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(72) Inventeurs/Inventors:
MILLER, JOHN MICHAEL, CA;
JIN, WENLIN, CA;
KEYWORTH, BARRIE, CA;
WALL, PIERRE D., CA

(73) Propriétaire/Owner:
JDS UNIPHASE INC., CA

(74) Agent: TEITELBAUM & MACLEAN

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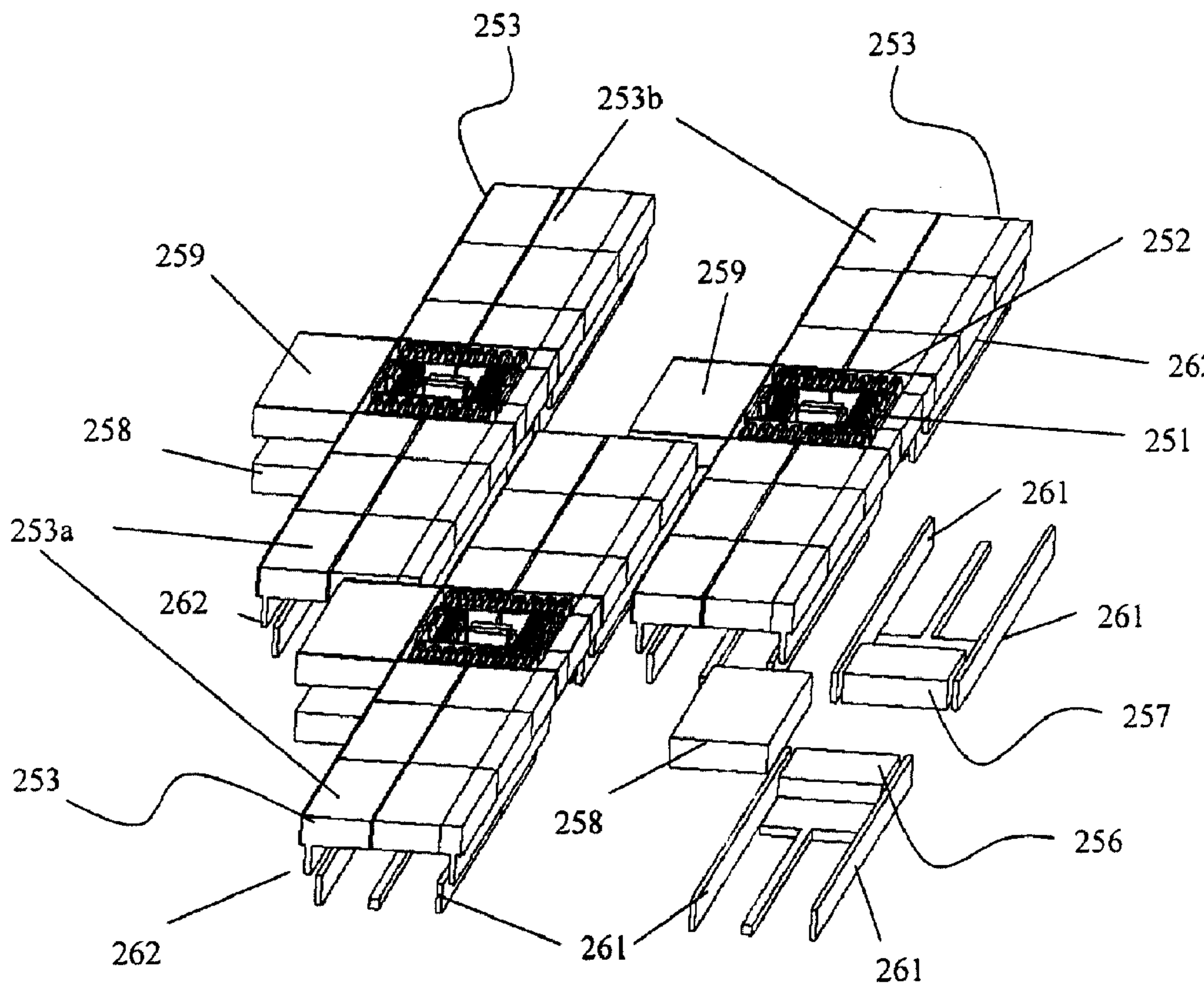

(57) Abrégé/Abstract:
A micro-electro-mechanical (MEMs) mirror device for use in an optical switch is disclosed. A "piano"-style MEMs device includes an elongated platform pivotally mounted proximate the middle thereof by a torsional hinge. The middle portion of the platform and the

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torsional hinge have a combined width less than the width of the rest of the platform, whereby several of these "piano" MEMs devices can be positioned adjacent each other pivotally mounted about the same axis with only a relatively small air gap therebetween. In a preferred embodiment of the present invention the spacing between electrodes is increased without effecting the fill factor of the mirrors by interlacing two sets of tilting platforms, whereby the reflecting portions of both sets of tilting platforms are adjacent one another, while the non-reflecting portions of adjacent platforms are remote from each other.

ABSTRACT OF THE DISCLOSURE

A micro-electro-mechanical (MEMs) mirror device for use in an optical switch is disclosed. A "piano"-style MEMs device includes an elongated platform pivotally mounted proximate the middle thereof by a torsional hinge. The middle portion of the platform and the torsional hinge have a combined width less than the width of the rest of the platform, whereby several of these "piano" MEMs devices can be positioned adjacent each other pivotally mounted about the same axis with only a relatively small air gap therebetween. In a preferred embodiment of the present invention the spacing between electrodes is increased without effecting the fill factor of the mirrors by interlacing two sets of tilting platforms, whereby the reflecting portions of both sets of tilting platforms are adjacent one another, while the non-reflecting portions of adjacent platforms are remote from each other.

INTERLACED ARRAY OF PIANO MEMS MICROMIRRORS

CROSS-REFERENCE TO RELATED APPLICATIONS

[01] The present application claims priority from United States Patent Application No 10/850,407 filed May 21, 2004. The present application also claims priority from United States Patent Application No. 60/558,563 filed April 2, 2004.

TECHNICAL FIELD

[02] The present invention relates to a micro-electro-mechanical (MEMs) mirror device for use in an optical switch, and in particular to an interlaced arrays of MEMs mirrors providing minimal electrical cross talk between mirrors.

BACKGROUND OF THE INVENTION

[03] Conventional MEMs mirrors for use in optical switches, such as the one disclosed in United States Patent No. 6,535,319 issued March 18, 2003 to Buzzetta et al, to redirect beams of light to one of a plurality of output ports include an electro-statically controlled mirror pivotable about a single axis. Tilting MEMs mirrors, such as the ones disclosed in United States Patent No 6,491,404 issued December 10, 2002 in the name of Edward Hill, and United States Patent Publication No. 2003/0052569, published March 20, 2003 in the name of Dhuler et al, comprise a mirror pivotable about a central longitudinal axis, and a pair of electrodes, one on each side of the central longitudinal axis for actuating the mirror. The Dhuler et al reference discloses the positioning of electrodes at an angle to the mirrored platform to improve the relationship between the force applied to the mirror and the gap between the mirror and the electrodes. The MEMs mirror device, disclosed in the aforementioned Hill patent, is illustrated in Figure 1, and includes a rectangular planar surface 2 pivotally mounted by torsional hinges 4 and 5 to anchor posts 7 and 8, respectively, above a substrate 9. The torsional hinges may take the form of serpentine hinges, which are disclosed in United States Patent No 6,327,855 issued December 11, 2001 in the name of Hill et al, and in United States Patent Publication No. 2002/0126455 published September 12, 2002 in the name of Robert Wood. In order to position conventional MEMs mirror devices in close proximity, i.e. with a high fill factor, fill factor=width/pitch, they must be positioned with their axes of rotation parallel to each other. Unfortunately, this mirror construction restraint greatly restricts other design choices that have to be made in building the overall switch.

[04] When using a conventional MEMs arrangement, the mirror 1 positioned on the planar surface 2 can be rotated through positive and negative angles, e.g. ± 2°, by attracting one side 10a or the other side 10b of the planar surface 2 to the substrate 6. Unfortunately, when the device is switched between ports at the extremes of the devices rotational path, the intermediate ports receive light for fractions of a millisecond as the mirror 1 sweeps the optical beam past these ports, thereby causing undesirable optical transient or dynamic cross-talk.

[05] One solution to the problem of dynamic cross-talk is to initially or simultaneously rotate the mirror about a second axis, thereby avoiding the intermediate ports. An example of a MEMs mirror device pivotable about two axes is illustrated in Figure 2, and includes a mirror platform 11 pivotally mounted by a first pair of torsion springs 12 and 13 to an external gimbal ring 14, which is in turn pivotally mounted to a substrate 16 by a second pair of torsion springs 17 and 18. Examples of external gimbal devices are disclosed in United States Patents Nos. 6,529,652 issued March 4, 2003 to Brenner, and 6,454,421 issued September 24, 2002 to Yu et al. Unfortunately, an external gimbal ring greatly limits the number of mirrors that can be arranged in a given area and the relative proximity thereof, i.e. the fill factor. Moreover, the external gimbal ring may cause unwanted reflections from light reflecting off the support frame. These references also require at least four electrodes to actuate each mirror.

[06] Another proposed solution to the problem uses high fill factor mirrors, such as the ones disclosed in United States Patent No. 6,533,947 issued March 18, 2003 to Nasiri et al, which include hinges hidden beneath the mirror platform. Unfortunately, these types of mirror devices require costly multi-step fabrication processes, which increase costs and result in low yields, and rely on four different pairs of electrodes for actuation.

[07] An object of the present invention is to overcome the shortcomings of the prior art by providing two interlaced arrays of MEMs mirror devices, the mirrors in each array being pivotable about different parrallel axes, thereby increasing the spacing between electrodes and minimizing electrical cross-talk.

SUMMARY OF THE INVENTION

[08] Accordingly, the present invention relates to a micro-electro-mechanical device A micro-electro-mechanical device mounted on a substrate comprising:

[09] an array of first pivoting members pivotally mounted on said substrate about a first lateral axis, each of said first pivoting members including a first and a second supporting region on opposite sides of said first lateral axis;

[10] an array of second pivoting members pivotally mounted on said substrate about a second lateral axis parallel to the first lateral axis, each of said second pivoting members including a first supporting region interleaved with the first supporting regions of the first array of pivoting members between said first and second lateral axes, and a second supporting region on an opposite side of the second lateral axis; and

[11] a first electrode beneath each of the second supporting region for pivoting the first and second pivoting members about the first axis from a rest position.

BRIEF DESCRIPTION OF THE DRAWINGS

[12] The invention will be described in greater detail with reference to the accompanying drawings which represent preferred embodiments thereof, wherein:

[13] Figure 1 is an isometric view of a conventional tilting MEMs mirror device;

[14] Figure 2 is a plan view of a pair of conventional external gimbal ring MEMs mirror devices;

[15] Figure 3 is an isometric view of a plurality of Piano-MEMs mirror devices;

[16] Figure 4 is an isometric view of a hinge structure of the mirror devices of Fig. 3;

[17] Figure 5 is an isometric view of an electrode structure of the mirror devices of Fig. 3;

[18] Figure 6 is an isometric view of a plurality of Piano-MEMs mirror devices according to an alternative embodiment of the present invention with electrode shields, light redirecting cusps, and a raised ground plane;

[19] Figure 7 is an isometric view of a plurality of Piano-MEMs mirror devices according to an alternative embodiment of the present invention with electrode shields;

[20] Figure 8 is a plan view of a pair of internal gimbal ring MEMs mirror devices according to the present invention;

[21] Figure 9 is an isometric view of an internal gimbal ring MEMs mirror device according to the present invention;

[22] Figure 10 is an isometric view of an alternative embodiment of the internal gimbal ring MEMs mirror devices according to the present invention;

[23] Figure 11a is an isometric view of a hinge structure of the mirror devices of Fig. 9;

[24] Figure 11b is an isometric view of an alternative hinge structure of the mirror devices of Fig. 9;

[25] Figure 12 is an isometric view of an electrode structure of the mirror devices of Figs. 9 and 10;

[26] Figure 13 is a graph of Voltage vs Time provided by the electrode structure of Fig. 11;

[27] Figure 14 is an isometric view of internal gimbal ring MEMs mirror devices utilizing a three electrode arrangement according to the present invention;

[28] Figure 15 is an isometric view of the three electrode arrangement of Figure 14;

[29] Figure 16 is a plan view of an ideal placement of the three electrodes of Figures 14 and 15 relative to the pivoting platform;

[30] Figure 17 is a plan view of a possible misalignment of the three electrodes of Figures 14 and 15;

[31] Figure 18 is a plan view of another possible misalignment of the three electrodes of Figures 14 and 15;

[32] Figure 19 is a graph of Voltage vs Time for the three electrodes of Figure 14 and 15;

[33] Figure 20 is an isometric view of another embodiment of the present invention with an offset section on the pivoting member;

[34] Figure 21 is a plan view of the embodiment of Figure 20;

[35] Figure 22 is an end view of the embodiment of Figures 20 and 21;

[36] Figure 23 is a top view of a pair of adjacent interlaced mirrors of Figs. 20 to 22 with an alternative reflective cusp;

[37] Figure 24 is a cross-sectional view taken along line A-A from Fig. 23;

[38] Figure 25 is a cross-sectional view taken along line B-B from Fig. 23;

[39] Figure 26 is a top view of an alternative embodiment of interlaced mirror arrays;

[40] Figure 27 is a side view of the embodiment of Fig. 26;

[41] Figure 28 is a schematic diagram of a wavelength switch utilizing the mirror devices of the present invention;

[42] Figure 29 is a schematic diagram of an input/output assembly for the wavelength switch of Fig 28; and

[43] Figure 30 is a schematic diagram of an alternative embodiment of an input assembly for the wavelength switch of Fig. 28.

DETAILED DESCRIPTION

[44] An array of "Piano" MEMs mirror devices 21, 22 and 23, which pivot about a single axis of rotation θ_y above a substrate 25, is illustrated in Figures 3, 4 and 5. Each mirror device 21, 22 and 23 includes a pivoting member or platform 26 defined by first and second substantially-rectangular planar supporting regions 27 and 28 joined by a relatively-thin substantially-rectangular brace 29 extending therebetween. Typically, each planar surface is coated with a reflective coating, e.g. gold, for simultaneously reflecting a pair of sub-beams of light traveling along parallel paths, as will be hereinafter discussed. Each brace 29 acts like a lever and is pivotally mounted to anchor posts 30 and 31 via first and second torsional hinges 32 and 33, respectively. The anchor posts 30 and 31 extend upwardly from the substrate 25. The ends of the first torsional hinge 32 are connected to the anchor post 30 and the brace 29 along the axis θ_y. Similarly, the ends of the second torsional hinge 32 are connected to the anchor post 31 and the brace 29 along the axis θ_y. Preferably, each of the first and second torsional hinges 32 and 33 comprises a serpentine hinge, which are considerably more robust than conventional torsional beam hinges. The serpentine hinge is effectively longer than a normal torsional hinge, which spans the same distance, thereby providing greater deflection and strength, without requiring the space that would be needed to extend a normal full-length torsional hinge.

[45] With particular reference to Figure 5, each platform 26 is rotated by the selective activation of a first electrode 36, which electro-statically attracts the first planar section 27 theretowards or by the selective activation of a second electrode 37, which electro-statically attracts the second planar section 28 theretowards. A gap 38 is provided between the first and second electrodes 36 and 37 for receiving the anchor posts 31, which extend from the substrate 25 to adjacent the platforms 26.

[46] In the disclosed open loop configuration, the angular position of the platforms 26 depend non-linearly on the voltage applied by the electrodes 36 (or 37), i.e. as the applied voltage is increased linearly, the incremental change in angular platform position is greater as the voltage increases. Accordingly, there is a maximum voltage, i.e. an angular platform position, at which the platform angular position becomes unstable and will uncontrollably tilt until hitting part of the lower structure, e.g. the electrode 36. This maximum voltage sets the range of angular motion that the platform 26 can travel. The instability in the platform's angular position is a result of the distance between the platform 26 and the electrode 36 (the hot electrode) decreasing more rapidly at the outer free ends of the platform 26 than at the inner sections, nearer the pivot axis θ_y. As a result, the force per unit length along the platform 26 increases more rapidly at the outer free ends of the platform 26 than the inner sections. To increase the platform's range of angular motion, the field strength, i.e. the force per unit area, that is sensed at the outer free ends of the platform 26 must be reduced. With reference to Figures 5, this is accomplished by providing the electrodes 36 and 37 with a two-step configuration. Upper steps 36a and 37a are positioned proximate the inner end of the platform 26, i.e. the Y axis, while lower steps 36b and 37b are positioned under the outer free ends of the platform 26, thereby making the gap between the platforms 26 and the electrodes 36 and 37 greater at the outer free end than the inner end. The area of the lower steps 36b and 37b can also be made smaller, thereby reducing the force per unit area sensed by the outer free end of the platform 26. Multi-step electrodes, e.g. three or more can also provide a more even distribution of force.

[47] A consequence of closely packed micro-mirrors is that the actuation of a single mirror will impart a torque, i.e. an angular rotation, onto adjacent mirrors as a result of fringing electric fields. In an effort to minimize this cross-talk, electrode grounding shields 41 are positioned on the substrate 25 around or on either side of the first and second electrodes 36 and 37 forming electrode cavities, which are electrically isolated from each other. Figure 5 illustrates C-shaped grounding shields 41, which include lateral portions 41a for partially surrounding the first and second electrodes 36 and 37. The grounding shields 41 are kept at ground potential, i.e. the same as the mirrored platforms 26, while one of the first and second electrodes is held at an activation voltage, e.g. 100 Volts.

[48] Trace lines 36c and 37c electrically connect the electrodes 36 and 37, respectively, to a voltage supply (not shown). Since the trace lines 36c and 37c also act as a hot electrode, i.e. contributing to the total torque applied to the platform 26, covering the traces 36c and 37c with a ground plane 43 (Figure 6) also reduces the force applied to the outer free end of the platform 26.

[49] Figure 6 also illustrates an alternative configuration for the electrode 36, in which the two step hot electrode 36 is sunken slightly below a surrounding grounded metallic surface, which is a continuation of the ground plane 43. A small vertical step 44 between the hot electrode 36 and the surrounding ground plane 43 is a dielectric surface that isolates the hot electrode 36 from the surrounding ground plane 43. This arrangement reduces the angular drift of the platform 26, which is caused by a build up of electrostatic charges on exposed dielectric or insulating surfaces. The electric field generated by these electrostatic charges perturbs the electric field generated by the applied voltage from the electrodes 36 and 37, thereby causing the angular position of the platform 26 to drift over time. The present arrangement limits the exposed dielectric to the small vertical surface 44, which generates electrostatic field lines that do not significantly affect the field lines between the hot electrodes 36 and 37 and the ground plane 43. To further reduce the angular drift of the platform 26, the vertical surface 44 can be under cut beneath the ground plane 43 at a slight negative angle ensuring that the gap between the hot electrode 36 and the ground plane 43 is substantially zero. The ground plane 43 could also be positioned slightly below the hot electrodes 36 and 37 to create the vertical step.

[50] Since the MEMs mirror devices 21, 22 and 23 are for use in optical devices, i.e. wavelength blockers and multiple wavelength switches (see Figure 23), which include a grating for dispersing the light into spectral wavelength component channels, it is an important performance requirement that the spectral response has a high rejection of light between the selected wavelength channels. Unfortunately, in conventional MEMs devices, light passes between the mirrors and is reflected off the substrate back into the optical device, thereby leading to a deterioration in the isolation between the wavelength channels. Accordingly, the present invention provides back reflection cusps 50, defined by angled, curved or concave reflecting surfaces intersecting along a ridge, extending longitudinally below the gap between the platforms 26, for scattering any light passing between the mirrored platforms 26 in a direction substantially parallel to the surface of the platforms 26.

[51] To further eliminate cross-talk between adjacent electrodes, additional platform shields 42 (Figure 7) can be added to the underside of the planar supporting regions 27 and 28, outside or inside of the electrode shields 41. Typically, in the rest position, the two different sets of shields 41 and 42 do not overlap; however, as the platform 26 tilts the platform shields 42 begin to overlap the grounding shielding 41. The added protection provided by overlapping shielding is particularly advantageous, when the tilt angle of the platform 26 is proportional to the voltage applied to the electrode 36 (or 37), such as in open loop configurations. Accordingly,

the greater the tilt angle, the greater the required voltage, and the greater the amount of potential cross-talk, but consequently the greater the amount of shielding provided by the overlapping ground and platform shields 41 and 42, respectively. Back reflection cusps 50 are also provided for reasons hereinbefore discussed. A single structure 50 between adjacent electrodes can replace the pair of adjacent shields 41.

[52] With reference to Figures 8, a pair of internal gimbal ring MEMs mirror devices 131 and 132 are illustrated mounted adjacent each other on a substrate 133. The present invention enables mirrors 134 and 135 to be positioned relatively close together, i.e. with a high fill factor, while still providing the two degrees of motion provided by the more complicated prior art.

[53] With further reference to Figure 9, a first torsion hinge 137, preferably in the form of a rectangular beam, is fixed, proximate the middle thereof, to the substrate 133 via a central anchor post 138. The supporting structure for the mirror device of the present invention is based on a single anchor post 138, rather than the dual anchor points required in the aforementioned external gimbal ring devices. The first torsion hinge 137 provides for rotation θ_y about a first axis Y, and may also include a serpentine hinge 140, as illustrated in mirror device 131, or any other torsional hinge known in the art. Opposite sides of an internal gimbal ring 139 are connected to opposite ends of the first torsion hinge 137, whereby the first torsion hinge 137 bisects the internal gimbal ring 139. The internal gimbal ring 139 is preferably not flexible, but can take various geometric forms, although rectangular or circular frames would be the most convenient to fabricate and use. Spring arms 141 and 142, which define a second torsion hinge, extend outwardly from opposite sides of the internal gimbal ring 139 perpendicular to the first torsion hinge 137. Each of the spring arms may also include a serpentine hinge as hereinbefore described. The second torsion hinge provides for rotation θ_x about a second axis X, which is perpendicular to the first axis Y, but still substantially in the same plane as the mirrors 134 and 135. A generally rectangular platform 143, for supporting one of the mirrors 134 or 135, is mounted on the ends of the spring arms 141 and 142. Preferably, the platform 143 is comprised of a pair of rectangular planar surfaces 144 and 145 joined together by a pair of elongated braces 147 and 148, which extend on either side of the internal gimbal ring 139 parallel with the spring arms 141 and 142.

[54] Fabrication of the preferred embodiment illustrated in Figures 8 and 9, is simplified by having all of the structural elements, i.e. the first torsional hinge 137, the gimbal ring 139, the spring arms 141 and 142, and the first and second planar surfaces 144 and 145, in the same upper substrate layer and having coplanar upper surfaces, whereby the same basic process steps are used as are used to fabricate the MEMs device illustrated in Figure 1. In particular, a single photolithographic step is used to identify the structural elements, followed by a deep reactive ion etching (DRIE) step used to remove the unwanted portions of the upper substrate. Finally the moveable elements in the upper substrate are released from the lower substrate by removal of a sacrificial layer therebetween.

[55] Figures 10 and 11a illustrate an array of internal gimbal ring MEMs mirror devices 201 utilizing a first pair of serpentine torsional hinges 202 for pivoting a rectangular platform 203, including first and second planar supporting regions 203a and 203b, about a first axis of rotation θ_x, and a second pair of serpentine torsional hinges 204 for rotating the platform 203 about a second axis of rotation θ_y above a base substrate 205. The first and second planar supporting regions are joined by a pair of elongated braces 200. The first pair of serpentine torsional hinges 202 extend from a single anchor post 206, which extends upwardly from the base substrate 205 through the center of the platform 203, i.e. at the intersection of the minor and major axes thereof. Outer ends of the first pair of torsional serpentine torsional hinges 202 are connected to a rectangular gimbal ring 208, which surrounds the first pair of serpentine hinges 202, at points along the minor axes (θ_y) of the platform 203. The second pair of serpentine torsional hinges 204 extend from opposite sides of the gimbal ring 208 into contact with the platform 203, at points along the major axis (θ_x) of the platform 203.

[56] An alternative hinge structure for the mirror array 201, illustrated in Figure 11b, includes the first pair of serpentine torsional hinges 202 extending from anchor post 206 enabling the platform 203 to rotate about the y axis; however, only a single serpentine torsional hinge 204 is provided enabling rotation about the x axis. Accordingly, a C-shaped gimbal ring 209 extends from the ends of the hinges 202, partially surrounding the hinges 202, into contact with the end of the single hinge 204.

[57] To provide a full range of motion for the platform 143 or 203, a set of four two-step electrodes 211, 212, 213 and 214 are provided (See Fig. 12); however, for the present invention only the first, second and third electrodes 211, 212 and 213 are required to roll the mirrors out of alignment with any intermediate output ports and then back into alignment with a designated output port. As in Figure 5, each of the electrodes 211, 212, 213 and 214 include an upper step 211a, 212a, 213a, and 214a, and a lower step 211b, 212b, 213b, 214b, respectively, for reasons discussed hereinbefore. Accordingly, first, second and third voltages can be established between the platform 143 or 203 and the first electrode 211, the second electrode 212 and the third electrode 213, respectively. Initially, the first and second electrodes 211 and 212 are activated to rotate the platform 143 or 203 about θ_x. Subsequently, the first voltage is gradually lowered to zero, while the third voltage is gradually increased until it is equivalent to the second voltage (See Fig 13). To minimize unwanted effected caused by ringing, i.e. vibration of the mirrors caused by an abrupt start or stop, the first, second and third voltages are increased and decreased gradually, e.g. exponentially, as evidenced in Figure 13, which illustrates the voltages curves for the various electrodes (first, second and third) over the actuation time of the mirror device. Various mirror tilting patterns can be designed based on the desired characteristics, e.g. attenuation, of the light.

[58] An improved electrode configuration is illustrated in Figures 14 and 15, in which a first two-step θ_y electrode 236 includes an upper U-shaped step 236a, and a lower rectangular step 236b. The arms of the U-shaped step 236a extend from the lower step 236b on opposite sides of the second hinge 204 beneath the first planar supporting region 203a. Similarly, a second two-step θ_y electrode 237 includes an upper U-shaped step 237a, and a lower rectangular step 237b. The arms of the U-shaped step 237a extend from the lower rectangular step 237b on opposite sides of the second hinge 204 beneath the second planar supporting region 203b. A single two-step θ_x electrode 238 includes an upper U-shaped step 238a, and lower rectangular steps 238b extending from each arm of the upper U-shaped step. The single θ_x electrode 238 extends from adjacent the first θ_y electrode 236 to adjacent the second θ_y electrode 237 across the gap therebetween, and beneath one side of both the first and second planar supporting regions 203a and 203b. The lower steps 238b provide a larger gap between the outer free ends of the platform 203, when the platform is tilted towards the first or the second θ_y electrode 236 or 237. The arms of the upper U-shaped step 238b extend on opposite sides of the first pair of hinges

202. The arms of the U-shaped step 238a are three to five times wider than the arms of the U-shaped step 236a or 237a. Multi-step electrodes are also possible to further spread the application of force over the length of the platform 203. Actuation of the electrodes is controlled by an electrode control 240, as will be discussed hereinafter with reference to Figure 19.

[59] An unfortunate consequence of relying on only three electrodes is that a slight misalignment in positioning the platform 203 over the first and second θ_y electrodes 236 and 237 can result in an imbalance that can not be corrected for using the single θ_x electrode 238. Figure 16 illustrates the ideal case, in which the longitudinal axis of the first electrode 236 is aligned with the longitudinal axis X of the platform 203. However, Figure 17 illustrates the results of a mask misalignment during fabrication, in which the longitudinal axis X of the platform 203 has a $+\Delta x$ misalignment relative to the electrode axis. Accordingly, actuation of the first θ_y electrode 236 would introduce an undesirable tilt in the platform 203 towards the bottom left hand corner, which could not be compensated by the single θ_x electrode 238. In Figure 18, the illustrated mask misalignment, in which the longitudinal axis X of the platform 203 has a $-\Delta x$ misalignment relative to the electrode axis. In this case, actuation of the first θ_y electrode 236 would introduce an undesirable tilt in the platform 203 towards the top left hand corner. However, this tilt can be compensated for by applying a voltage to the single θ_x electrode 238. Accordingly, the solution to the problem of mask misalignment is to introduce an intentional or predetermined $-\Delta x$ misalignment, which would cancel or at least minimize any $+\Delta x$ misalignment and which could be compensated for by the single θ_x electrode 238.

[60] Figure 19 illustrates an electrode voltage vs time graph, detailing the voltages of the three electrodes 236, 237 and 238 as the platform 203 is switched from one position to another by an electrode control, i.e. from reflecting light from one port to another, without traveling directly, i.e. without reflecting light into any intermediate ports. To prevent undesirable "ringing" of the platform 203, the voltage VyR of the first θ_y electrode 236 is gradually decreased as the voltage Vx of the single θ_x electrode 238 is increased. As the voltage VyR decreases to zero, the voltage VyL of the second θ_y electrode 237 gradually increases. As the voltage VyL reaches its set amount to maintain the platform in the desired position, the voltage Vx is decreased to a minimum amount, assuming no compensation voltages are required.

[61] When the size of the platform 203 is decreased, e.g. for small pitch micro-mirrors in the order of <100um, the electrodes 236, 237 and 238 must also be constructed correspondingly smaller. However, due to the fact that the electrodes necessarily become thinner, while sharing the same mirror section, stable tilt angles are difficult to achieve at high resonant frequencies. Accordingly, the size requirement of the electrode, and the required electrode spacing become the limiting factor in determining the maximum fill factor. An alternative embodiment of a three electrode configuration is illustrated in Figures 20 and 21, in which two parallel arrays of platforms 253 and 254 are made smaller than the original platforms 203 with first and second two-step θ_y electrodes 256 and 257 positioned therebelow. A single θ_x electrode 258 is positioned below each offset section 259 and 260, which extend from the side of the platforms 253 and 254, respectively, adjacent the mid-section thereof, i.e. the area of first and second hinges 251 and 252. This arrangement enables the single θ_x electrode 258 to be separated from the other two electrodes 256 and 257, and therefore, be larger in size, which enables the electrostatic torque to be increased for a common voltage. The added separation between the electrodes 256, 257 and 258 minimizes the angular instabilities, when the single θ_x electrode 238 is actuated, and reduces the amount of electrical x-talk. Preferably, the two-step θ_x electrodes 256 and 257 include the ground plane arrangement as disclosed in Figure 6 with hot electrodes sunken relative to a surrounding ground plane, and only a vertically extending dielectric layer, which provides a substantially zero-width vertical gap between the hot electrode and the ground plane.

[62] For high fill factor applications, a first planar section 253a of one platform 253 from the first array is positioned beside a second planar section 254b of an adjacent platform 254 from the second array, as in Figures 20 and 21, whereby adjacent mirrors have offset x axes X_1 and X_2, and every other platform pivots about the same laterally extending x axis. Each or the platforms 253 and 254 are also rotatable about separate parallel longitudinal axes. Only the relatively closely disposed planar sections would require reflective material thereon, and reflective cusps 260 would only be required therebelow (Figure 22).

[63] Substrate-mounted, grounded cross-talk shields 261 and platform mounted cross-talk shields 262 are provided to further minimize the amount of electrical cross-talk between adjacent mirrors. The platform mount cross-talk shields 262 are preferably mounted outside of the platform mounted cross-talk shields 262 with enough spacing to enable rotation about both the x and the y axis; however, any combination for offsetting the shields 261 and 262 is possible.

[64] Figures 23 to 25 illustrate another embodiment of the reflective cusps specific to the interlaced mirrors of Figures 20 to 22. To ensure that the outer free ends of the platforms 253 and 254 does not contact the reflective cusps 260, a portion of the reflective cusp 260a is positioned below the platforms 253 extending from an inner end proximate the anchor post to proximate the midway point of the first planar section 253a, and a portion of the reflective cusp 260b is positioned below the platforms 254 extending from proximate the anchor post to proximate the midway point of the second planar section 254b. The portions of the reflective cusp 260a and 260b can extend any suitable length, whereby the ends thereof are directly adjacent each other providing overlapping protection. The portions of the reflective cusps 260a and 260b can have the same or different lengths.

[65] A simple alternative to the interlaced mirrors of Figures 20 to 25 are illustrated in Figures 26 and 27, in which a first array of 1-d Piano MEMs mirrors 273 pivot about a first lateral axis X_1 via a single pair of torsional hinges 274, and a second array of 1-d Piano MEMs mirrors 275 pivot about a second lateral axis X_2 via a single pair of torsional hinges 276. A first sections 273a and 275a of the platforms 273 and 275, respectively, are preferably larger than a second sections 273b and 275b, respectively, to enable the size of single electrodes 277 and 278 to be wider and/or shorter than the size of the second sections 273b and 275b. Activation of the single electrodes 277 and 278 attracts the first sections 273a and 275a, respectively, thereby pivoting the platforms 273 and 275 about the first lateral axes X_1 and X_2, respectively. The platforms 273 and 275 returns to the horizontal set position when the single electrodes 277 and 278 are deactivated due to the resilient spring force inherent in the platforms 273 and 275. Since the hinges 274 and 274 are not as wide as the second sections 273b and 275b, the second sections 273b and 275b form an array of closely packed reflective surfaces between the first and second lateral axes X_1 and X_2. Preferably, the electrodes 277 and 278 are two step electrodes, as above, and include the ground plane arrangement as disclosed in Figure 6 with hot electrodes sunken relative to a surrounding ground plane, and only a vertically extending dielectric layer, which provides a substantially zero-width vertical gap between the hot electrode and the ground plane.

[66] With the aforementioned configuration, the mirror to mirror electrical crosstalk can be reduced even for relatively small mirror pitches, e.g. < 70 um, because the closest adjacent electrodes are separated by a mirror length in one direction, and by up to half a mirror pitch in the other direction. The voltage-tilt angle and the resonant frequency characteristics are also improved for low pitches due to the increase electrode area and resultant electrostatic torque. Furthermore, the electrical pin-out is reduced to one connection per mirror.

[67] The "piano" MEMs mirror devices according to the present invention are particularly useful in a wavelength switch 301 illustrated in Figures 28, 29 and 30. In operation, a beam of light with a plurality of different wavelength channels is launched via an input/output assembly 302, which comprises a plurality of input/output ports, e.g. first, second, third and fourth input/output ports 303, 304, 305 and 306, respectively. The beam is directed to an element having optical power, such as concave mirror 309, which redirects the beam to a dispersive element 311, e.g. a Bragg grating. The dispersive element separates the beam into the distinct wavelength channels (λ_1, λ_2, λ_3), which are again directed to an element having optical power, e.g. the concave mirror 309. The concave mirror 309 redirects the various wavelength channels to an array of "piano" MEMs mirror devices 312 according to the present invention, which are independently controlled to direct the various wavelength channels back to whichever input/output port is desired. Wavelength channels designated for the same port are reflected back off the concave mirror 309 to the dispersive element 311 for recombination and redirection off the concave mirror 309 to the desired input/output port. The concave mirror 309 can be replaced by a single lens with other elements of the switch on either side thereof or by a pair of lenses with the dispersive element 311 therebetween.

[68] With particular reference to Figure 29, the input/output assembly 302 includes a plurality of input/output fibers 313a to 313d with a corresponding collimating lens 314a to 314d. A single lens 316 is used to convert a spatial offset between the input/output ports into an angular offset. Figure 30 illustrates a preferred embodiment of the input/output assembly, in which the unwanted effects of polarization diversity are eliminated by the use of a birefringent crystal 317 and a waveplate 318. For incoming beams, the lens 316 directs each beam through the birefringent crystal 317, which separates the beam into two orthogonally polarized sub-beams (o and e). The half waveplate 318 is positioned in the path of one of the sub-beams for rotating the polarization thereof by 90°, so that both of the sub-beams have the same polarization for transmission into the remainder of the switch. Alternatively, the waveplate 318 is a quarter waveplate and rotates one of the sub-beams by 45° in one direction, while another quarter waveplate 319 rotates the other sub-beam by 45° in the opposite direction, whereby both sub-beams have the same polarization. For outgoing light, the polarization of one (or both) of the similarly polarized sub-beams are rotated by the waveplate(s) 318 (and 319), so that the sub-beams become orthogonally polarized. The orthogonally polarized sub-beams are then recombined by the birefringent crystal 317 and output the appropriate input/output port. The micro-electro-mechanical devices according to the present invention are particularly well suited for use in switching devices with polarization diversity front ends, since they provide a pair of reflecting surfaces, i.e. one for each sub-beam

WE CLAIM:

1. A micro-electro-mechanical device mounted on a substrate comprising:

an array of first pivoting members pivotally mounted on said substrate about a first lateral axis, each of said first pivoting members including a first and a second supporting region on opposite sides of said first lateral axis;

an array of second pivoting members pivotally mounted on said substrate about a second lateral axis parallel to the first lateral axis, each of said second pivoting members including a first supporting region interleaved with the first supporting regions of the first array of pivoting members between said first and second lateral axes, and a second supporting region on an opposite side of the second lateral axis; and

a first electrode beneath each of the second supporting regions for pivoting the first and second pivoting members about the first and second axes, respectively from a rest position;

first torsional hinges anchored to the substrate along the first lateral axis enabling the first array of pivoting members to pivot about the first lateral axis; and

second torsional hinges anchored to the substrate along the second lateral axis enabling the second array of pivoting members to pivot about the second lateral axis;

wherein the first and second torsional hinges also enable the first and second pivoting members to rotate about longitudinal axes perpendicular to the first and second lateral axes; and

wherein each of the first and second torsional hinges includes a first hinge anchored to the substrate, and a second hinge anchored to the first and second pivoting members.

2. The device according to claim 1, wherein the first and second torsional hinges are resilient for restoring the pivoting members to the rest position.

3. The device according to claim 1 or 2, wherein the first supporting region is wider than the first and second torsional hinges enabling adjacent first supporting regions to be positioned in close proximity.

4. The device according to claim 1, 2 or 3, further comprising a gimbal ring between the first hinge and the second hinge at least partially surrounding the first hinge.

5. A micro-electro-mechanical device mounted on a substrate comprising:

an array of first pivoting members pivotally mounted on said substrate about a first lateral axis, each of said first pivoting members including a first and a second supporting region on opposite sides of said first lateral axis, the first supporting regions including a reflective material thereon for reflecting light;

an array of second pivoting members pivotally mounted on said substrate about a second lateral axis parallel to the first lateral axis, each of said second pivoting members including a first supporting region interleaved with the first supporting regions of the first array of pivoting members between said first and second lateral axes, and a second supporting region on an opposite side of the second lateral axis, the first supporting regions disposed adjacent one another between the first and second lateral axes and including a reflective material thereon for reflecting light; and

a first electrode beneath each of the second supporting regions for pivoting the first and second pivoting members about the first and second axes, respectively, from a rest position;

wherein the second supporting regions of the first and second pivoting members are wider than the first supporting regions of the first and second pivoting members, respectively, for increasing electrostatic torque on the first and second pivoting members.

6. The device according to claim 5, further comprising first torsional hinges anchored to the substrate along the first lateral axis enabling the first array of pivoting members to pivot about the first lateral axis; and second torsional hinges anchored to the

substrate along the second lateral axis enabling the second array of pivoting members to pivot about the second lateral axis.

7. A micro-electro-mechanical device mounted on a substrate comprising:

an array of first pivoting members pivotally mounted on said substrate about a first lateral axis, each of said first pivoting members including a first and a second supporting region on opposite sides of said first lateral axis;

an array of second pivoting members pivotally mounted on said substrate about a second lateral axis parallel to the first lateral axis, each of said second pivoting members including a first supporting region interleaved with the first supporting regions of the first array of pivoting members between said first and second lateral axes, and a second supporting region on an opposite side of the second lateral axis;

a first electrode beneath each of the second supporting regions for pivoting the first and second pivoting members about the first and second axes, respectively, from a rest position;

first torsional hinges anchored to the substrate along the first lateral axis enabling the first array of pivoting members to pivot about the first lateral axis;

second torsional hinges anchored to the substrate along the second lateral axis enabling the second array of pivoting members to pivot about the second lateral axis, wherein the first and second torsional hinges also enable the first and second pivoting members to rotate about longitudinal axes perpendicular to the first and second lateral axes;

an offset section extending from each of the first and second pivoting members from adjacent said first and second torsional hinges; and

a second electrode beneath each of the offset sections for pivoting the first and second pivoting members about one of the longitudinal axes.

8. The device according to claim 7, wherein the offset sections of the first pivoting members extend to adjacent an end of the second pivoting members.

9. The device according to claim 7 or 8, further comprising: a third electrode beneath each of the first supporting regions; and electrode control means for each of the first and second pivoting members for gradually decreasing a voltage to said first electrode to a minimum, while increasing a voltage to said second electrode to a maximum, and for gradually increasing a voltage to said third electrode, while decreasing the voltage to said second electrode to a minimum, thereby indirectly rotating the first or second pivoting member about the first or second lateral axes, respectively.

10. A micro-electro-mechanical device mounted on a substrate comprising:

an array of first pivoting members pivotally mounted on said substrate about a first lateral axis, each of said first pivoting members including a first and a second supporting region on opposite sides of said first lateral axis;

an array of second pivoting members pivotally mounted on said substrate about a second lateral axis parallel to the first lateral axis, each of said second pivoting members including a first supporting region interleaved with the first supporting regions of the first array of pivoting members between said first and second lateral axes, and a second supporting region on an opposite side of the second lateral axis; and

a first electrode beneath each of the second supporting regions for pivoting the first and second pivoting members about the first and second axes ~~axis~~ from a rest position; and

shields disposed on each side of said first electrodes beneath the first and second pivoting members for limiting the amount of electrical cross-talk between adjacent first electrodes, thereby enabling the first supporting regions of the first and second pivoting members to be closely packed;

wherein the shields extend upwardly from the substrate above a top surface of the first electrodes; and

wherein each shield includes a light reflective cusp comprising a ridge with a angled reflective surface extending therefrom for redirecting light passing between adjacent first supporting regions, thereby preventing light from being reflected back.

11. The device according to claim 10, wherein the first and second torsional hinges also enable the first and second pivoting members to rotate about longitudinal axes perpendicular to the first and second lateral axes.

12. The device according to claim 10 or 11, wherein the shields also extend downwardly from an undersurface of said first and second pivoting members.

13. The device according to claim 10 or 11, wherein the shields extend upwardly from the substrate above a top surface of the first electrode, and downwardly from an undersurface of said first pivoting member inside or outside of the upwardly extending shields.

14. The device according to any one of claims 10 to 13, wherein the light reflective cusps beneath the first pivoting members extend beneath the first supporting regions from beneath an inner end thereof to beneath a point between the inner end and an outer free end thereof; wherein the light reflective cusps under the second pivoting members extend beneath the first supporting regions from beneath an inner end thereof to beneath a point between the inner end and an outer free end thereof; and wherein light passing between the first supporting regions of the first and second pivoting members will reflect off of either the light reflective cusps beneath the first pivoting members or the light reflective cusps under the second pivoting members.

15. The device according to claim 14, wherein the light reflective cusps beneath the first supporting region of the first and second pivoting members extend substantially half way between the inner end and the outer free end thereof.

Figure 1
Prior Art

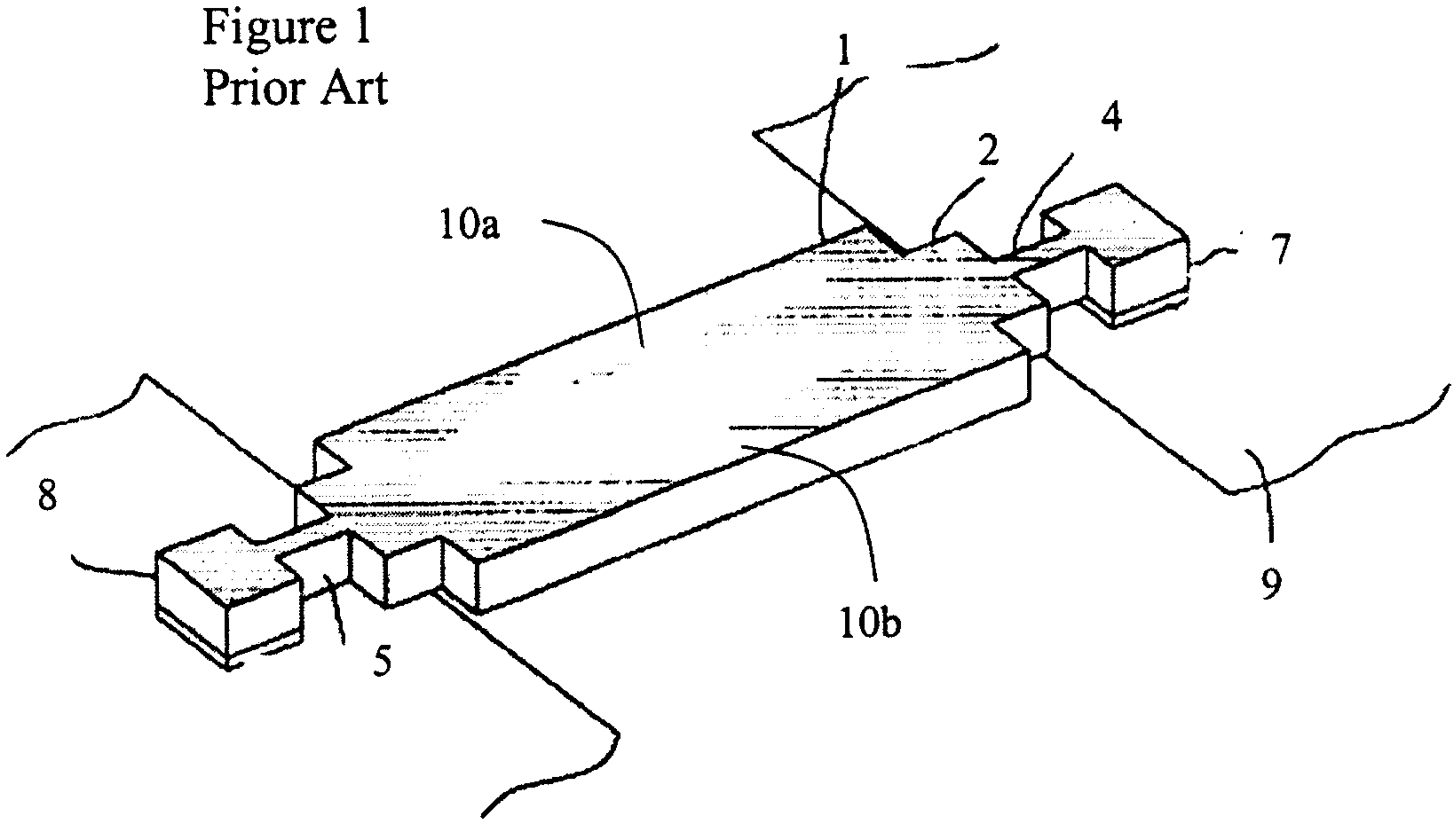


Figure 2
Prior Art

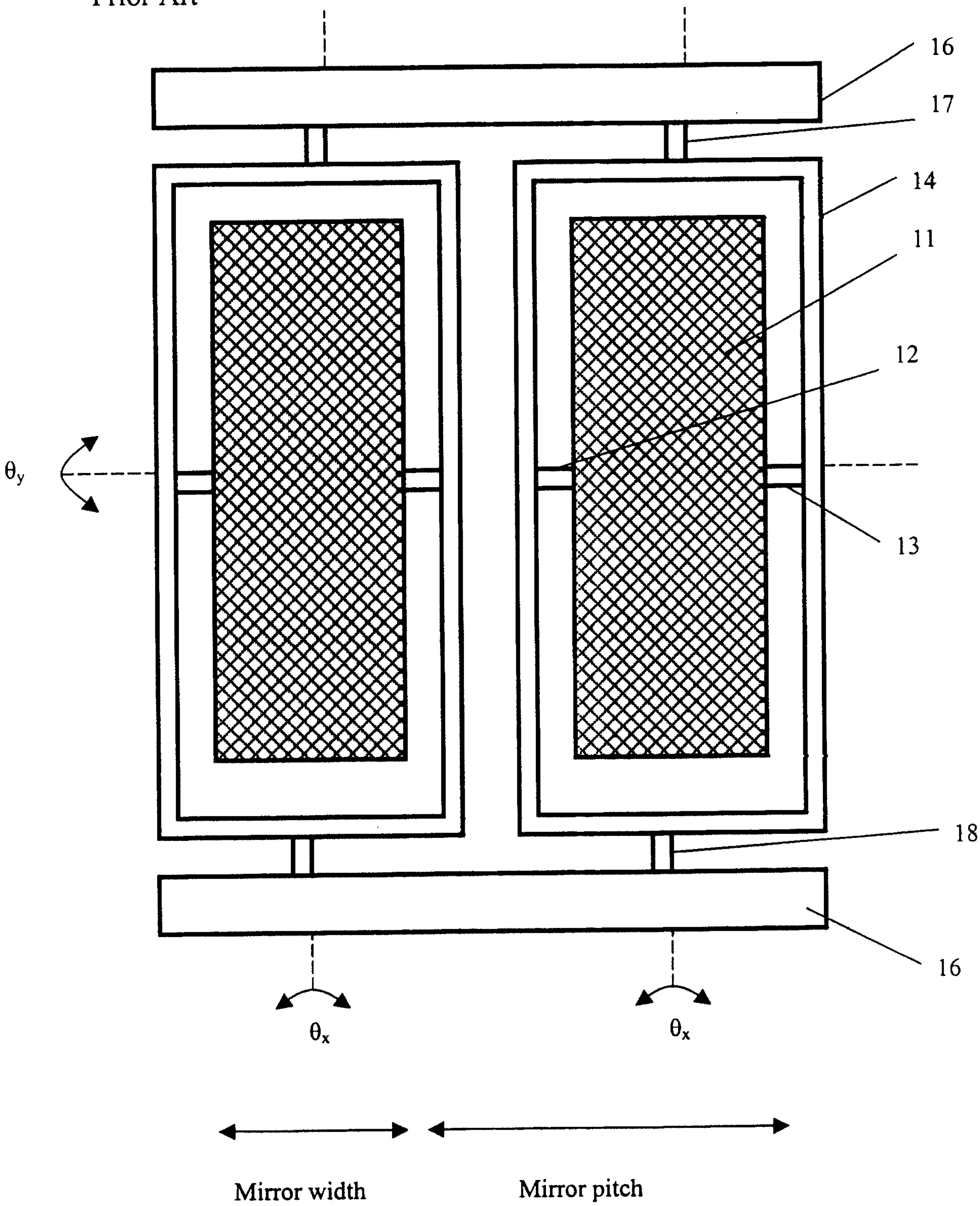


Figure 3

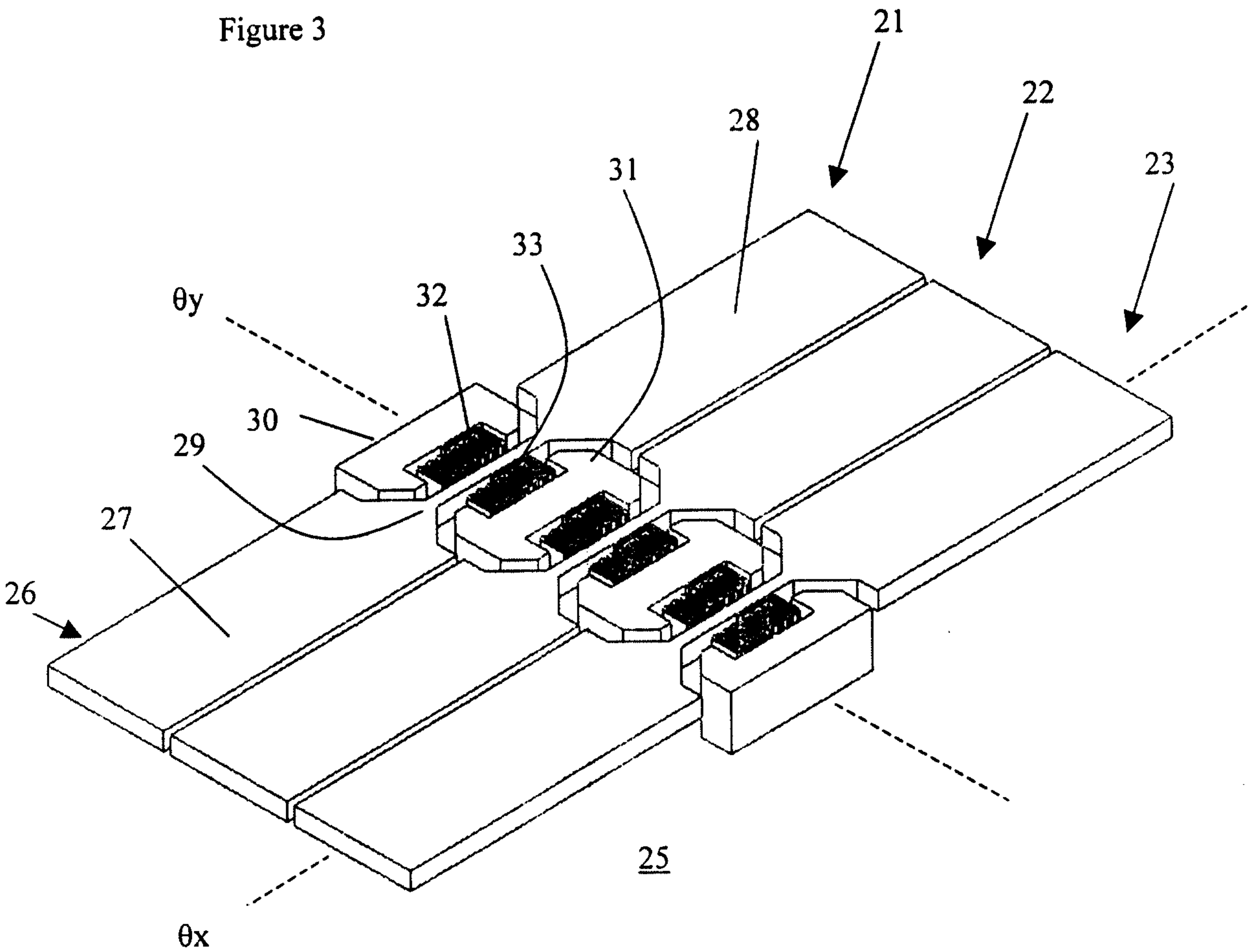


Figure 4

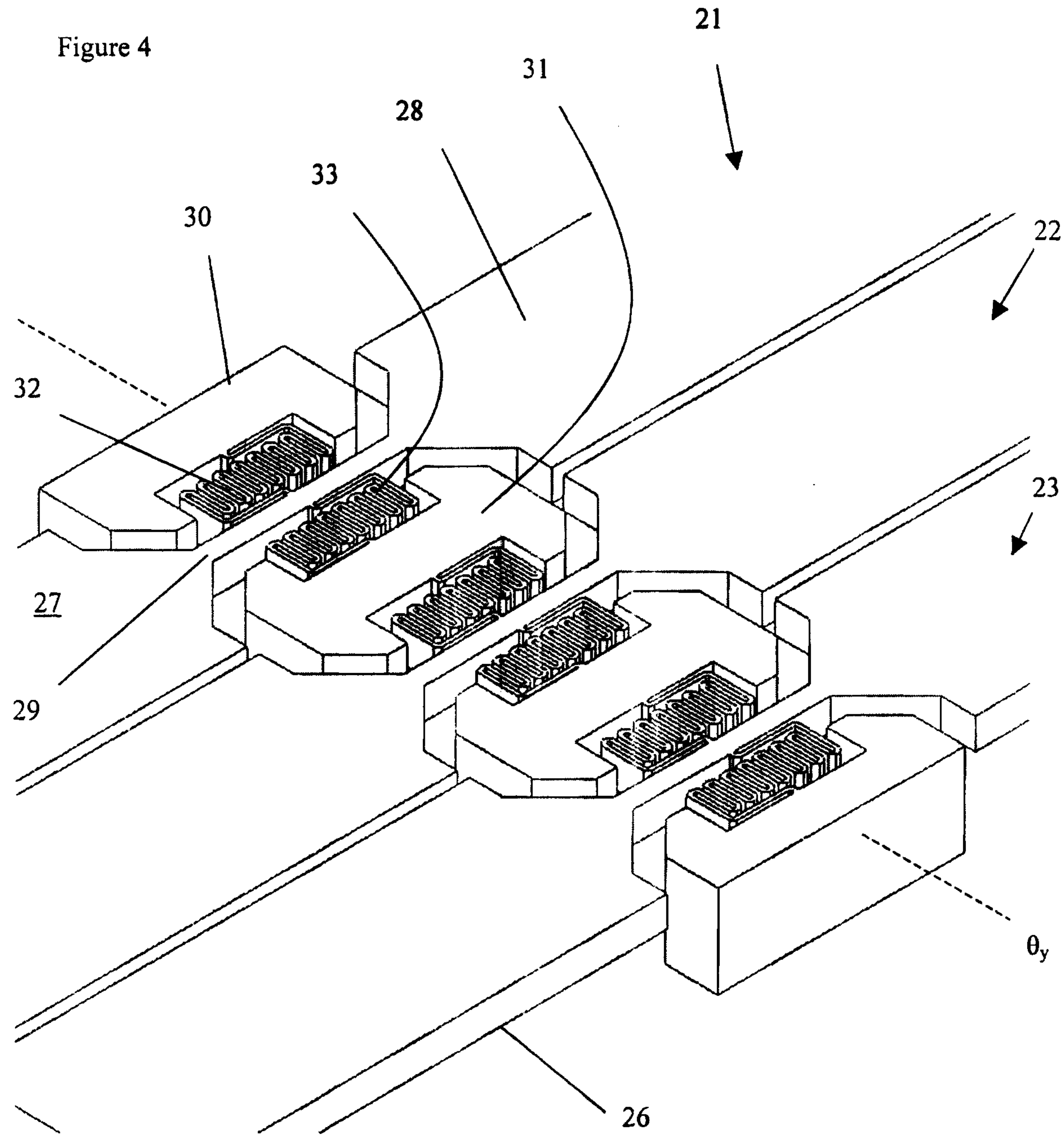
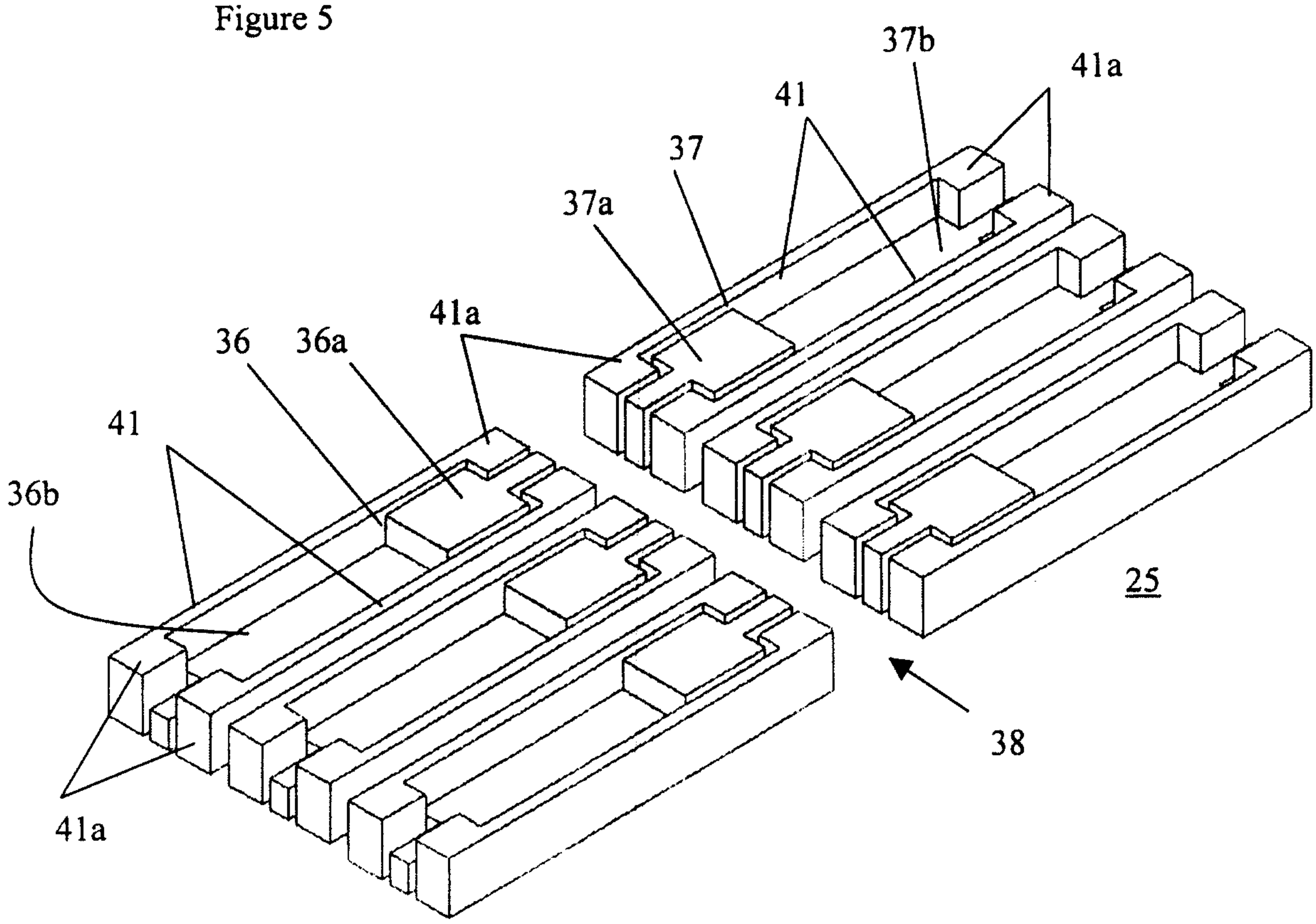


Figure 5



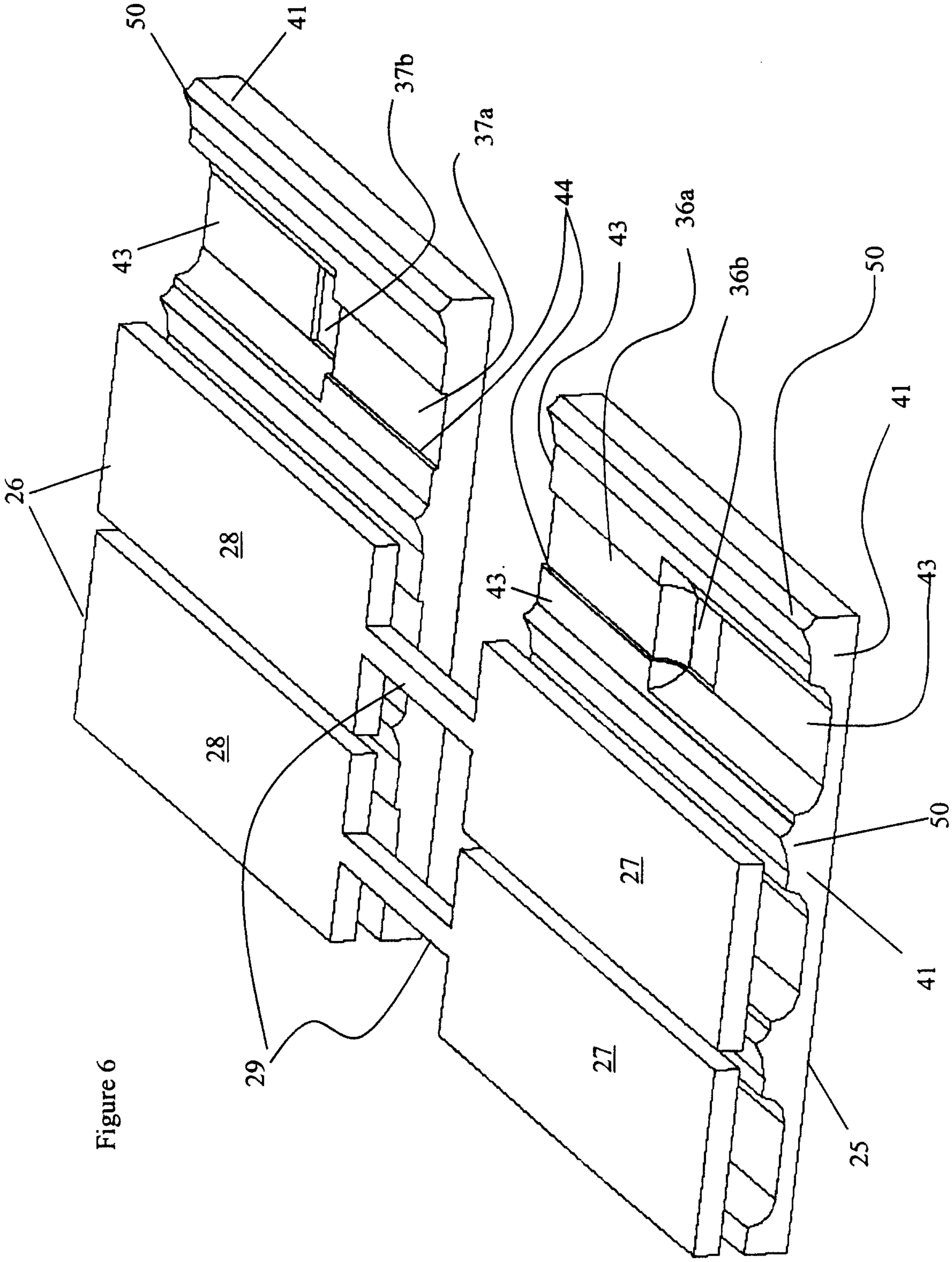


Figure 6

Figure 7

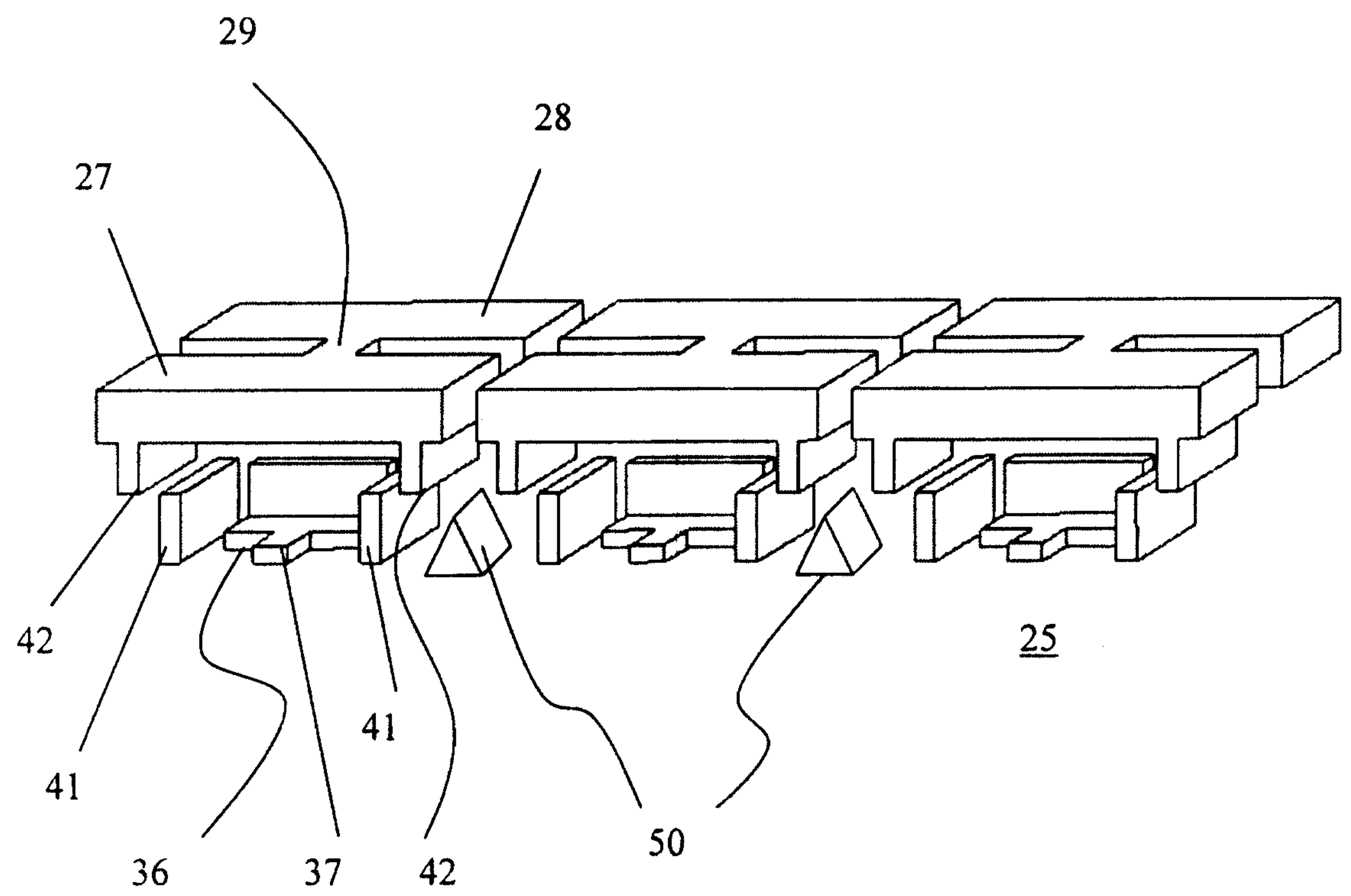


Figure 8

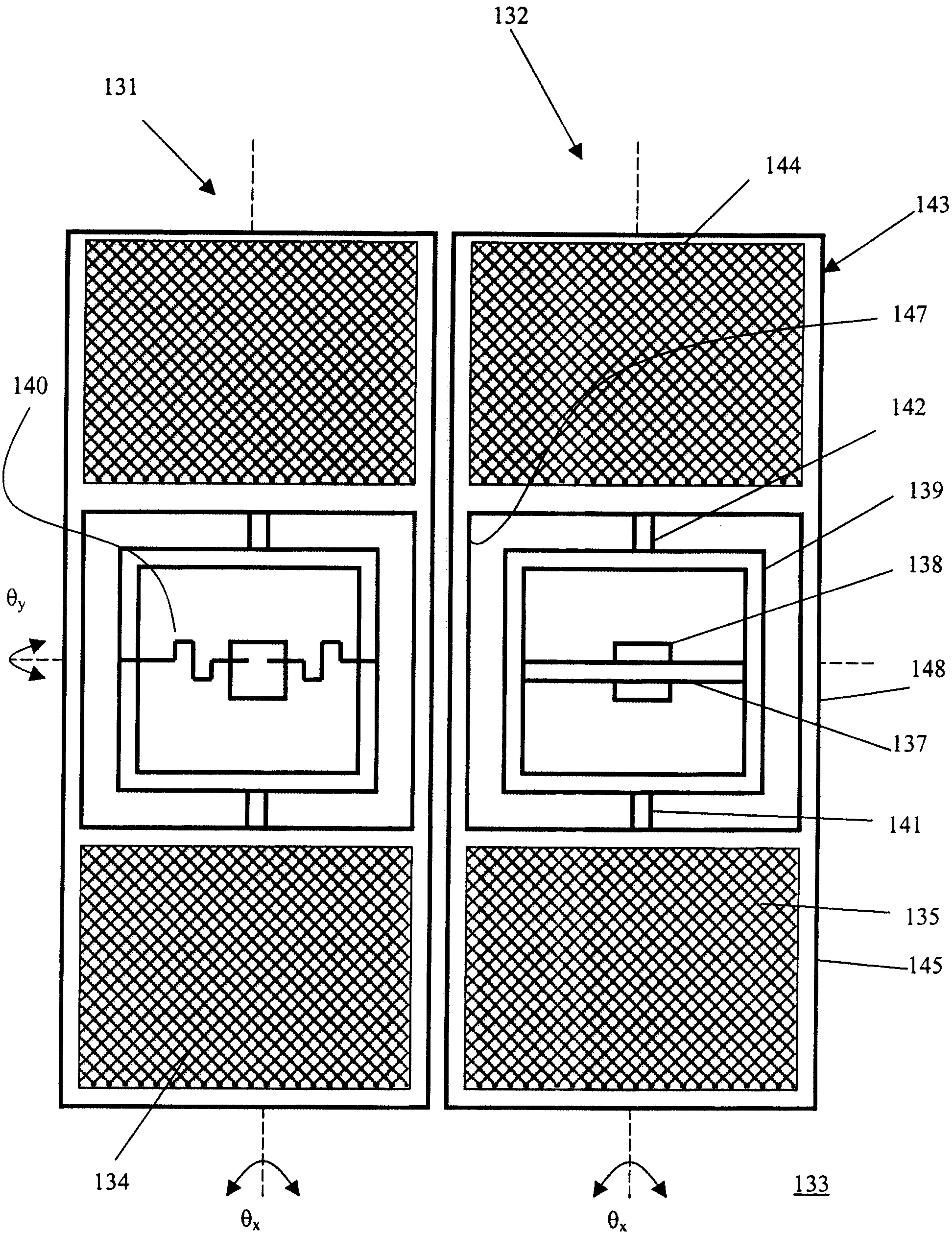
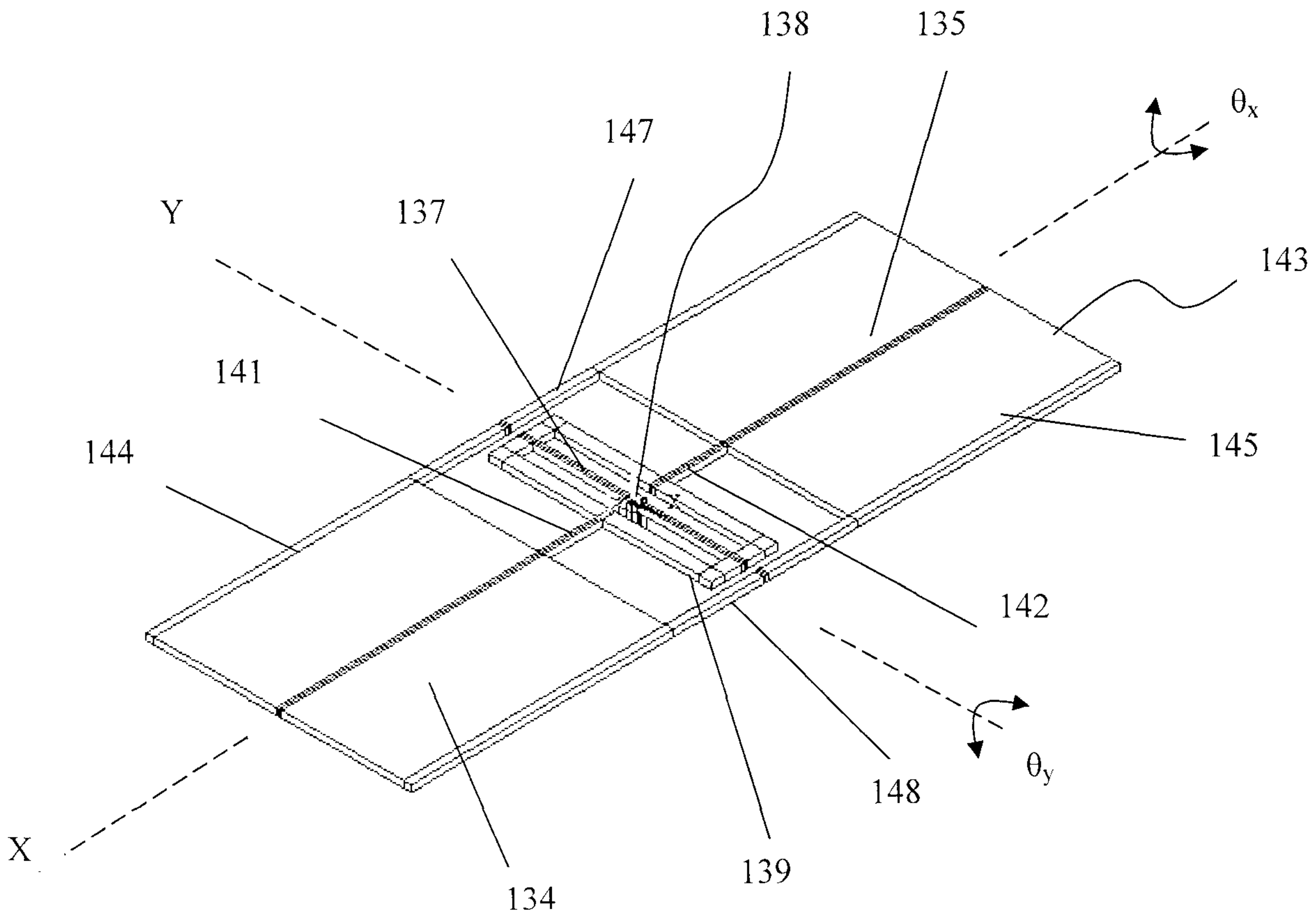
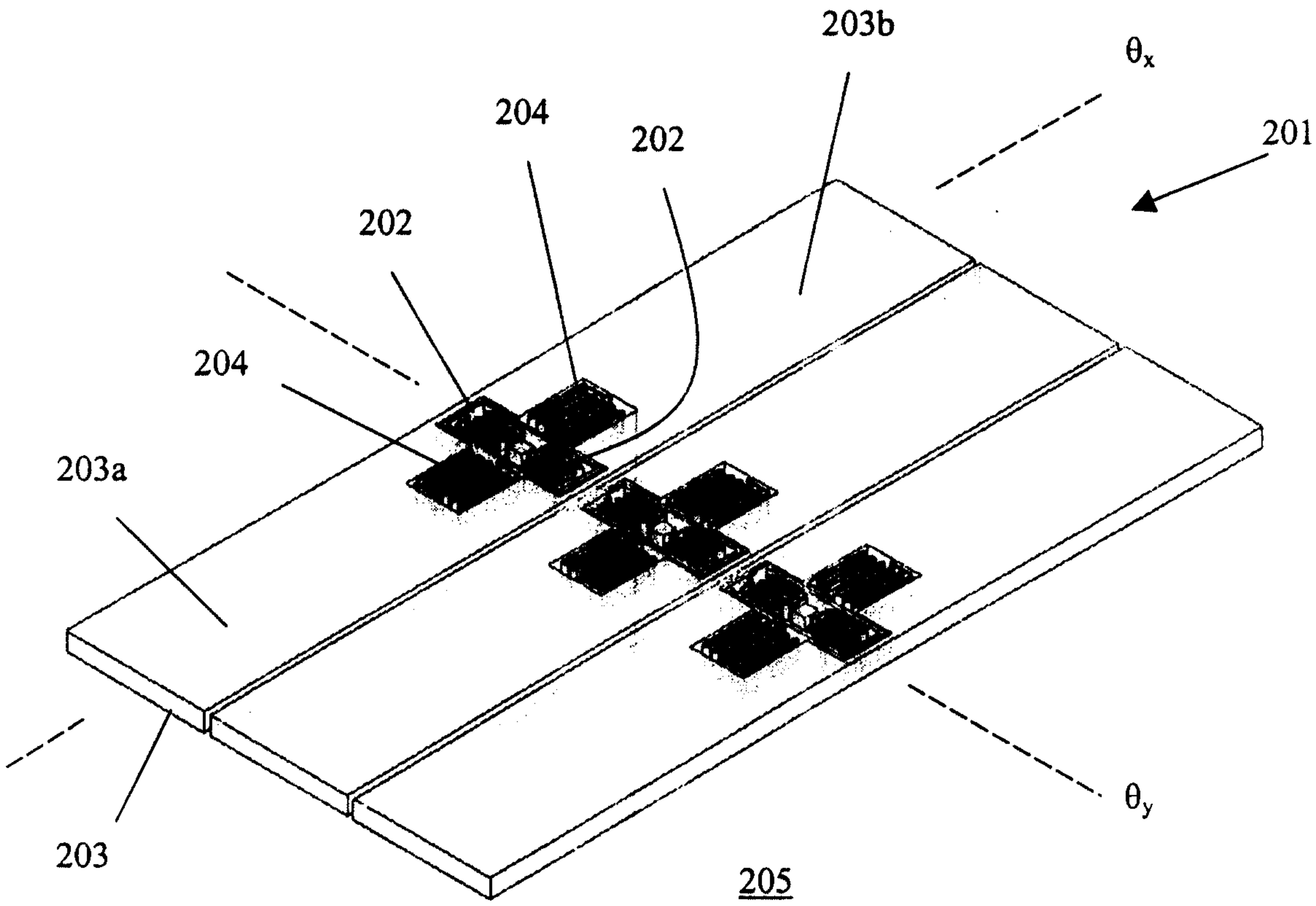

132
131
144
143
147
140
142
139
138
θy
148
137
141
135
145
134
θx
θx
133

Figure 9



133

Figure 10



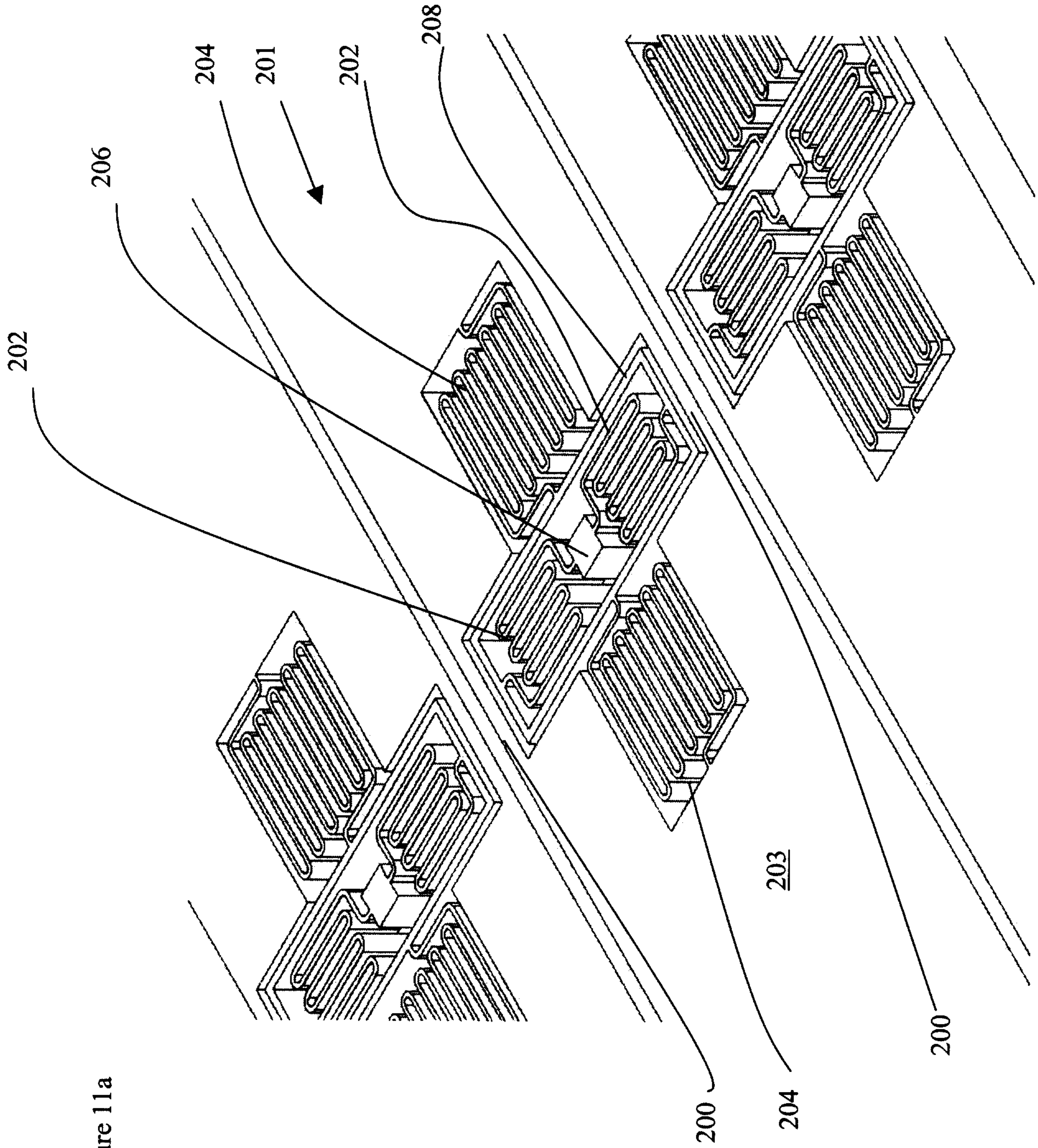


Figure 11a

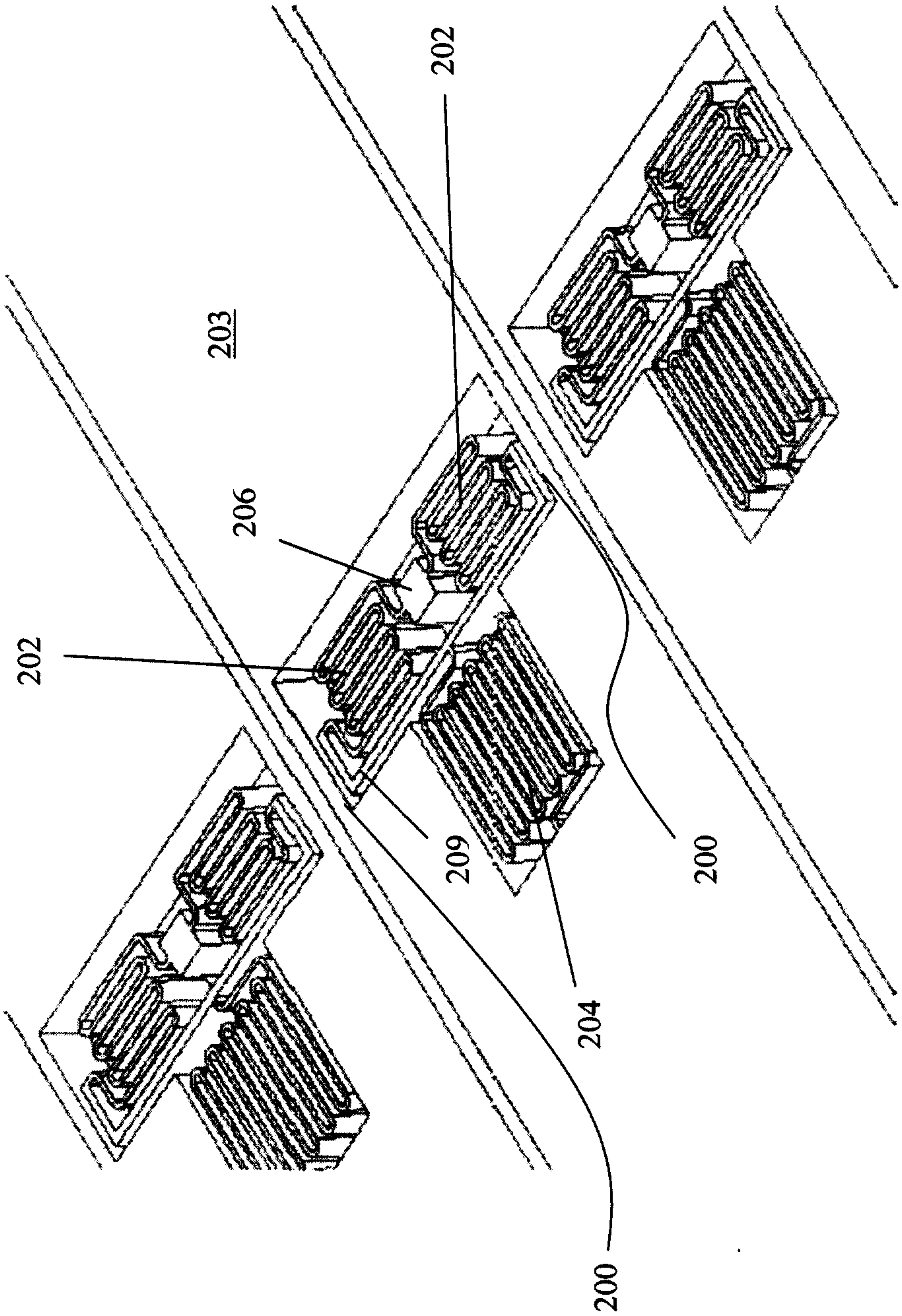


Figure 11b

Figure 12

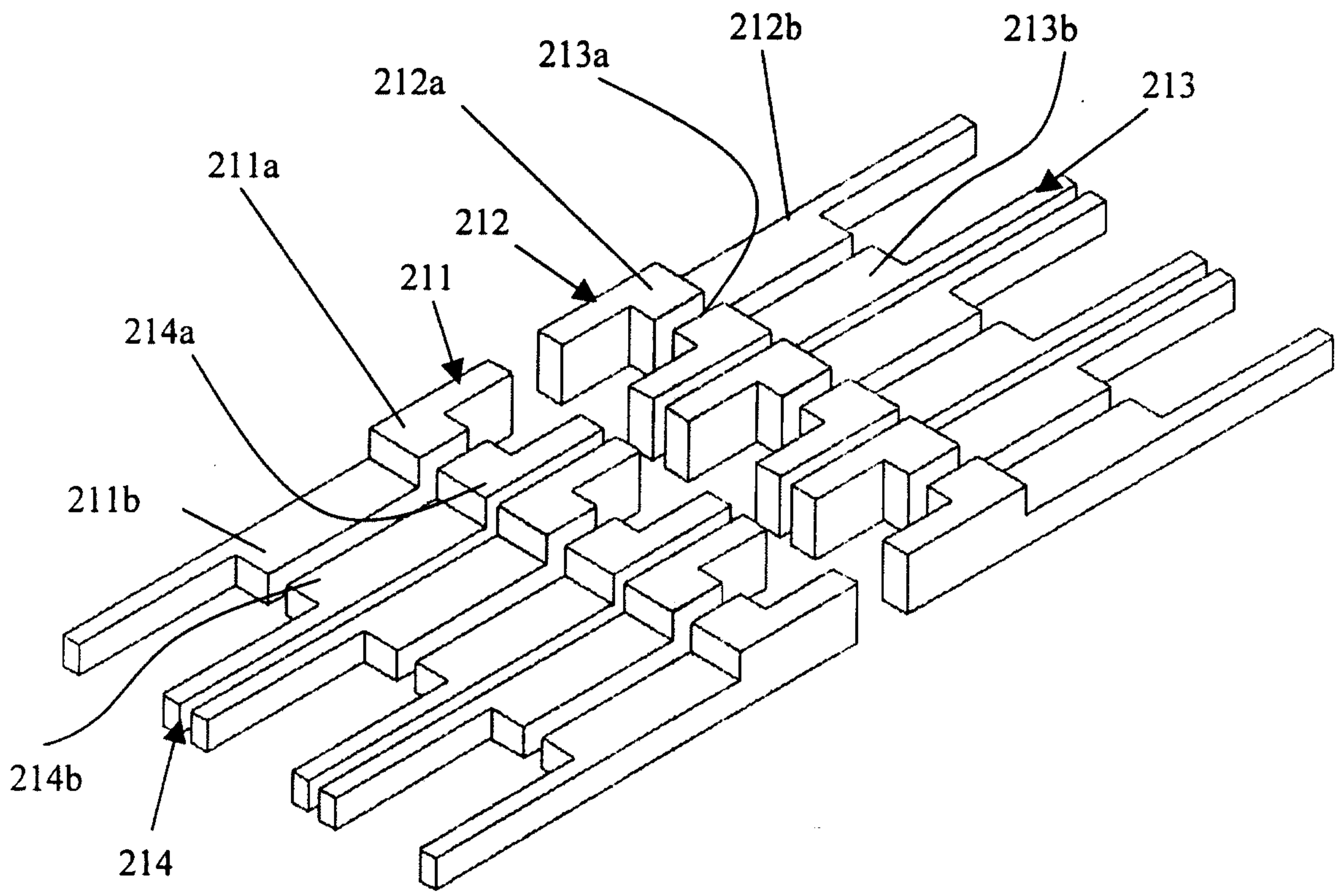


Figure 13

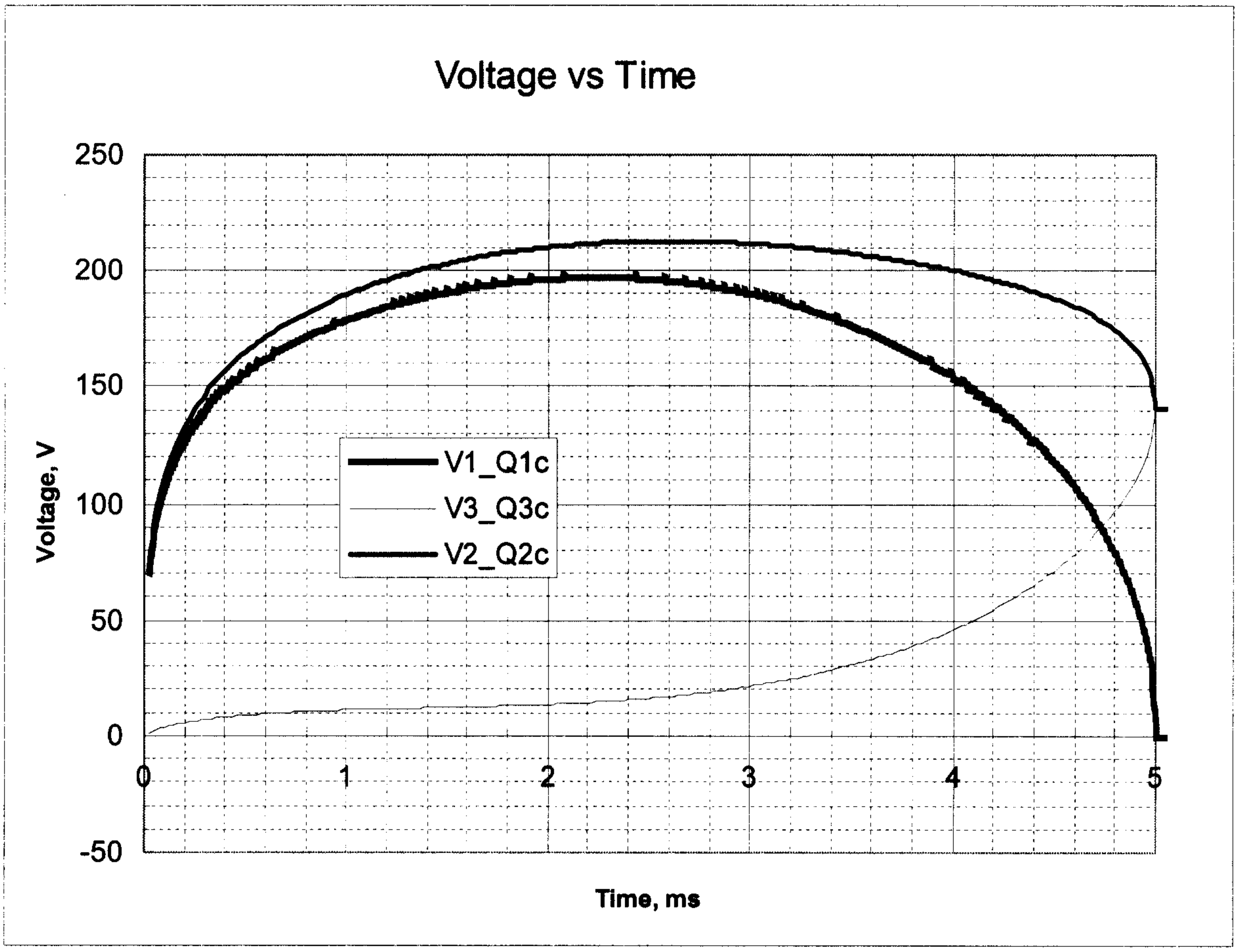

Voltage vs Time
250
200
150
100
50
0
-50
Voltage, V
0
1
2
3
4
5
Time, ms
V1_Q1c
V3_Q3c
V2_Q2c

Figure 14

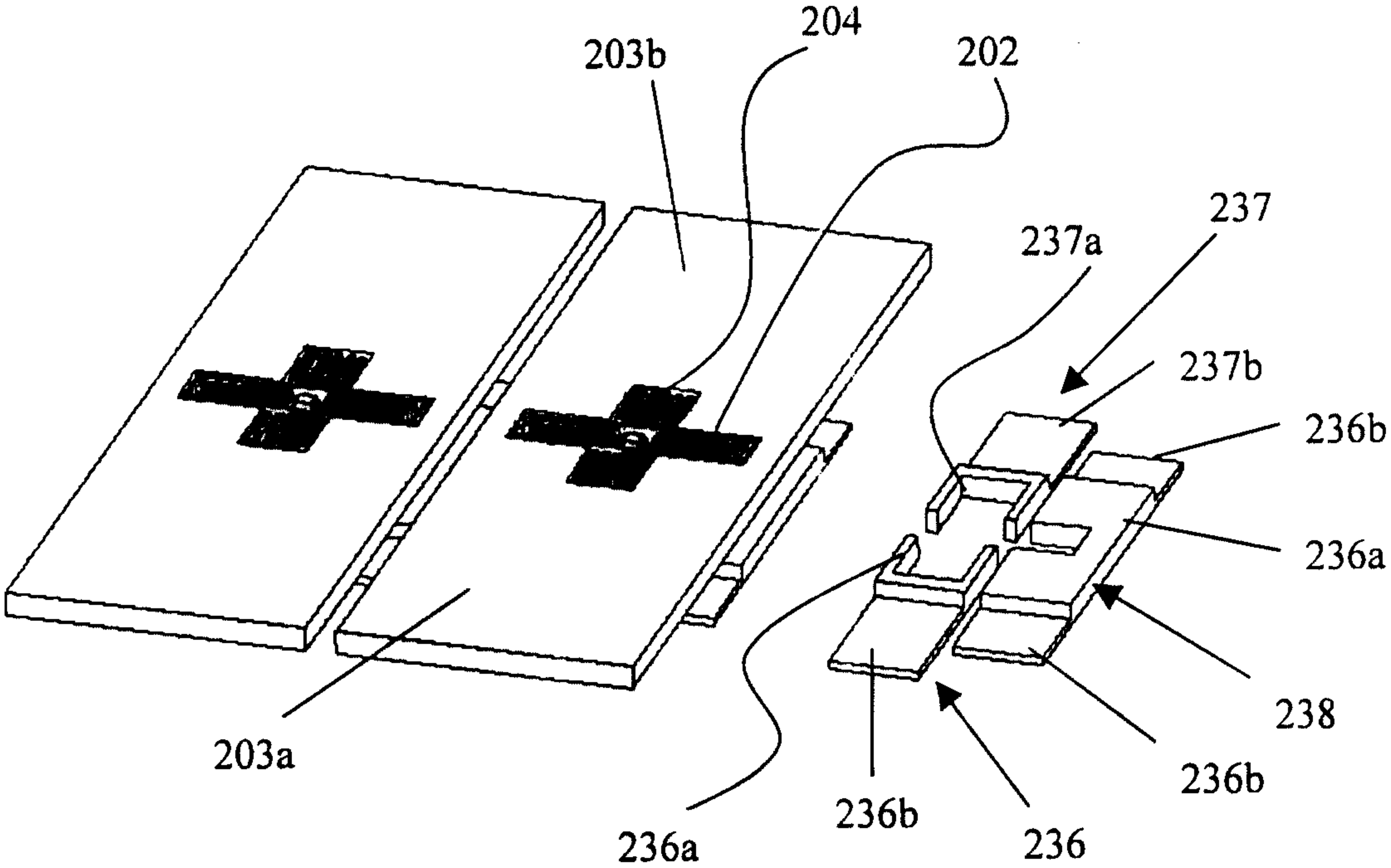
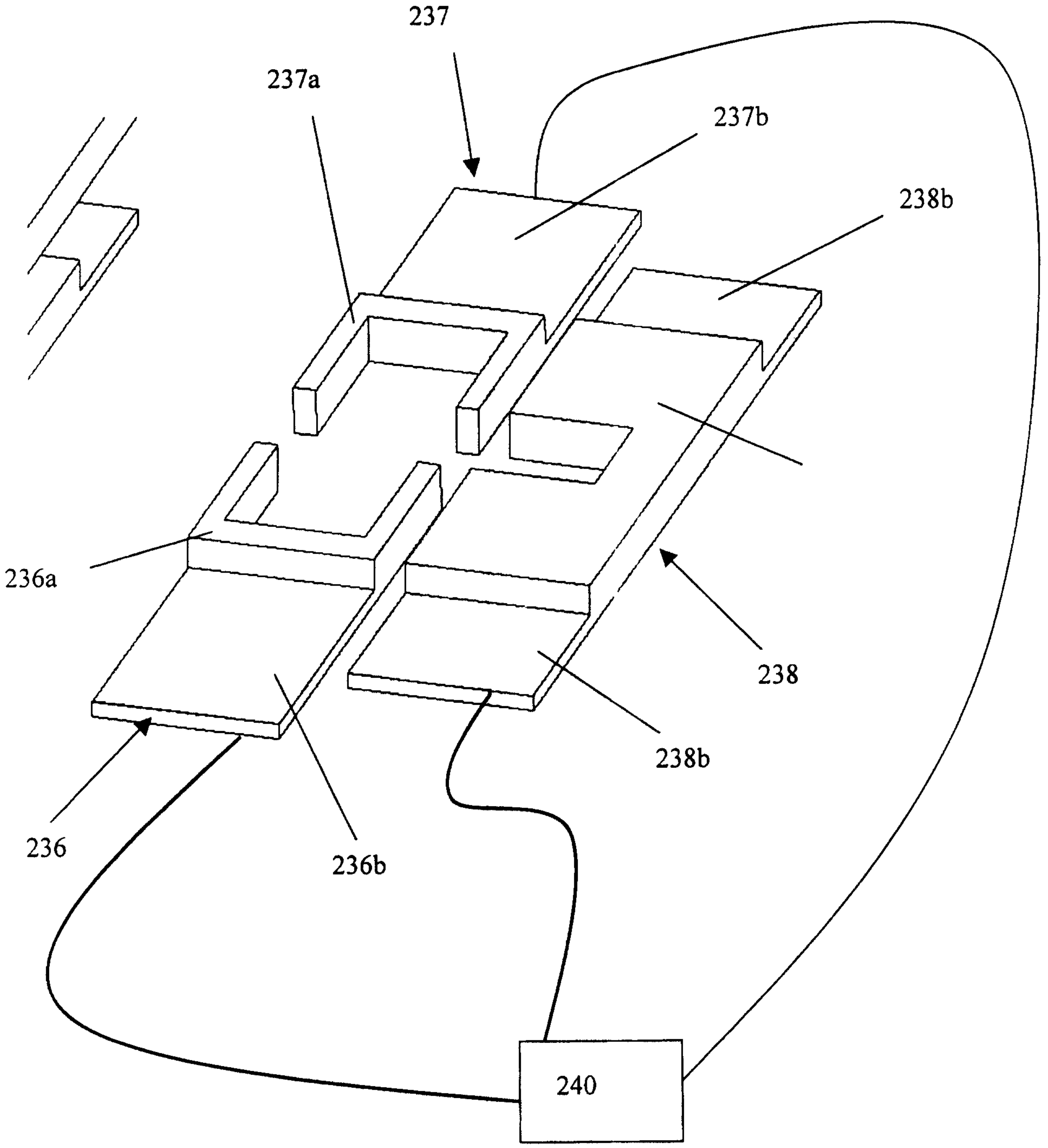

204
203b
202
237
237a
237b
236b
236a
238
203a
236b
236
236b
236a

Figure 15



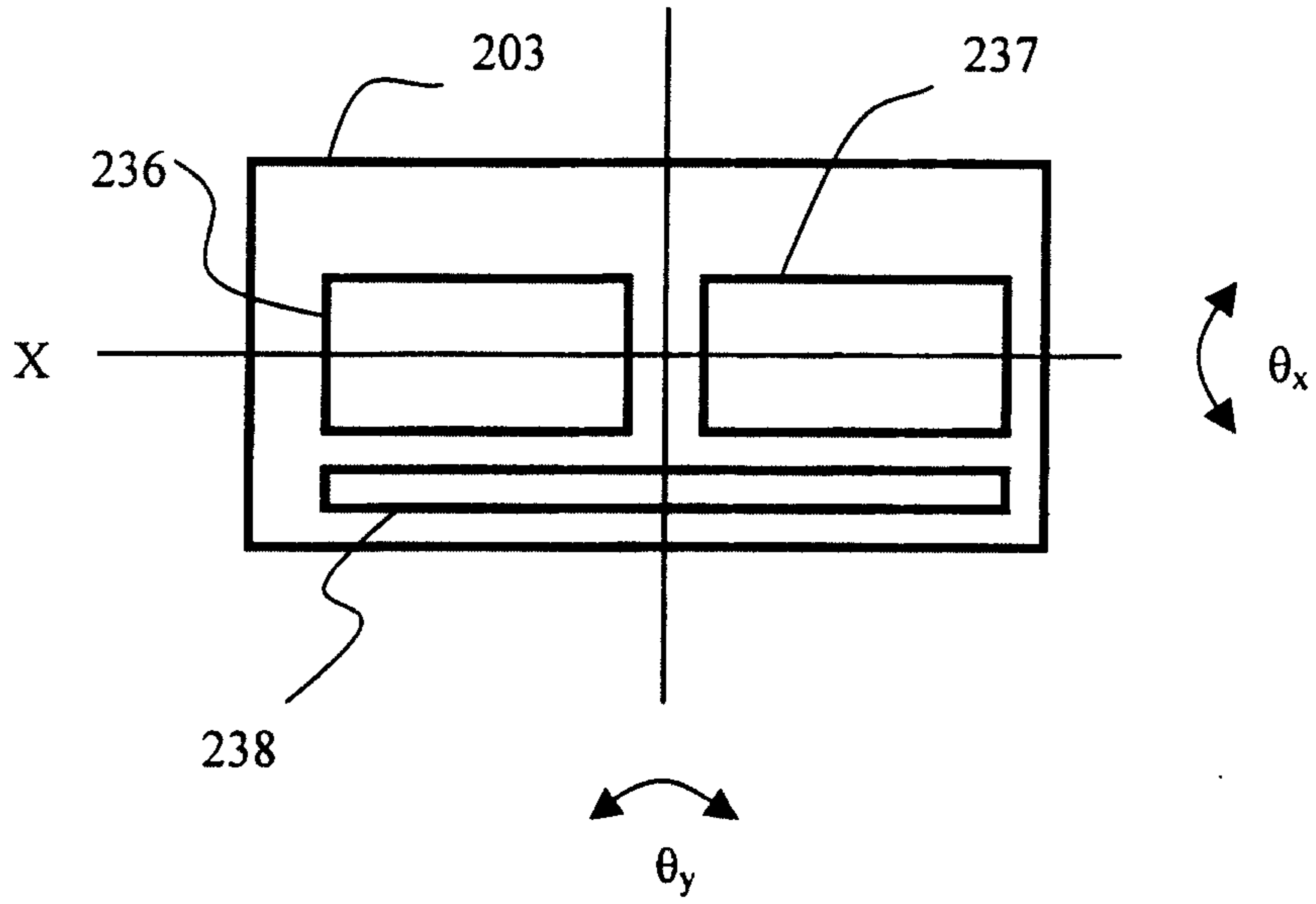


Figure 16

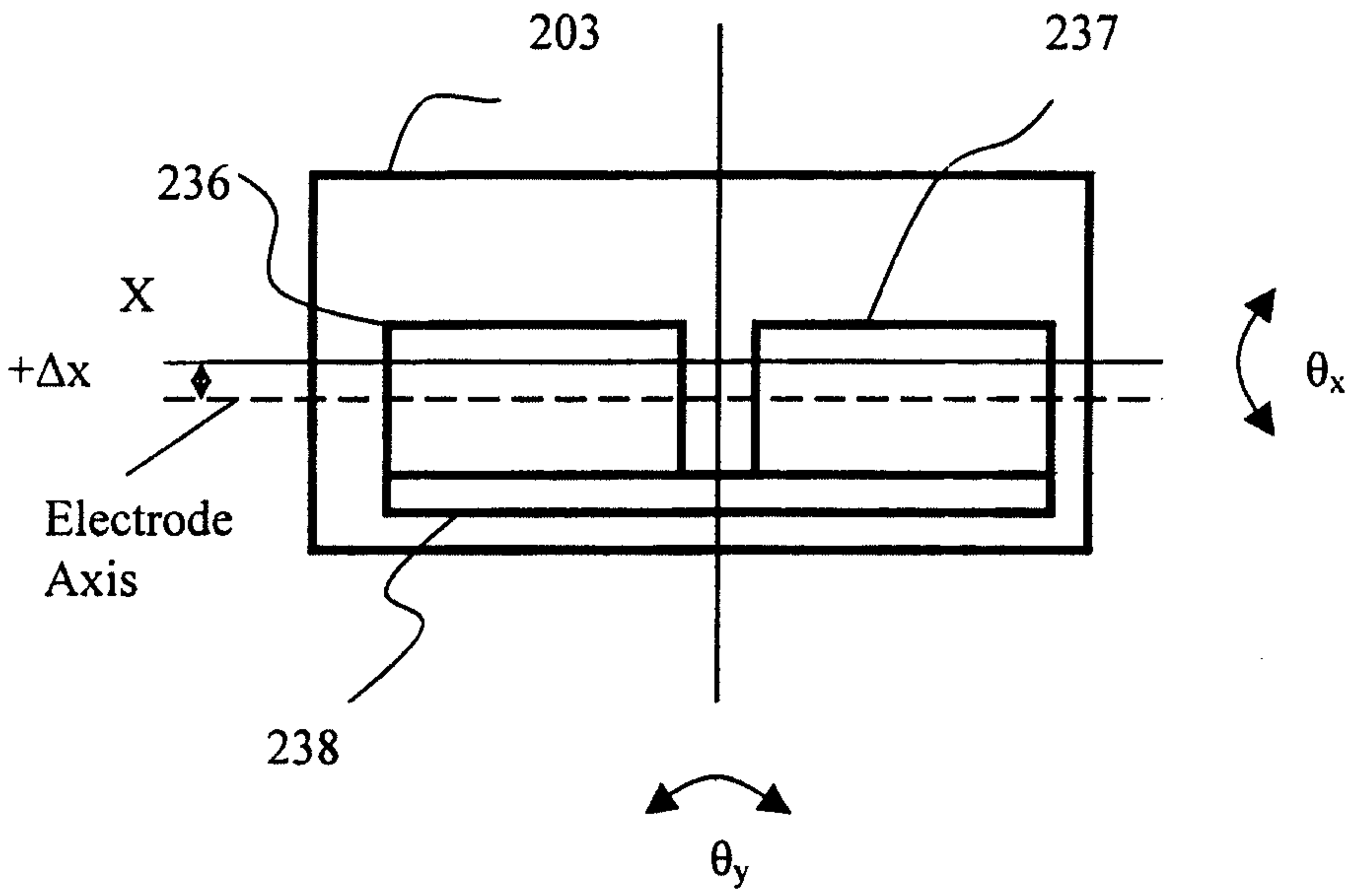


Figure 17

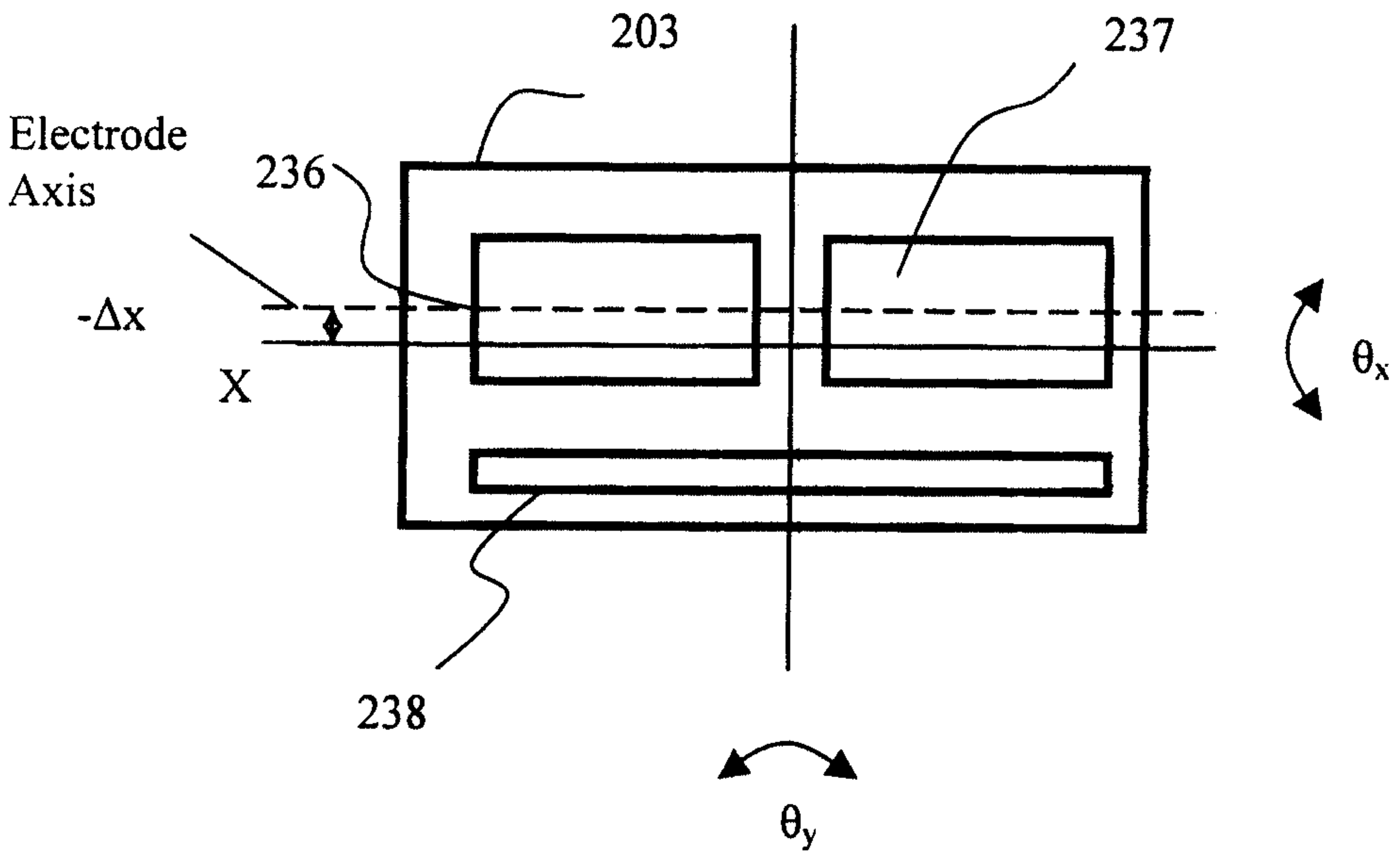


Figure 18

Figure 19

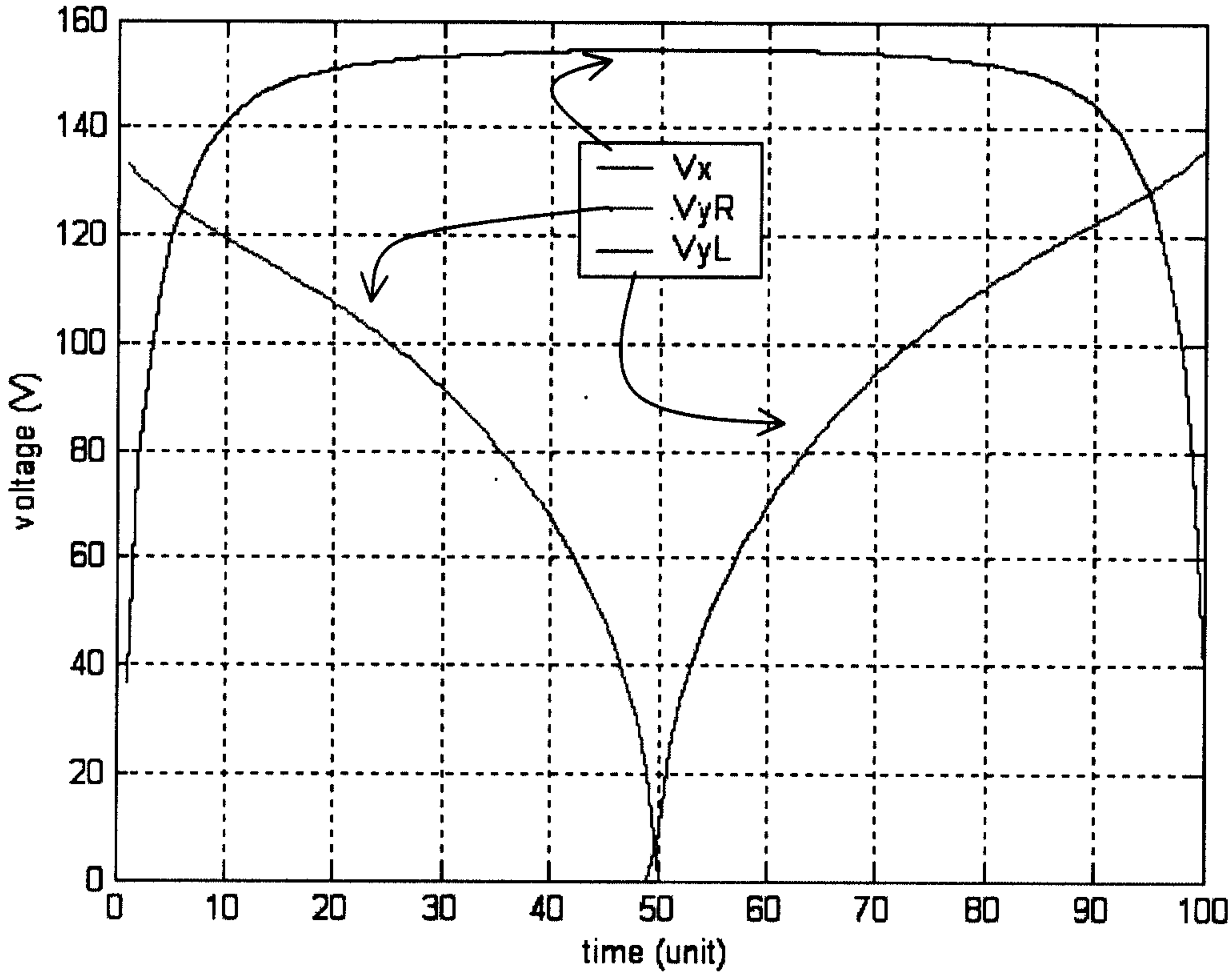

160
140
120
100
80
60
40
20
0
voltage (V)
0
10
20
30
40
50
60
70
80
90
100
time (unit)
Vx
VyR
VyL

Figure 20

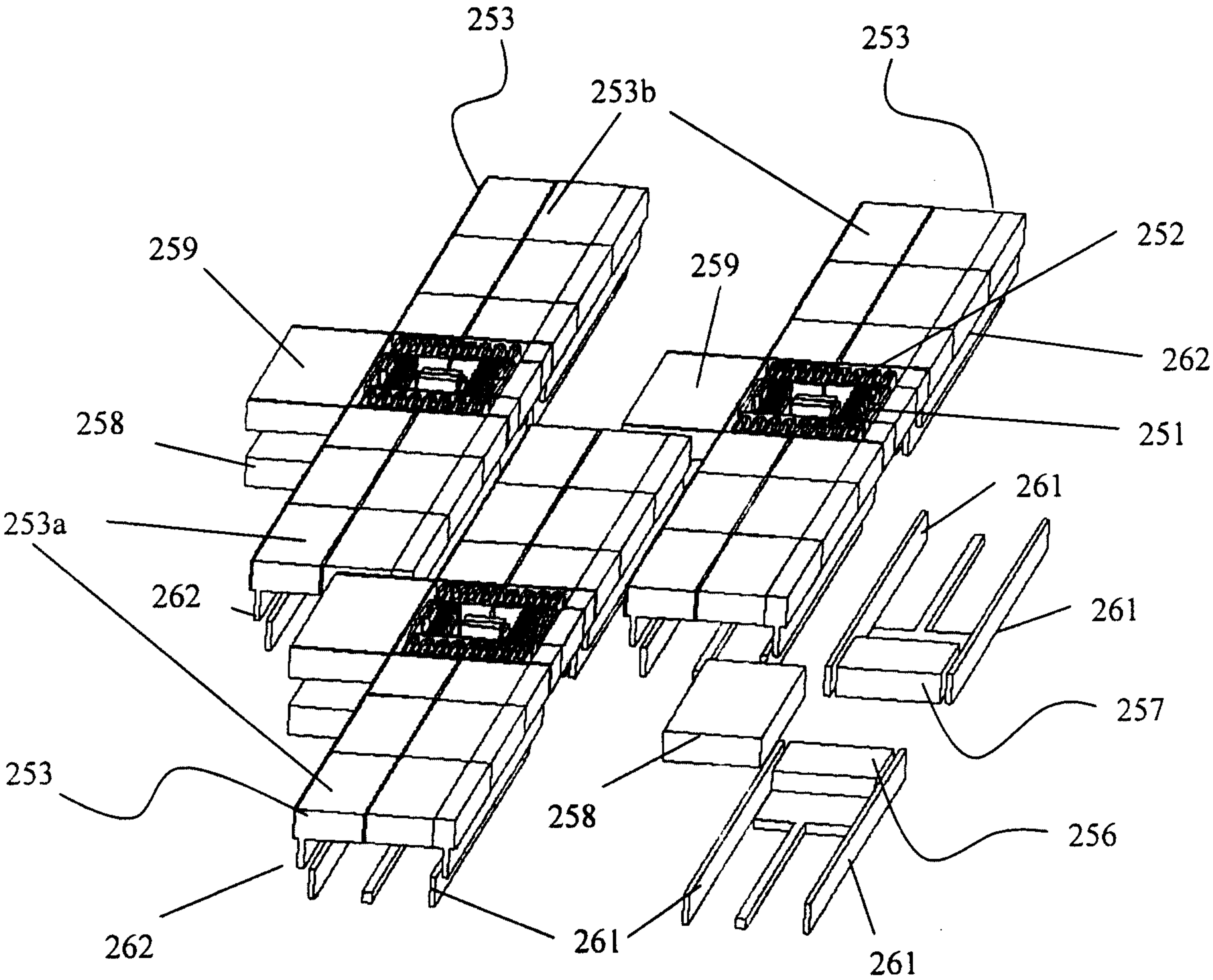

253
253
253b
259
259
252
262
258
251
253a
261
262
261
257
253
258
256
262
261
261
261

Figure 21

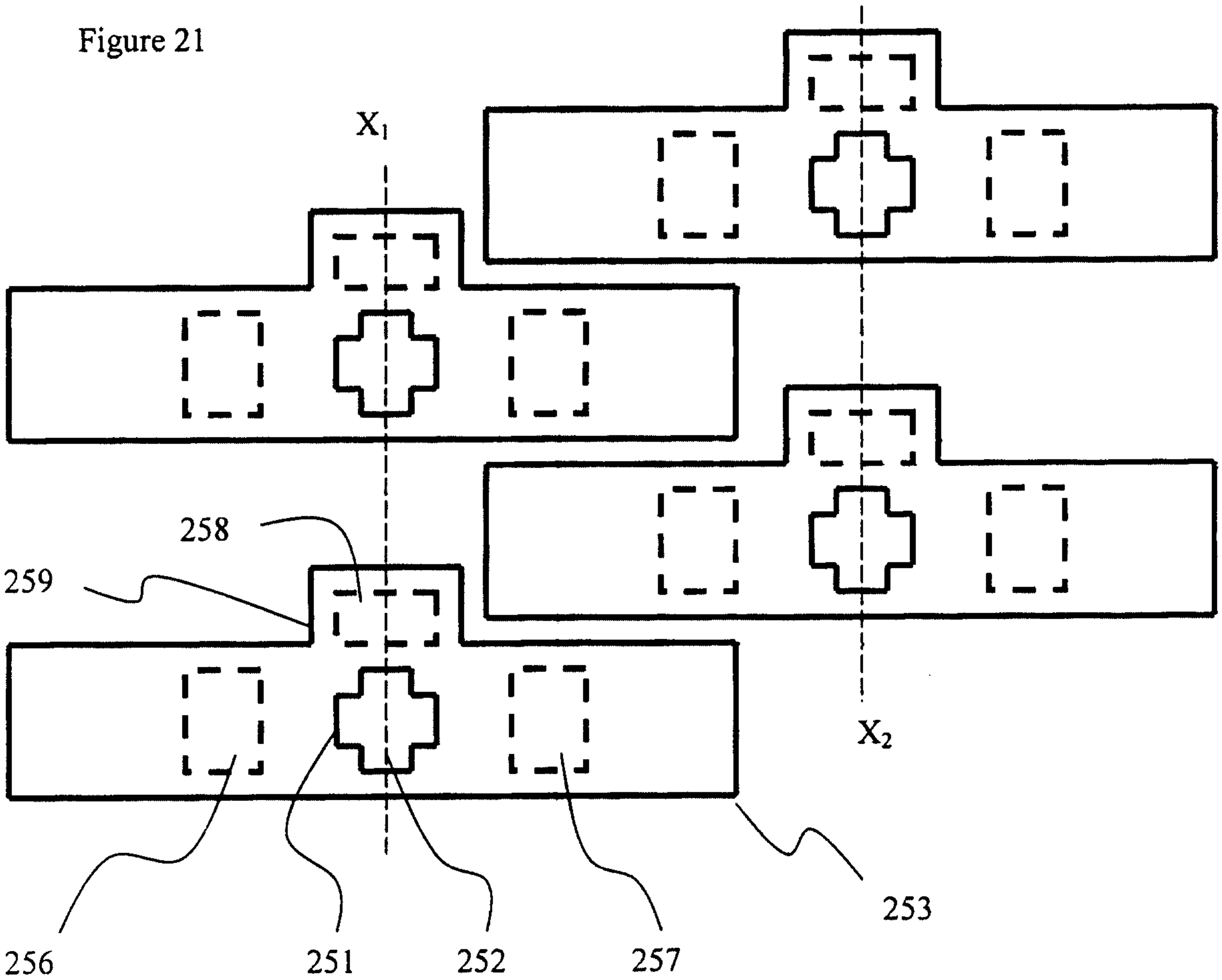
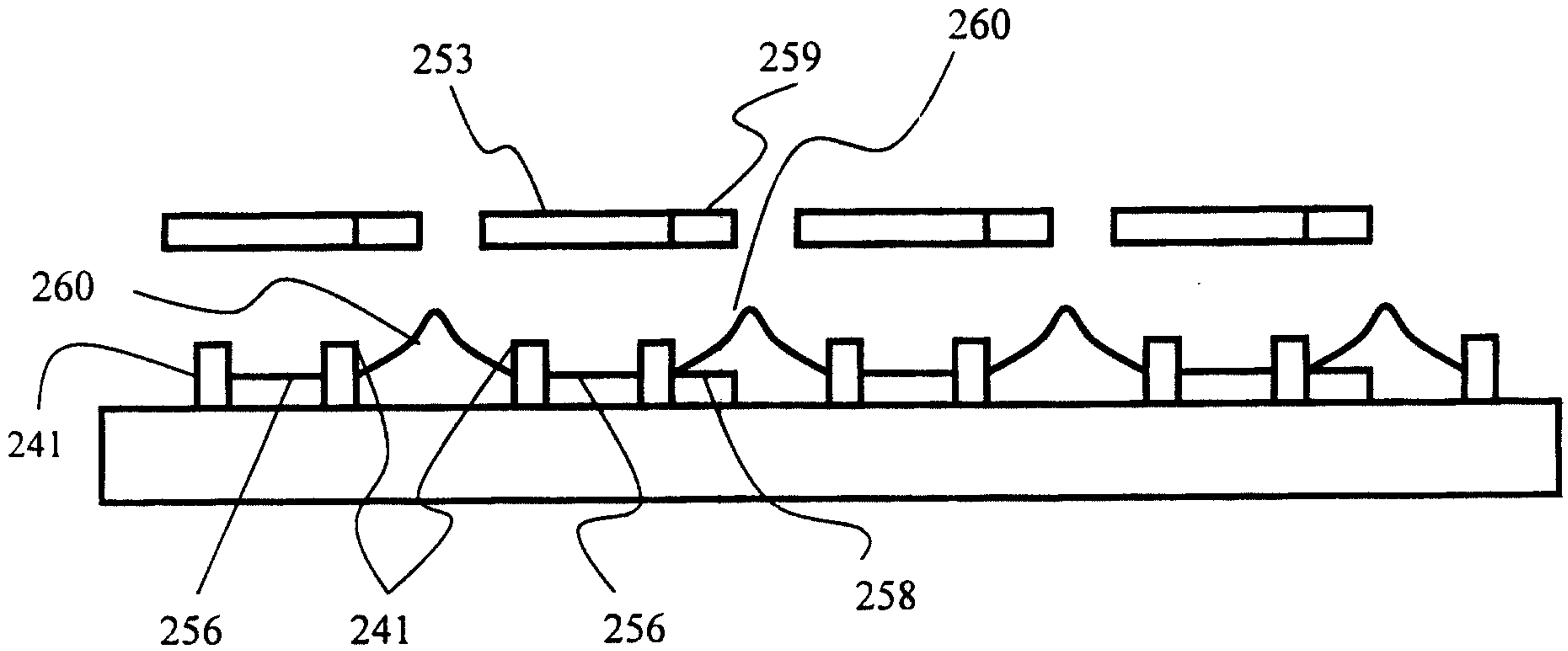


Figure 22



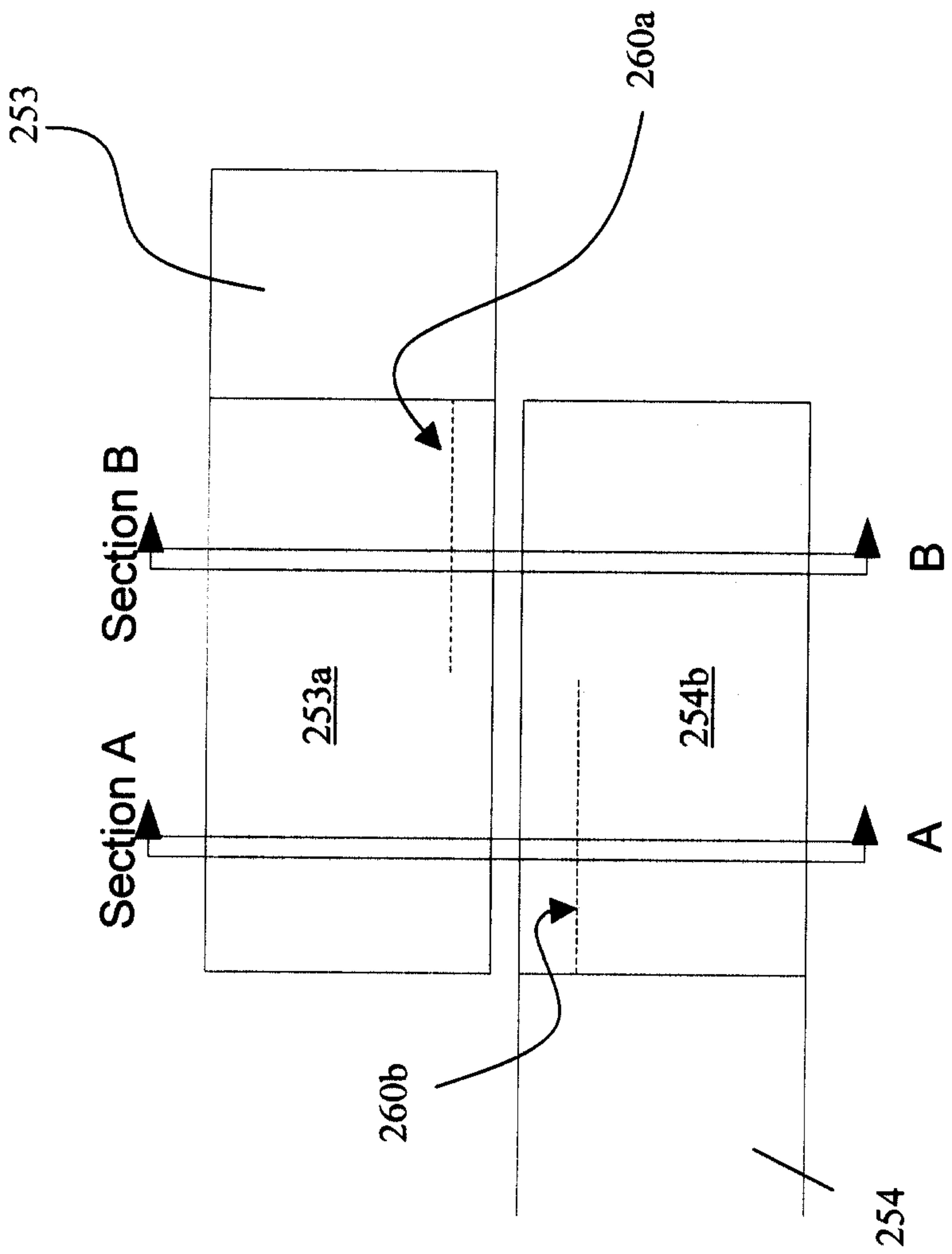


Figure 23

Figure 24

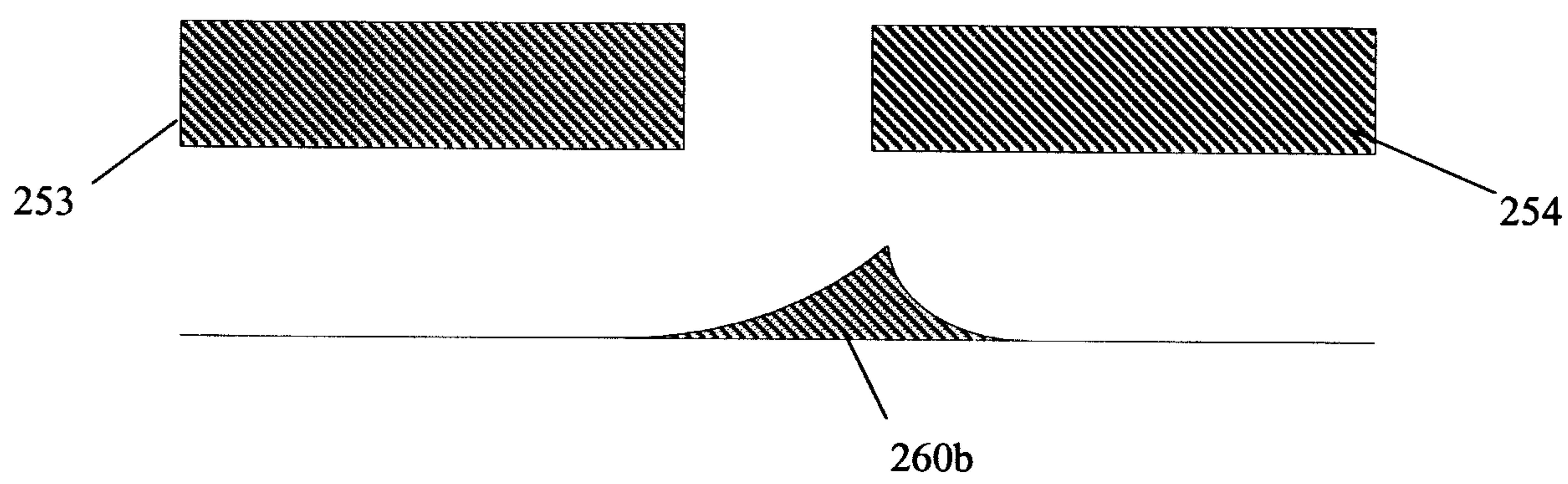
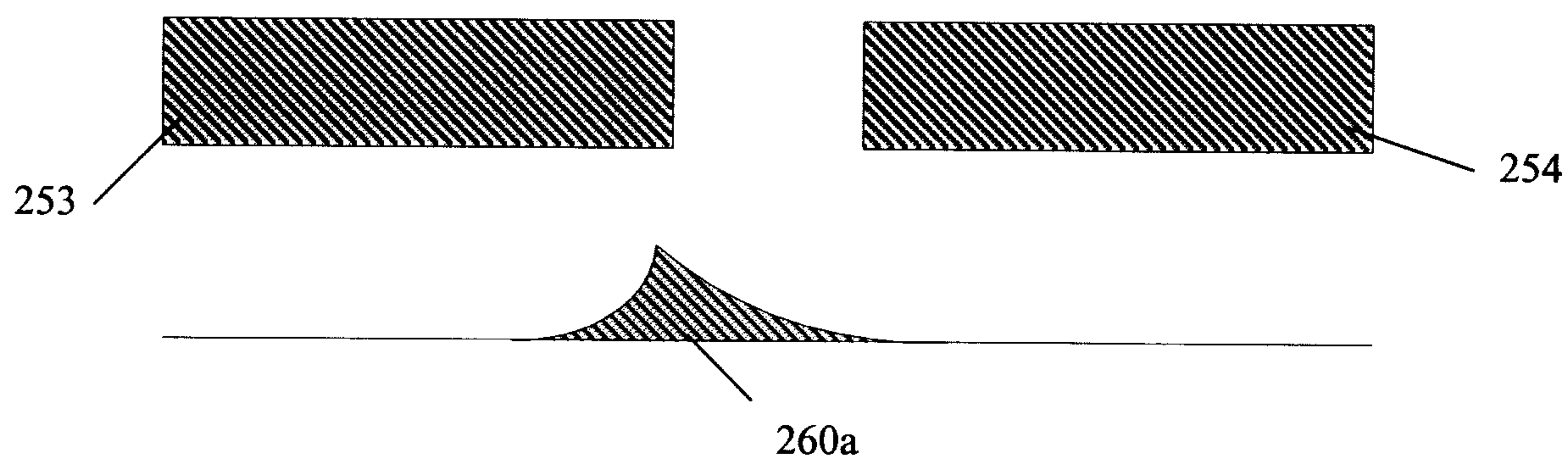


Figure 25



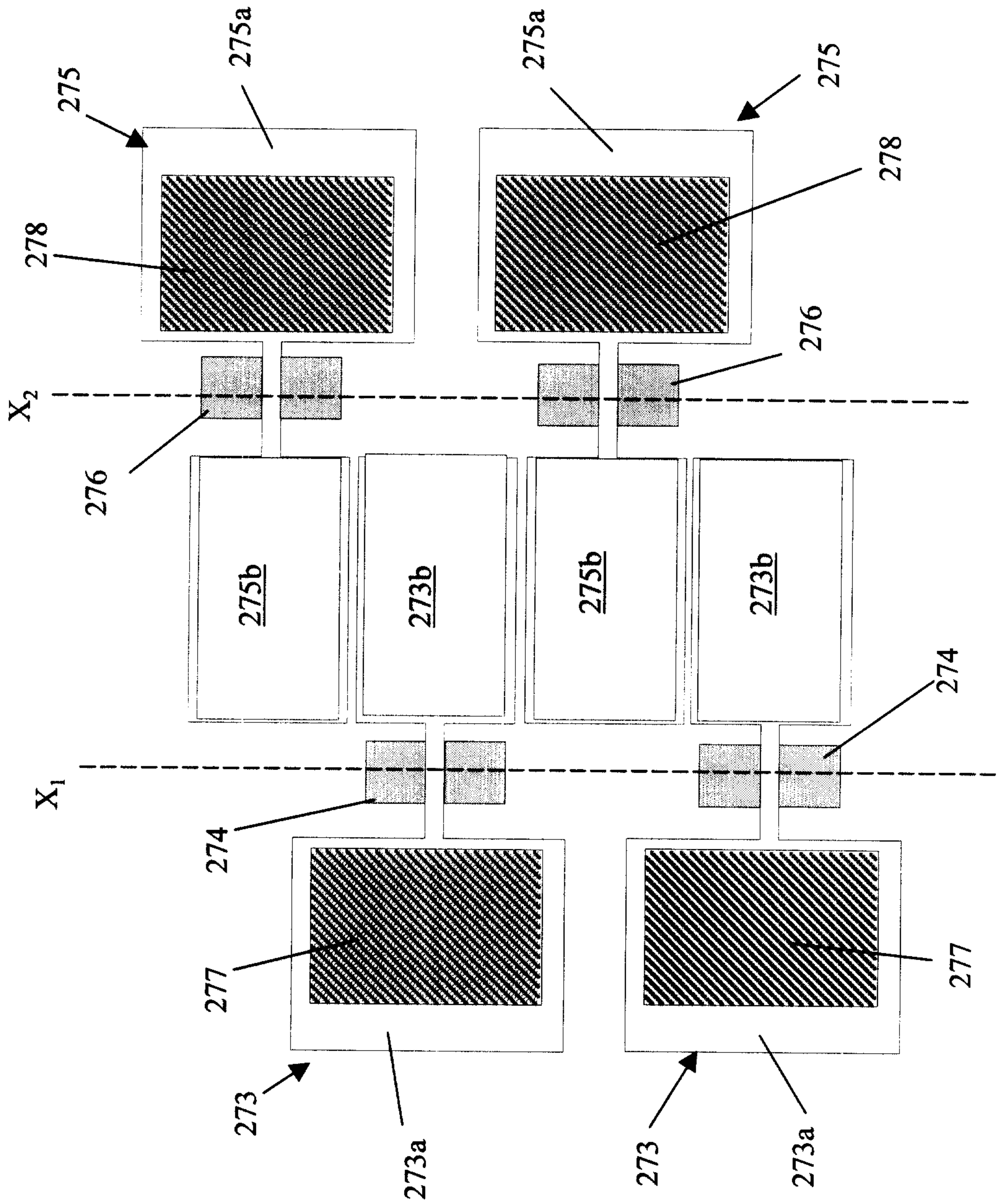

275
275a
278
275a
275
278
X2
276
276
275b
273b
275b
273b
274
X1
274
277
277
273
273a
273
273a

Figure 26

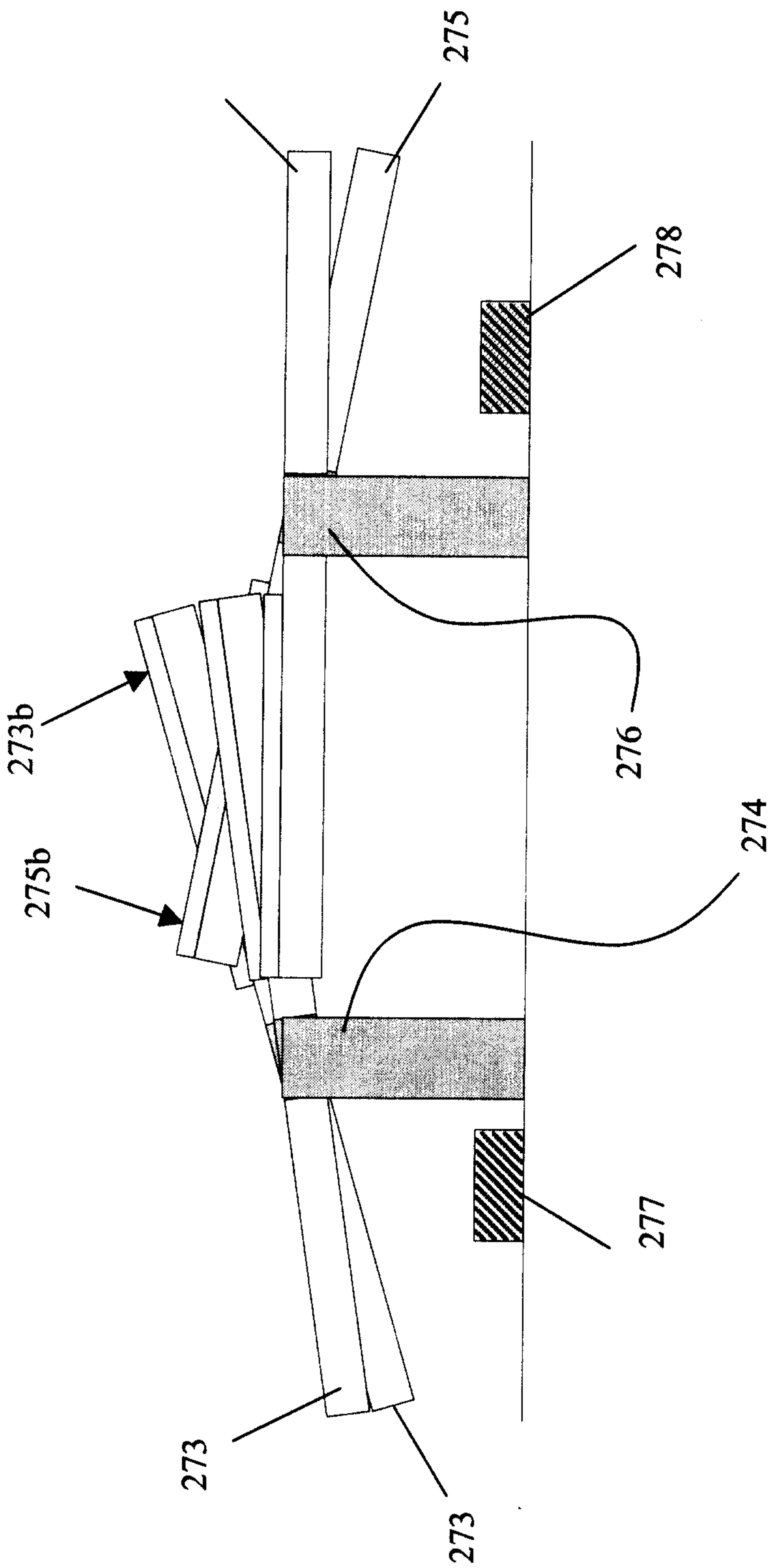


Figure 27

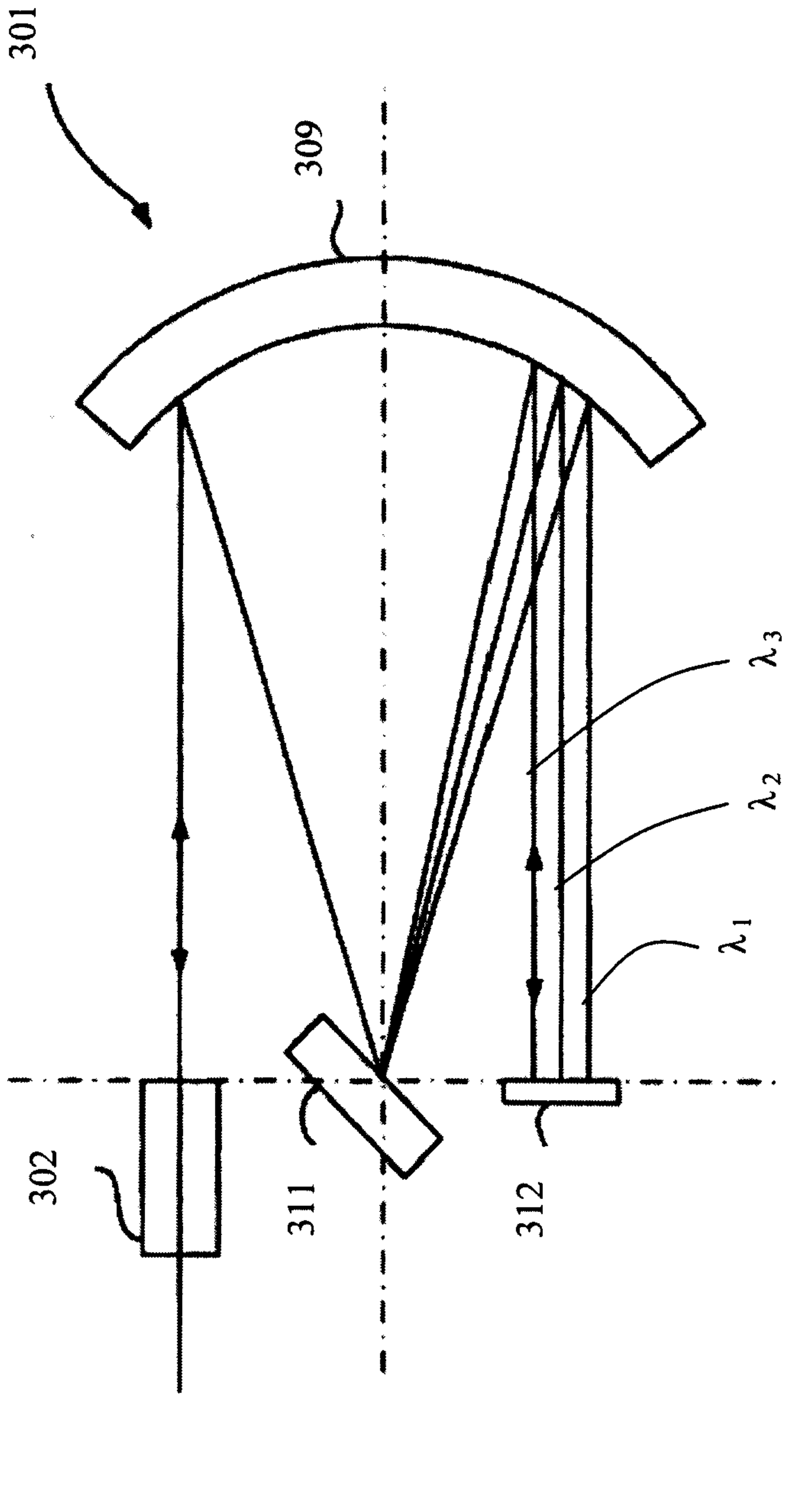


Figure 28

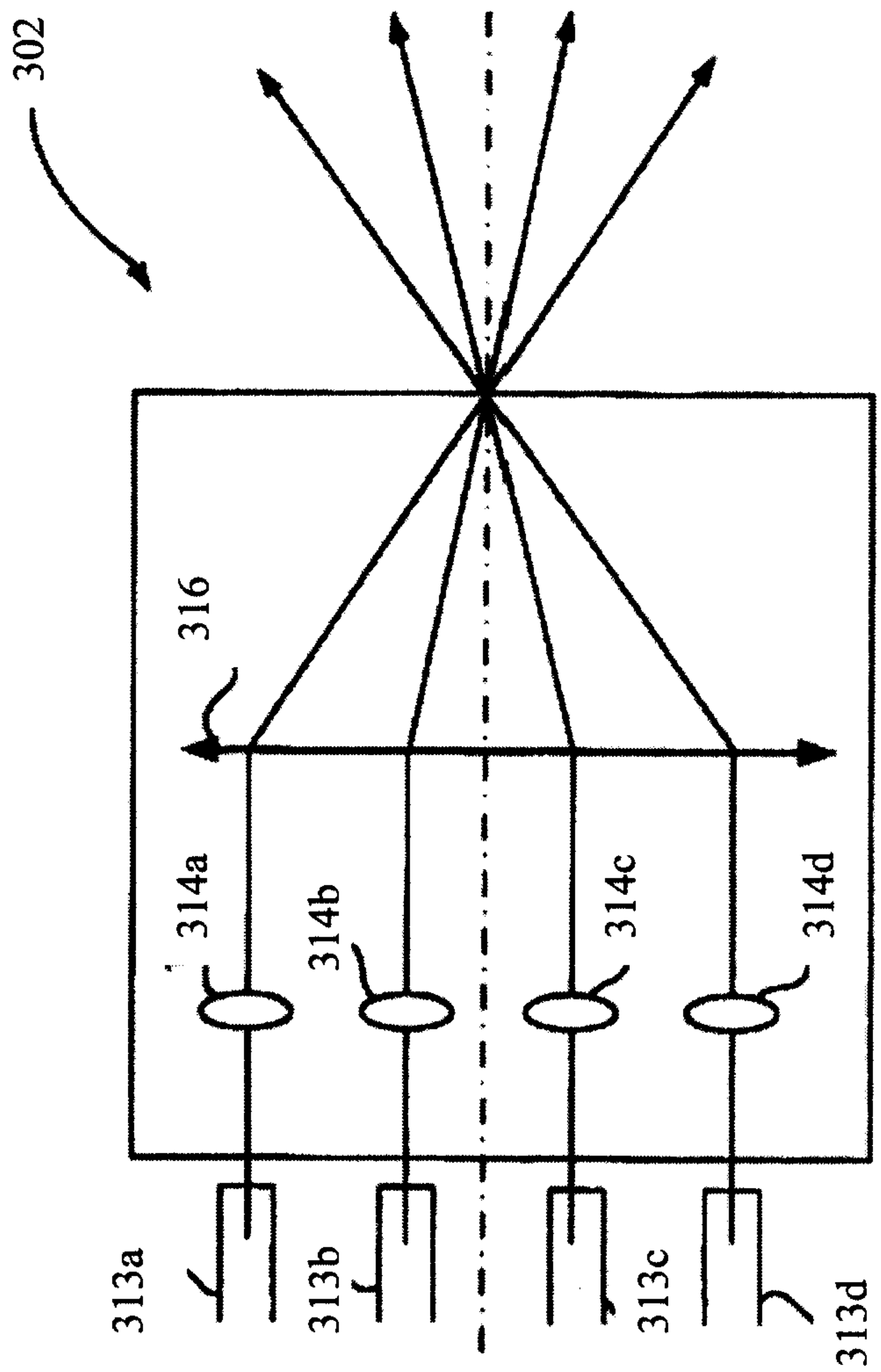
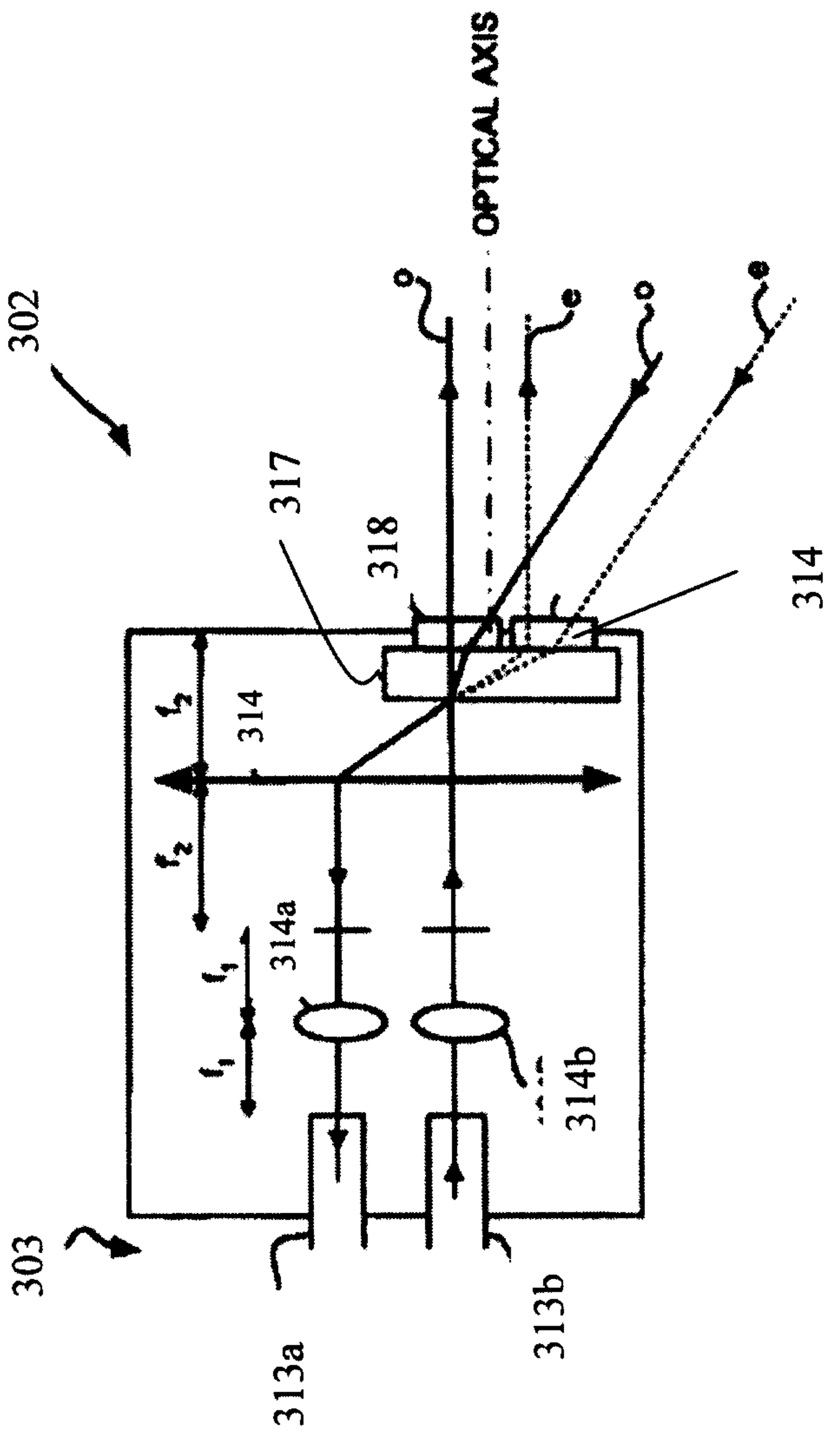
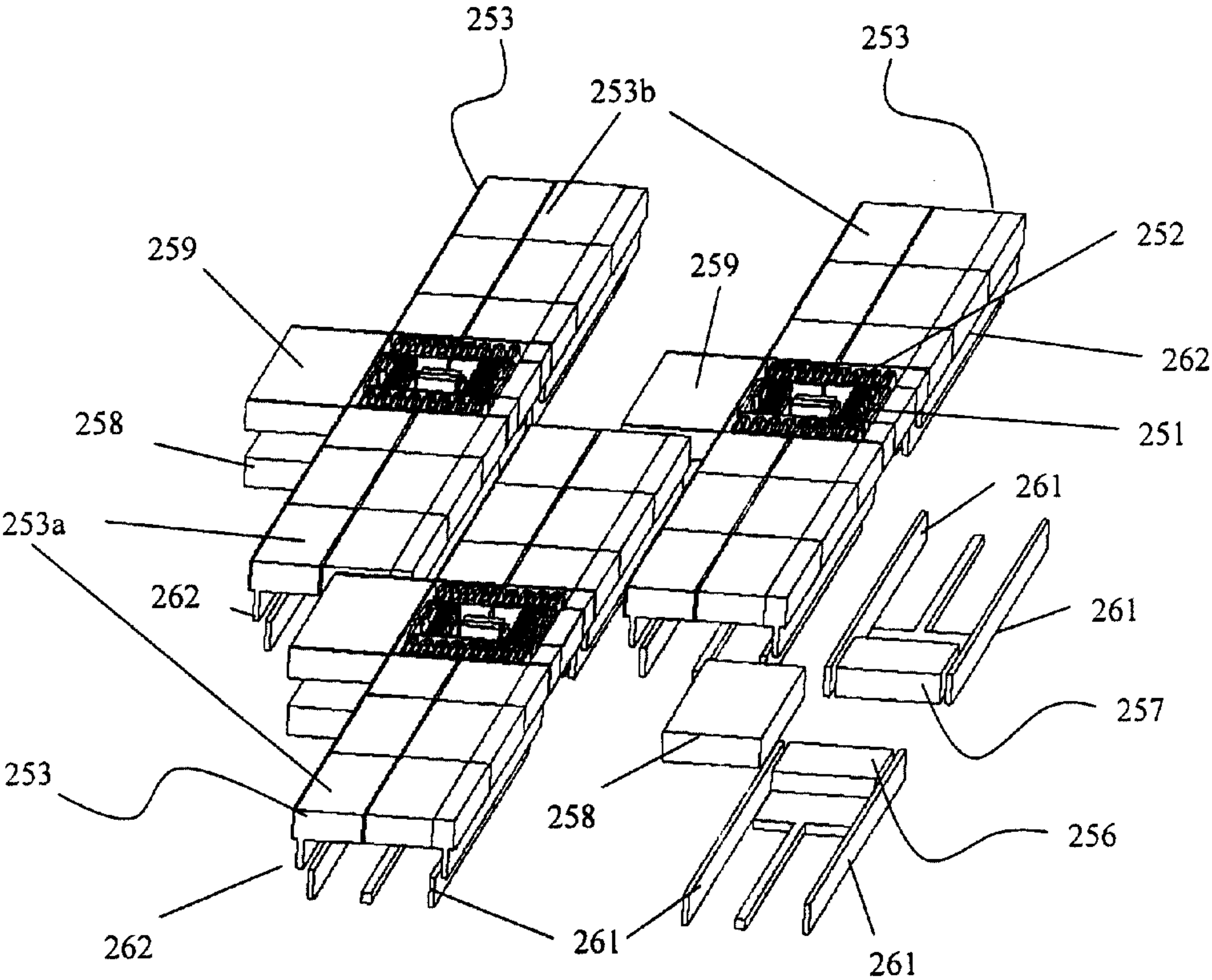


Figure 29



302
303
317
318
314
314
314a
314b
313a
313b
OPTICAL AXIS
o
e
o
e
f2
f2
f1
f1

Figure 30



253
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