in contact with the electrostatic comb drive and in contact with the at least one rotatable disc.

**26.** The micropump of claim 25, wherein the at least one gear has a 12:1 torque amplification gear train.

**27.** A method of pumping fluids, comprising:

rotating at least one rotatable disc positioned in a pumping chamber of a micropump formed from a monolithic body having a thickness no more than about 12 microns and containing the at least one rotatable disc; wherein a fluid is drawn through an inlet in the pumping chamber and expelled from an outlet in the pumping chamber.

**28.** The method of claim 27, wherein rotating at least one rotatable disc comprises rotating at least one disc comprising at least one protrusion extending from the disc.

**29.** The method of claim 28, wherein rotating at least one rotatable disc having at least one protrusion extending from the disc comprises rotating at least one disc having a spiral shaped protrusion extending from the disc.

**30.** The method of claim 28, wherein rotating at least one rotatable disc having at least one protrusion extending from the disc comprises rotating at least one disc having a spiral shaped protrusion extending from the disc.

**31.** The method of claim 27, wherein rotating at least one rotatable disc is accomplished using at least one electrostatic comb drive.

**32.** The method of claim 27, wherein rotating at least one rotatable disc drives at least one idler gear positioned in the pumping chamber of the at least one rotatable disc.

**33.** The method of claim 27, wherein rotating the at least one rotatable disc comprises rotating at least three gears in the pumping chamber.

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