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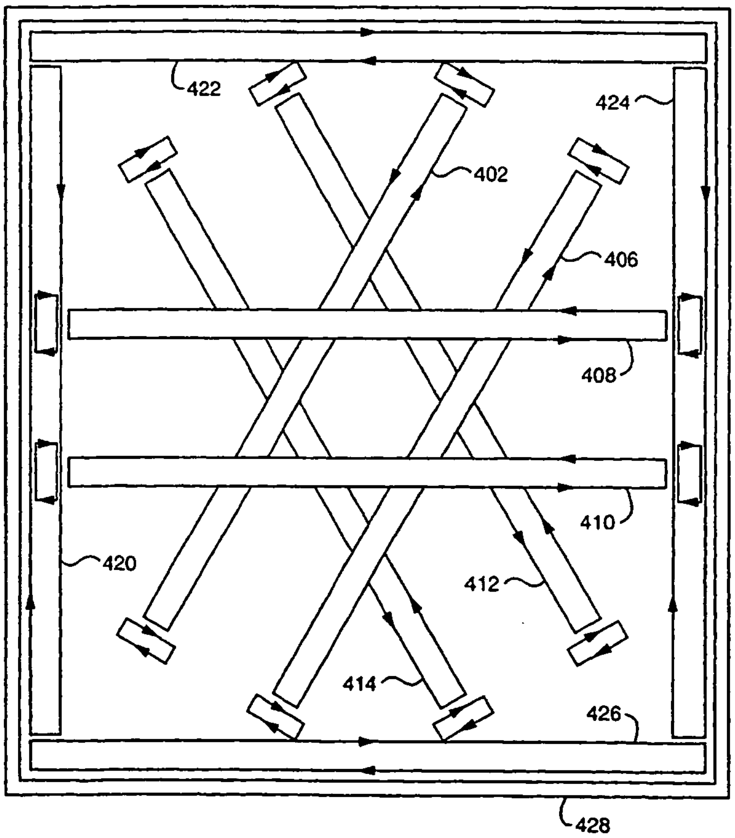

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(57) Abstract: An apparatus for determining a location of a sensor in a surgical navigation domain includes a first magnetic field generator having a first coil set (402-414), a second magnetic field generator having a second coil set (408-428). The first and second coil sets (420-428) are disposed substantially within a common plane. The apparatus further includes a processor configured to receive a plurality of signals and calculates the location of the sensor from the plurality of signals. The sensor produces the plurality of signals in response to magnetic fields generated by the first and second magnetic field generators.

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COIL STRUCTURES AND METHODS FOR GENERATING MAGNETIC FIELDS

BACKGROUND OF THE INVENTION

This invention relates to methods of and devices for generating magnetic fields, and more particularly to the physical characteristics of magnetic field generating coils.

There are various known methods for determining the position of a medical instrument during surgery. For instance, United States Patent No. 5,592,939 to Martinelli, hereby incorporated by reference, discloses a method and apparatus for detecting the position of a medical instrument during surgery. This invention, however, is not limited to any specific method of determining the position of a medical instrument during surgery. For example, FIG. 1 is a diagram of an examination deck 200 with a medical instrument in a surgical environment. During surgery, for example, examination deck 200 lies below a patient. The medical device, such as a catheter 203, is placed inside the patient. Catheter 203 has a coil 14 at its distal end. Methods and systems consistent with the '939 patent determine the location and orientation of catheter 203 inside the patient relative to examination deck 200.

Catheter 203 includes a conductor 16 that leads along catheter 203 to a location outside the patient. Examination deck 200 comprises magnetic field generating coils that produce magnetic fields within a navigational domain 12. The magnetic fields induce voltage signals in sensing coil 14. Measurements taken at conductor 16 of the induced voltage signals provide sufficient information to compute the orientation and position of sensing coil 14.

FIGS. 2A, 2B, 2C, and 3 show magnetic field generating coils. FIG. 2A is a diagram of a coil set 202 for generating a substantially uniform magnetic field in the X direction. Driver 28 supplies current in the direction indicated by the arrows. Coil elements 20 and 22 are horizontal, while coil elements 24 and 26 are vertical. Elements 24 and 26 are "compensation" coils, i.e. "Cunard" coils, which cancel some undesirable field components generated by elements 20 and 22 in the Y and Z directions. As a result, coil set 202 generates a substantially uniform X direction field as indicated by field line 27.

FIG. 2B is a diagram of a coil set 204 for generating a substantially uniform magnetic field in the Y direction. Coil set 204 includes element 30 spaced from element 32, but parallel to element 32. Driver 34 supplies current in the direction indicated by the arrows. Coil set 204 generates a substantially uniform Y direction field as indicated by field line 33.

FIG. 2C is a diagram of a coil set 206 for generating a substantially uniform magnetic field in the Z direction. Driver 44 supplies current in the direction indicated by the arrows. Coil elements 36 and 38 are horizontal, while elements 40 and 42 are vertical. Elements 40 and 42 are compensation coils, i.e. Cunard coils, that cancel some undesirable field components in the X and Y directions. As a result, coil set 206 generates a substantially uniform Z direction magnetic field as indicated by field line 43.

FIG. 3 is a diagram of three pairs of delta coil sets 300 for generating three gradient magnetic fields. The configuration includes a first delta coil pair 50-52, a second delta coil pair 54-56, and a third delta coil pair 58-60. Delta coil pairs 50-52, 54-56, and 58-60 are arranged in a circular orientation about the Y axis such that there is an axis perpendicular to the direction of elongation of the coils at 0, 120, and 240 relative to the Z axis. The magnetic field generated by long delta coil 50 and short delta coil 52 is shown by the field lines extending from coils 50-52. The field lines from delta coils 50-52 group form a family of substantially constant signal surfaces, i.e. the magnetic fields have a spatial gradient in two of the axis dimensions and a substantially zero field value in the remaining axial dimension.

Discussion of FIGS. 1, 2A, 2B, 2C, and 3 are for illustrative purposes only. See U.S. Patent No. 5,592,939 for further examples.

FIG. 3B is a diagram of a patient undergoing cranial surgery with a device consistent with this invention. In FIG. 3B, the medical device is a probe 302 that is placed inside a head 308 of a patient.

Coil sets 202-204, 300 in FIGS. 2A-2C, and 3 are contained within the examination deck 200 of FIG. 1. Placing all these coils in examination deck 200, however, causes examination deck 200 to be relatively thick. It is desirable, however, that examination deck 200 be relatively thin for a number of reasons. First, a thinner examination deck 200 is lighter, less cumbersome, and requires less space in a crowded surgery room. Second, if coil sets 202-204, 300 are arranged so that each is a different distance from navigational domain 12, then the magnetic field strength in navigational domain 12 from each coil set is different. Different magnetic field strengths reduce accuracy of the positioning system. Further, it can be less expensive and easier to manufacturer a thin examination deck as compared to a thick examination deck.

Examination deck 200, in turn, is placed on an examination table 306. FIG. 3A is a diagram of examination deck 200 placed on the examination table 306, consistent with this invention, in a medical setting. Examination table 306 introduces other design constraints, including the width and length of the examination deck 200, which introduces design constrains on the size and shape of coils inside examination deck 200. Preferably, the magnetic field generating coils are such that examination deck easily fits onto standard size examination tables, such as examination table 306.

Therefore, it is desirable to provide an apparatus that allows coil sets to be arranged substantially coplanar with respect to navigational domain 12. It is also desirable to provide an apparatus that allows examination deck 200 to fit on a standard examination table.

It is an object of the present invention to substantially overcome the above-identified disadvantages and drawbacks of the prior art.

SUMMARY OF THE INVENTION

The foregoing and other objects are achieved by the invention which in one aspect comprises an apparatus for determining a location of a sensor in a surgical navigation domain. The apparatus includes a first magnetic field generator having a first coil set, a second magnetic field generator having a second coil set. The first and second coil sets are disposed substantially within a common plane. The apparatus further includes a processor configured to receive a plurality of signals. The processor calculates the location of the sensor from the plurality of signals. The sensor produces the plurality of signals in response to magnetic fields generated by the first and second magnetic field generators.

In another embodiment of the invention, the first coil set includes at least one delta coil pair for generating a gradient magnetic field in the navigation domain.

In another embodiment of the invention, each delta coil pair further includes one or more end correction coils. Each delta coil pair is electrically coupled to the corresponding end correction coil, and current flows through the end correction coil in a direction opposite of the direction of the current flowing through the corresponding delta coil pair.

In another embodiment of the invention, the second coil set includes at least one uniform coil pair for generating a uniform magnetic field in the navigational domain.

In another embodiment of the invention, the first coil set includes a first delta coil pair longitudinally oriented along a first axis, a second delta coil pair longitudinally oriented along a second axis, and a third delta coil pair longitudinally oriented along a third axis. The three delta coil pairs are arranged such that the second axis is rotated within the common plane substantially sixty degrees with respect to the first axis, and the third axis is rotated within the common plane substantially one hundred and twenty degrees with respect to the first axis.

In another embodiment of the invention, each of the first, second and third delta coil pairs lies within a distinct plane that is parallel to the common plane, such that the delta coil pairs overlap one another.

In another embodiment of the invention, each of the first, second and third delta coil pairs includes two or more distinct coil elements, electrically coupled, such that the aggregate of the distinct coil elements produces the corresponding gradient magnetic field.

In another embodiment of the invention, intersecting delta coil pairs share one or more common coil elements.

In another embodiment of the invention, intersecting delta coil pairs include distinct coil elements in an intersecting region where the delta coil pairs overlap.

In another embodiment of the invention, each of the delta coil pairs further include one or more end correction coils. Each of the delta coil pairs is electrically coupled to the corresponding end correction coil, and electrical current flows through the end correction coils in a direction opposite of the direction of the current flowing through the corresponding delta coil pair.

In another embodiment of the invention, at least one of the delta coil pairs is characterized by a length that is different from the length of the other delta coil pairs.

In another embodiment of the invention, each of the delta coil pairs includes a short coil and a long coil. The short coil further includes a first end correction element and a second end correction element for reducing unwanted magnetic field components. Electrical current flows through the end correction coils in a direction opposite of the direction of the current flowing through the corresponding short coil. The long coil further includes a central compensating coil for reducing unwanted magnetic field components. Electrical current flows through the central compensating coil in a direction opposite of the direction of the current flowing through the corresponding long coil.

In another embodiment of the invention, one or more of the delta coil pairs overlap a coplanar uniform coil pair.

In another embodiment of the invention, each of the one or more overlapping delta coil pairs includes two or more distinct coil elements. The distinct coil elements are electrically coupled, such that the aggregate of the distinct coil elements produces the corresponding gradient magnetic field.

In another aspect, the invention comprises an apparatus for determining a location of a sensor in a surgical navigation domain. The apparatus includes a first magnetic field generator including at least one delta coil pair for generating a gradient magnetic field in said navigation domain. The at least one delta coil pair disposed within a first plane. The apparatus further includes a second magnetic field generator including at least one uniform coil pair for generating a uniform magnetic field in the navigational domain. The at least one uniform coil pair disposed within a second plane. The first plane is offset from the second plane by an offset angle calculated to reduce undesirable uniform field components. The apparatus also includes a processor, configured to receive a plurality of signals, for calculating the location of the sensor from the plurality of signals. The sensor produces the plurality of signals in response to magnetic fields generated by the first and second magnetic field generators.

In another aspect, the invention comprises an apparatus for determining a location of a sensor in a surgical navigation domain, including a first magnetic field generator having a common coil, a second magnetic field generator also including the common coil, and a processor for calculating the location of the sensor. The sensor produces a plurality of signals in response to a first magnetic field generated by the first magnetic field generator, and in response to a second magnetic field of a different shape with respect to the first magnetic field generated by the second magnetic field generator. In yet another aspect, the invention comprises a method of determining a location of a sensor in a surgical navigation domain. The method includes generating a first magnetic field using a first magnetic field generator having a first coil set, and generating a second magnetic field using a second magnetic field generator having a second coil set. The first and second coils are disposed substantially within a common plane. The method further includes calculating the location of the sensor from a plurality of signals. The sensor produces the plurality of signals in response to magnetic fields generated by the first and second generated magnetic fields.

In another embodiment, the method further includes generating a gradient magnetic field in said navigation domain using at least one delta coil pair for generating.

In another embodiment, the method further includes generating a gradient magnetic field in said navigation domain using two or more distinct coil elements, electrically coupled, such that the aggregate of the distinct coil elements produces the corresponding gradient magnetic field.

In another embodiment, the method further includes generating a gradient magnetic field in said navigation domain using delta coil pairs having one or more end correction coils. Each of the delta coil pairs is electrically coupled to the corresponding end correction coil, and electrical current flows through the end correction coils in a direction opposite of the direction of the current flowing through the corresponding delta coil pair.

In another aspect, the invention comprises a method of determining a location of a sensor in a surgical navigation domain, including generating a gradient magnetic field in said navigation domain using a first magnetic field generator including at least one delta coil pair disposed within a first plane. The method further includes generating a uniform magnetic field in the navigational domain using a second magnetic field generator including at least one uniform coil pair for. The at least one uniform coil pair is disposed within a second plane. The first plane is offset from the second plane by an offset angle calculated to reduce undesirable uniform field components. The method also includes calculating the location of the sensor from a plurality of signals. The sensor produces the plurality of signals in response to magnetic fields generated by the first and second generated magnetic field.

In another aspect, the invention comprises a method of determining a location of a sensor in a surgical navigation domain, including generating a first magnetic field using a magnetic field generator that includes a common coil. The method further includes generating a second magnetic field of a different shape than the first magnetic field, using a second magnetic field generator that includes the common coil. The method also includes calculating the location of the sensor from a plurality of signals. The sensor produces the plurality of signals in response to magnetic fields generated by the first and second magnetic field generators.

BRIEF DESCRIPTION OF DRAWINGS

The foregoing and other objects of this invention, the various features thereof, as well as the invention itself, may be more fully understood from the following description, when read together with the accompanying drawings in which:

FIG. 1 is a diagram of an examination deck 200 with a medical instrument in a medical environment;

FIGS. 2A, 2B, 2C, and 3 show magnetic field generating coils;

FIG. 3A is a diagram of the examination deck in FIG. 1 placed on an examination table, consistent with this invention, in a medical setting;

FIG. 3B is a diagram of a patient undergoing cranial surgery with a device consistent with this invention;

FIG. 4 is a top view of coil sets arranged to be disposed within in examination deck 200;

FIG. 5 is a top view of coil sets, consistent with this invention, arranged substantially coplanar for generating magnetic fields;

FIG. 6 is an exploded top view of a portion of two delta coils in FIG. 5, consistent with this invention, arranged substantially coplanar;

FIG. 6A is an electrical diagram of the coils shown in FIG. 6 configured with switches;

FIG. 7 is an exploded top view of a portion of two delta coils in FIG. 5, consistent with this invention, arranged substantially coplanar for generating magnetic fields;

Fig. 7A is an electrical diagram of the coils shown in FIG. 7;

FIG. 8 is a top view of coil sets, consistent with this invention, arranged substantially coplanar for generating magnetic fields;

FIG. 8A is an electrical diagram of the coils shown in FIG. 9;

FIG. 9 is an exploded top view of a delta coil and a uniform coil in FIG. 8, consistent with this invention, arranged substantially coplanar;

FIG. 9A is an exploded side view of a uniform coil set, consistent with this invention;

FIG. 10 is a top view of coil sets, consistent with this invention, arranged substantially coplanar for generating magnetic fields;

FIG. 11 is a diagram of a top view of a delta coil arrangement relative to an inner circular space;

FIG. 12 schematically depicts an examination deck;

FIGS. 13A, 13B, 13C, and 13D show magnetic field generating coils;

FIG. 14 is an engineering drawing of the coil sets, consistent with this invention, shown in FIG. 5;

FIG. 15 is an engineering drawing of the coil sets, consistent with this invention, shown in FIG. 10;

FIGS. 16 and 17 are engineering drawings, consistent with this invention, of the coil sets shown in FIG. 8;

FIG. 18 shows a constant signal pattern for a catheter in a magnetic field generated by the delta coil set of FIG. 10;

FIG. 19 is a diagram of a surgical table with an integrated examination deck; and

FIG. 20 is a top view, side view, and an end view of an examination deck with an integrated examination deck.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The following description of embodiments of this invention refers to the accompanying drawings. Where appropriate, the same reference numbers in different drawings refer to the same or similar elements.

FIG. 4 is a top view of coil sets, consistent with this invention, arranged to be placed in examination deck 200. An arrangement 400 comprises a first delta coil pair 402-406, a second delta coil pair 408-410, and a third delta coil pair 412-414. First through third delta coil pairs 402-414 create gradient fields similar to those described with respect to FIG. 3 above. Arrangement 400 also comprises a first uniform coil pair 420, 424, and a second uniform coil pair 426, 422. First and second uniform coil pairs generate substantially uniform magnetic fields similar to the fields described with respect to FIGS. 2A and 2C above. Arrangement 400 also comprises a girth coil 428 that creates a substantially uniform magnetic field similar to the magnetic field described with respect to FIG. 2B above. Arrows indicate a possible direction of current flowing in the coils. Arrangement 400 is advantageous because it may be configured to in examination deck 200 so that it can fit on and be integrated into a standard examination or surgical table.

Methods and systems consistent with this invention arrange the coil sets so that they are substantially coplanar. FIG. 5 is a top view of coil sets, consistent with this invention, arranged substantially coplanar for generating magnetic fields. An arrangement 500 comprises a first delta coil pair 502-506, a second delta coil pair 508-510, and a third delta coil pair 512-514. First through third delta coil pairs 508-

514 create gradient fields similar to those described with respect to FIG. 3 above. Arrangement 500 also comprises a first uniform coil pair 520, 524, and a second uniform coil pair 526, 522. First and second uniform coil pairs generate uniform magnetic fields similar to the fields described with respect to FIGS. 2A and 2C above. Arrangement 500 also comprises a girth coil 528 that creates a substantially uniform magnetic field similar to the magnetic field described with respect to FIG. 2B above. Arrows indicate a possible direction of current flowing in the coils.

In FIG 5, coil 506 has nine elements 506a-i. When coil 506 generates a magnetic field, nine elements 506a-i are electrically connected in series so such that they produce magnetic fields that are nearly identical to coil 406 in FIG. 4. Coil 508 also has nine separate elements 508a-i. When coil 508 generates a magnetic field, nine elements 508a-i are electrically connected in series such that they produce magnetic fields that are nearly identical to coil 406 in FIG. 4. Coils 510, 512, 514, and 502 also comprise nine elements and are configured in a similar fashion.

FIG. 6 is an exploded top view of a portion of two delta coils, consistent with this invention, arranged substantially coplanar. In the embodiment shown in FIG. 6, element 506b and element 508b are the same element. When coil 508 generates a magnetic field, switches 602, 604 create one electrical path through elements 508a, 508b (506b), and 508c. When coil 506 generates a magnetic field, switches 602, 604 create one electrical path through elements 506a, 506b (508b), and 508c. Arrows indicate a possible direction of current flowing in coils 506a-c and 508a-c. In this fashion, coil 508 and coil 506 share an element so that the coils can be arranged substantially coplanar.

FIG. 6A is an electrical diagram of coils 506a-c and 508a-c shown in FIG. 6 configured with switches. When coil 508 generates a magnetic field, switches 602, 604 are in position A, which creates one electrical path through elements 508a, 508b (506b), and 508c. When coil 506 generates a magnetic field, switches 602, 604 are in position B, which creates one electrical path through elements 506a, 506b (508b), and 506c. Arrows indicate a possible direction of current flowing in coils 506a-c and 508a-c.

FIG. 7 is an exploded top view of a portion of two delta coils, consistent with this invention, arranged substantially coplanar for generating magnetic fields. In the embodiment shown in FIG. 7, element 506b and element 508b are separate elements comprising two separate coils wrapped around substantially the same area. In the embodiment shown in FIG. 7, no switches are necessary, which eliminates complexity and hardware. Instead, elements 508a, 508b, and 508c, are always connected in series to form one electrical path. Likewise, elements 506a, 506b, and 506c are always connected in series to form one electrical path. FIG. 7 also provides a cross sectional view of elements 506b and 508b. As shown in this cross sectional view, coil 506b is wound outside coil 508b such that coil 506b encloses a greater area than coil 506b. In order to compensate for the smaller area enclosed by 508b, it is possible to include one or more extra windings of element 508b compared to element 506b.

Fig. 7A is an electrical diagram of coils 506a-c and 508a-c of FIG. 7. In this embodiment, there are no switches and there is one electrical path through elements 508a, 508b, and 508c. Likewise, there is one electrical path through elements 506a, 506b, and 506c. Arrows indicate a possible direction of current flowing in coils 506a-c and 508a-c.

Thus, referring back to FIG. 5, delta coil pairs 502-506, 508-510, and 512-514 lie substantially coplanar because of the configurations in FIGS. 6 and 7. In FIG. 5, there are twelve elements that "intersect," i.e., they may implement the configuration in FIGS. 6 and 7. Further, first unidirectional coil pair 520, 524 and second unidirectional coil pair 522, 528 are coplanar with first through third delta coil pairs 502-514. Lastly, girth coil 526 is coplanar with first through third delta coil pairs 502-514 and first unidirectional coil pair 520, 524 and second unidirectional coil pair 522, 528. Thus, all coil sets in FIG. 5 are coplanar.

FIG. 5 also shows "end correction" coils 530-540. Coils 530-540 are electrically in series with the nearest delta coil pairs, but carry current in the reverse direction. End correction coils 530-540 help to reduce unwanted magnetic field components in the non-gradient direction.

FIG. 8 is a top view of coil sets, consistent with this invention, arranged substantially coplanar for generating magnetic fields. The arrangement 800 comprises a first delta coil pair 802-804, a second delta coil pair 806-808, and a third delta coil pair 810-812. First through third delta coil pairs 802-812 create gradient fields similar to those described above with respect to FIG. 3. Arrangement 800 also comprises a first uniform coil pair 814, 818 and a second uniform coil pair 816, 820. First and second uniform coil pairs 816, 820 generate uniform magnetic fields similar to the magnetic fields discussed with respect to FIGS. 2A and 2C above. Arrangement 800 also comprises a girth coil 824 that generates a substantially uniform magnetic field similar to the magnetic fields discussed with respect to FIG. 2B above.

In FIG. 8, first delta coil set 802-804 intersects second delta coil set 806-808 at element 808b. Second delta coil set 806-808 intersects third delta coil set 810-812 at element 810b. Finally, third delta coil set 810-812 intersects first delta coil set 802-804 at element 804b. These intersections are constructed as described above with respect to FIGS. 6 and 7, so that first through third delta coil sets 802-812 are coplanar.

Also in FIG. 8, first delta coil set 802-804 intersects first uniform coil pair 814, 818 at element 802b. First delta coil set 802-804 also intersects second uniform coil pair 820, 816 at element 802c. Likewise, second delta coil set 810-812 intersects first uniform coil pair 814 at element 812b. Second delta coil set 810-812 also intersects second uniform coil pair 820, 816 at element 812c. Despite these intersections, however, first and second delta coil set 802-804, 810-812 are arranged coplanar with first and second uniform coil set 814, 818, and 816, 820.

FIG. 9 is an exploded top view of delta coil 802 and uniform coil 816, consistent with this invention, arranged substantially coplanar. Delta coil element 802b is separate from element 802a, but is electrically in series with element 802a so that the magnetic field created by the two elements is substantially similar to a coil that would cover the combined area of element 802a and element 802b. In this fashion, mechanical interference between delta coil pair 802 and uniform coil pair 806 is avoided. Elements 812c, 812b, and 802c are substantially similar to that of element 802b and are substantially coplanar. FIG. 8A is an electrical diagram of the coils 802a-b and 816 as shown in FIG. 9. As shown, coil 802a and 802b are connected in series. Coil 816 is a single coil as shown.

FIG. 9A is an exploded side view of a uniform coil set, consistent with this invention. In FIG. 9A, first, second, and third delta coil sets (not shown) are substantially in a plane 902. First uniform coil set 816, 812, in this embodiment is displaced by an angle from plane 902 as shown. Offset angle eliminates the need for compensation coils 24 and 26 in FIG. 2A while achieving the same result. Thus, displacing first uniform coil set 816, 820 by angle cancels undesirable magnetic field components in the Y and Z directions. As a result, uniform coil set 816, 820 generates a substantially uniform X direction field. Second uniform coil set 814, 818 may also be displaced by angle . It is evident to one of ordinary skill in the art how to calculate angle necessary to create equivalent correction to eliminate elements 24, 26.

FIG. 10 is a top view of coil sets, consistent with this invention, arranged substantially coplanar for generating magnetic fields. An arrangement 1000 comprises a first delta coil pair 1002 a second delta coil pair 1004 and a third delta coil pair 1006. First through third delta coil pairs 1002-1004 create gradient fields similar those discussed above with respect to FIG. 3. Arrangement 1000 also comprises a first uniform coil pair 1012-14 and a second uniform coil pair 1008-1010. First and second uniform coil pair 1012-1014, 1008-1010 generate uniform magnetic fields similar to those discussed above with relation to FIGS. 2A and 2C. Arrangement 1000 also comprises a girth coil 1024 that generates a substantially uniform magnetic field similar to the magnetic fields discussed above with respect to FIG. 2B. First delta coil pair 1002, which in this embodiment is shorter than second delta coil pair 1004 and third delta coil pair 1006, contains end correction elements 1018, 1016, 1022, and 1020. End correction elements carry current in the reverse direction to reduce unwanted magnetic field components.

FIG. 11 is a diagram of a top view of a delta coil arrangement 1100 relative to an inner circular space 104. In arrangement 1100, a short coil 52 is provided with end correction elements 94, 96. Long coil 50 comprises a central compensating or "sucker" coil 88, which carries current in the opposite direction than coil 50 and eliminates some unwanted magnetic field components. Long coil 50 and short coil 52 are modified by compensation coils 80-82, 84-86, 88, 90-94, and 92-96. Long coil 50 and short coil 52 are shown schematically for sets 50-52, but similar configurations likewise exist for coil sets 54-56 and 58-60.

FIG. 12 schematically depicts another examination deck in accordance with another embodiment of the present invention. FIGS. 13A-C are diagrams of unidirectional coils. The assembly for the X direction unidirectional coil set is shown in FIG. 13A and includes two coil elements 110 and 112. Elements 110, 112 project a substantially uniform field in the X direction throughout the navigational domain. FIG. 13B schematically depicts the Y direction unidirectional coils including coil elements 114, 116, 118, and 120. FIG. 13C schematically depicts the Z direction unidirectional coils including coil elements 122-124, and 126-128. FIG. 13D shows the delta coil arrangement used in the railed configuration. The arrangement in FIG. 13D is the same as used in FIG. 3 described above.

Discussion of FIG. 11, 12, 13A, 13B, 13C, and 13D are for illustrative purposes only. See U.S. Patent No. 5,592,939 for further examples.

FIG. 14 is an engineering drawing of the coil sets, consistent with this invention, shown in FIG. 5. FIG. 15 is an engineering drawing of the coil sets, consistent with this invention, shown in FIG. 10. As shown in FIG. 15, the coils can easily fit onto an operating table that is twenty inches wide and twenty-two inches long. FIGS. 16 and 17 are an engineering drawings, consistent with this invention, of the coil sets shown in FIG. 8. FIG. 18 shows the constant signal pattern for a catheter at $= 90$ and $= 90$ degrees of a magnetic field generated by a delta coil set in FIG. 10.

FIG. 19 is a diagram of a surgical table 1900 with an integrated examination deck. The examination deck comprising field generating coils may be integrated at any or all locations 1902, 1904, and 1906. Alternatively, field generating coils may be integrated directly into surgical table 1900 at any or all locations 1902, 1904, and 1906. FIG. 20 is a top view, side view, and an end view of surgical table 2000 with an integrated examination deck. The examination deck comprising field generating coils may be integrated at any or all locations 2002, 2004, and 2006. Alternatively, field generating coils may be integrated directly into surgical at any or all locations 2002, 2004, and 2006.

The invention may be embodied in other specific forms without departing from the spirit or essential characteristics thereof. The present embodiments are therefore to be considered in respects as illustrative and not restrictive, the scope of the invention being indicated by the appended claims rather than by the foregoing description, and all changes which come within the meaning and range of the equivalency of the claims are therefore intended to be embraced therein.

What is claimed is:

1. An apparatus for determining a location of a sensor in a surgical navigation domain, comprising:

a first magnetic field generator including a first coil set;

a second magnetic field generator including a second coil set, wherein the first and second coil sets are disposed substantially within a common plane; and,

a processor, configured to receive a plurality of signals, for calculating the location of the sensor from the plurality of signals, wherein the sensor produces the plurality of signals in response to magnetic fields generated by the first and second magnetic field generators.

2. An apparatus according to claim1, wherein the first coil set includes at least one delta coil pair for generating a gradient magnetic field in the navigation domain.

3. An apparatus according to claim 2, each delta coil pair further including one or more end correction coils, wherein each delta coil pair is electrically coupled to the corresponding end correction coil, and current flows through the end correction coil in a direction opposite of the direction of the current flowing through the corresponding delta coil pair.

4. An apparatus according to claim 1, wherein the second coil set includes at least one uniform coil pair for generating a uniform magnetic field in the navigational domain.

5. An apparatus according to claim 1, wherein the first coil set includes a first delta coil pair longitudinally oriented along a first axis, a second delta coil pair longitudinally oriented along a second axis, and a third delta coil pair longitudinally oriented along a third axis, such that the second axis is rotated within the common plane substantially sixty degrees with respect to the first axis, and the third axis is rotated within the common plane substantially one hundred and twenty degrees with respect to the first axis.

6. An apparatus according to claim 5, wherein each of the first, second and third delta coil pairs lies within a distinct plane that is parallel to the common plane, such that the delta coil pairs overlap one another.

7. An apparatus according to claim 5, wherein each of the first, second and third delta coil pairs includes two or more distinct coil elements, electrically coupled, such that the aggregate of the distinct coil elements produces the corresponding gradient magnetic field.

8. An apparatus according to claim 7, wherein intersecting delta coil pairs share one or more common coil elements.

9. An apparatus according to claim 7, wherein intersecting delta coil pairs include distinct coil elements in an intersecting region where the delta coil pairs overlap.

10. An apparatus according to claim 5, each of the delta coil pairs further including one or more end correction coils, wherein each of the delta coil pairs is electrically coupled to the corresponding end correction coil, and electrical current flows through the end correction coils in a direction opposite of the direction of the current flowing through the corresponding delta coil pair.

11. An apparatus according to claim 5, wherein at least one of the delta coil pairs is characterized by a length different from the length of the other delta coil pairs.

12. An apparatus according to claim 5, wherein each of the delta coil pairs includes:

a short coil, further including a first end correction element and a second end correction element for reducing unwanted magnetic field components, wherein electrical current flows through the end correction coils in a direction opposite of the direction of the current flowing through the corresponding short coil; and,

a long coil, further including a central compensating coil for reducing unwanted magnetic field components, wherein electrical current flows through the central compensating coil in a direction opposite of the direction of the current flowing through the corresponding long coil.

13. An apparatus according to claim 5, wherein one or more of the delta coil pairs overlap a coplanar uniform coil pair.

14. An apparatus according to claim 13, wherein each of the one or more overlapping delta coil pairs includes two or more distinct coil elements, electrically coupled, such that the aggregate of the distinct coil elements produces the corresponding gradient magnetic field.

15 An apparatus for determining a location of a sensor in a surgical navigation domain, comprising:

a first magnetic field generator including at least one delta coil pair for generating a gradient magnetic field in said navigation domain, the at least one delta coil pair disposed within a first plane;

a second magnetic field generator including at least one uniform coil pair for generating a uniform magnetic field in the navigational domain, the at least one uniform coil pair disposed within a second plane, wherein first plane is offset from the second plane by an offset angle calculated to reduce undesirable uniform field components; and,

a processor, configured to receive a plurality of signals, for calculating the location of the sensor from the plurality of signals, wherein the sensor produces the plurality of signals in response to magnetic fields generated by the first and second magnetic field generators.

16. An apparatus for determining a location of a sensor in a surgical navigation domain, comprising:

a first magnetic field generator including a common coil;

a second magnetic field generator including the common coil;

a processor, configured to receive a plurality of signals, for calculating the location of the sensor, wherein the sensor produces the plurality of signals in response to a first magnetic field generated by the first magnetic field generator and in response to a second magnetic field of a different shape than the first magnetic field generated by the second magnetic field generator.

17. A method of determining a location of a sensor in a surgical navigation domain, comprising:

generating a first magnetic field using a first magnetic field generator including a first coil set;

generating a second magnetic field using a second magnetic field generator including a second coil set, wherein the first and second coil are disposed substantially within a common plane;

calculating the location of the sensor from a plurality of signals, wherein the sensor produces the plurality of signals in response to magnetic fields generated by the first and second generated magnetic fields.

18. A method according to claim17, wherein generating a first magnetic field further includes generating a gradient magnetic field in said navigation domain using at least one delta coil pair for generating.

19. A method according to claim17, wherein generating a first magnetic field further includes generating a gradient magnetic field in said navigation domain using two or more distinct coil elements, electrically coupled, such that the aggregate of the distinct coil elements produces the corresponding gradient magnetic field.

20. A method according to claim17, wherein generating a first magnetic field further includes generating a gradient magnetic field in said navigation domain using delta coil pairs having one or more end correction coils, wherein each of the delta coil pairs is electrically coupled to the corresponding end correction coil, and electrical current flows through the end correction coils in a direction opposite of the direction of the current flowing through the corresponding delta coil pair.

21 A method of determining a location of a sensor in a surgical navigation domain, comprising:

generating a gradient magnetic field in said navigation domain using a first magnetic field generator including at least one delta coil pair disposed within a first plane;

generating a uniform magnetic field in the navigational domain using a second magnetic field generator including at least one uniform coil pair for, the at least one uniform coil pair disposed within a second plane, wherein the first plane is offset from the second plane by an offset angle calculated to reduce undesirable uniform field components; and,

calculating the location of the sensor from a plurality of signals, wherein the sensor produces the plurality of signals in response to magnetic fields generated by the first and second generated magnetic fields.

22. A method of determining a location of a sensor in a surgical navigation domain, the method comprising:

generating a first magnetic field using a magnetic field generator including a common coil;

generating a second magnetic field of a different shape than the first magnetic field using a second magnetic field generator including the common coil;

calculating the location of the sensor from a plurality of signals, wherein the sensor produces the plurality of signals in response to magnetic fields generated by the first and second magnetic field generators.

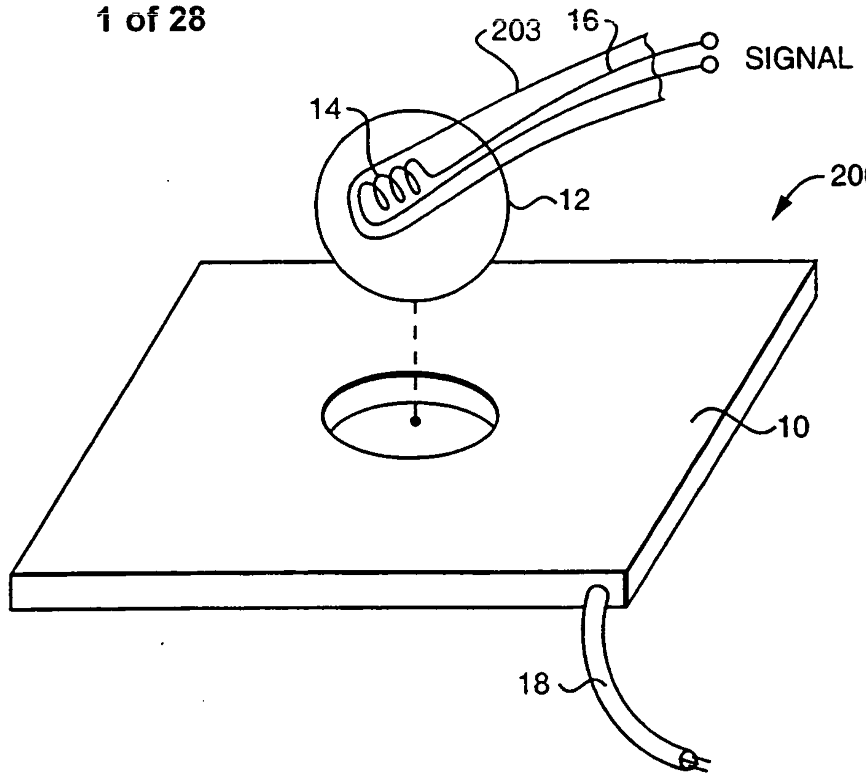
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FIG. 1

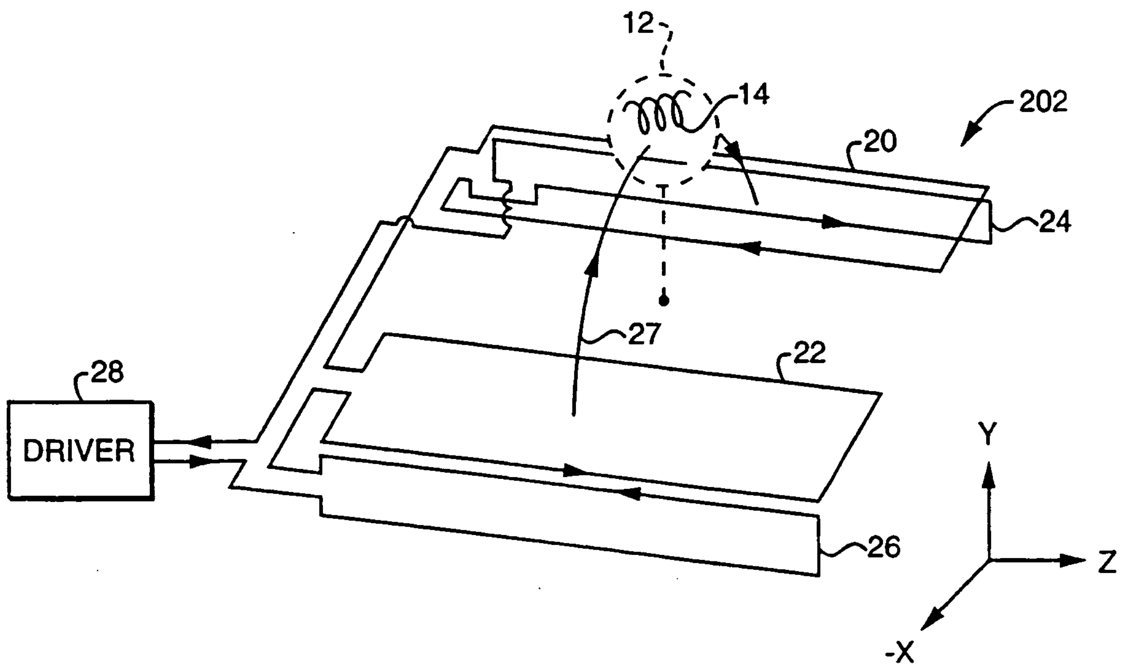
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FIG. 2A

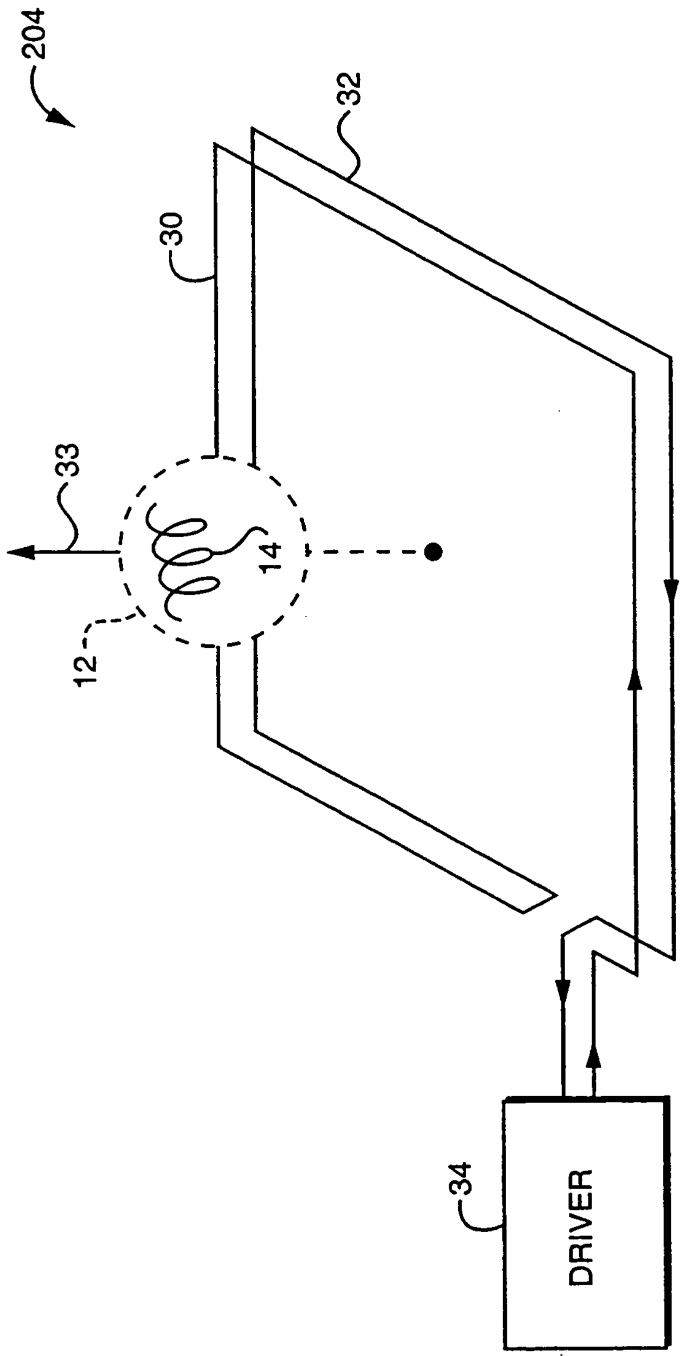

FIG. 2B

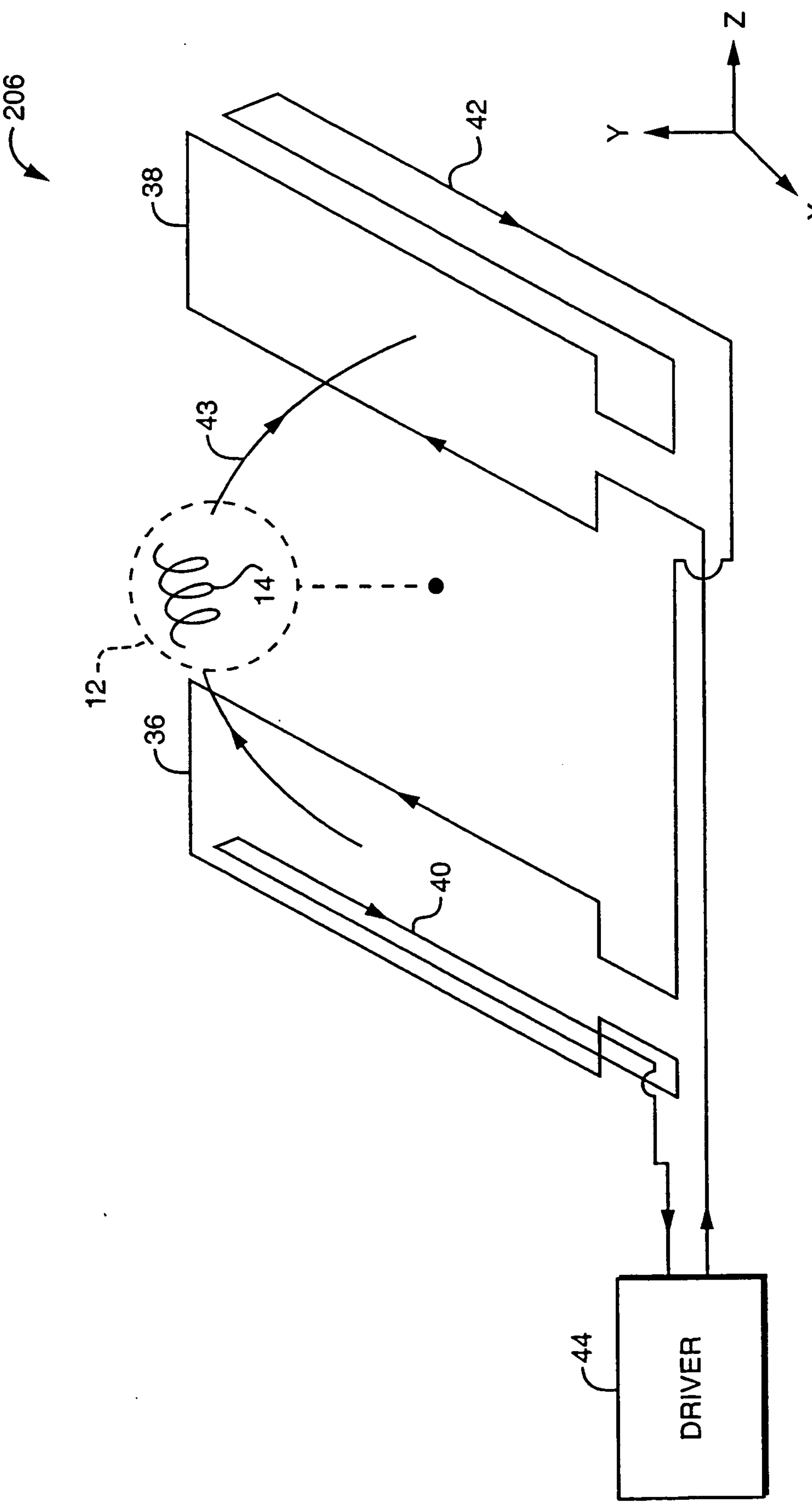

FIG. 2C

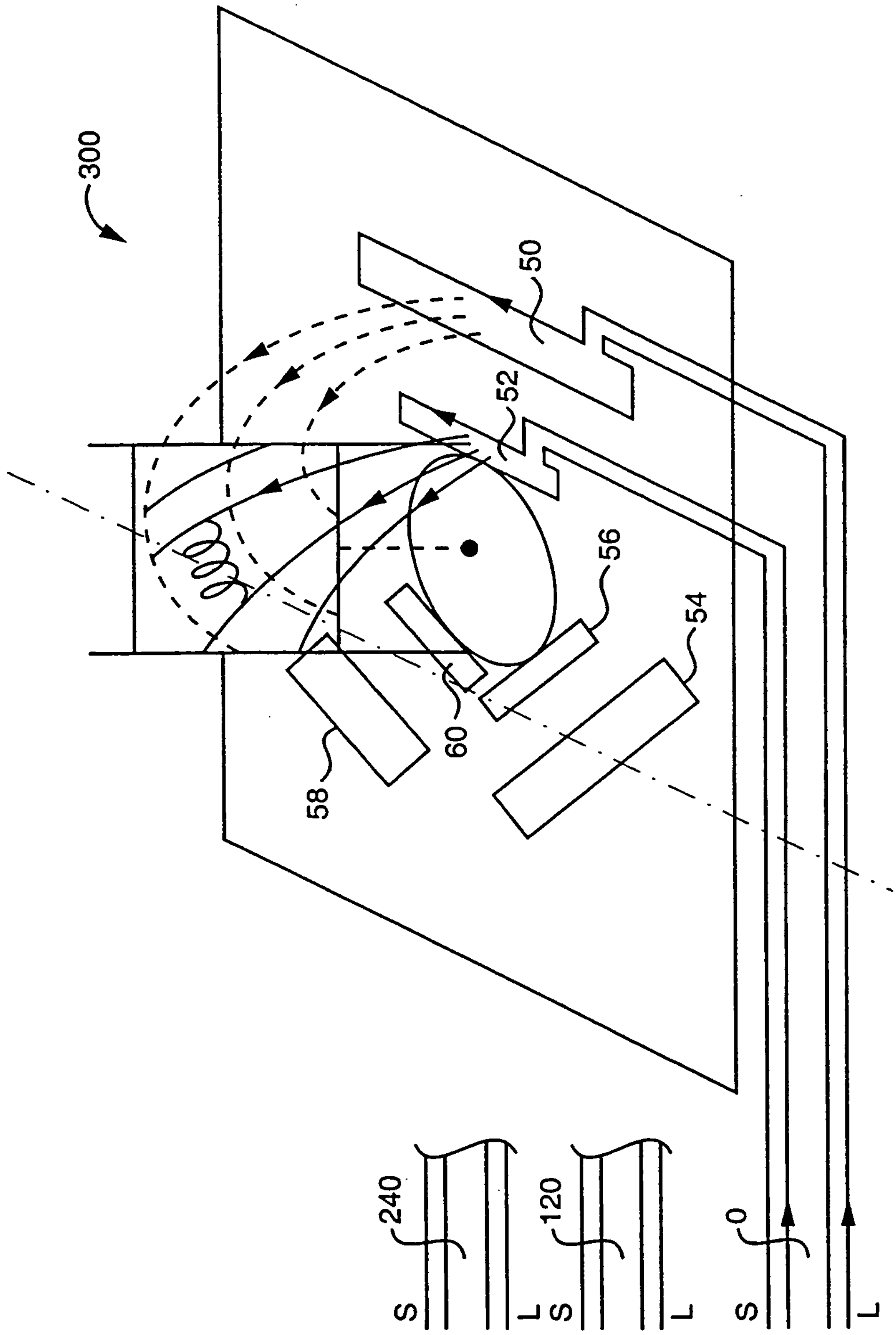

FIG. 3

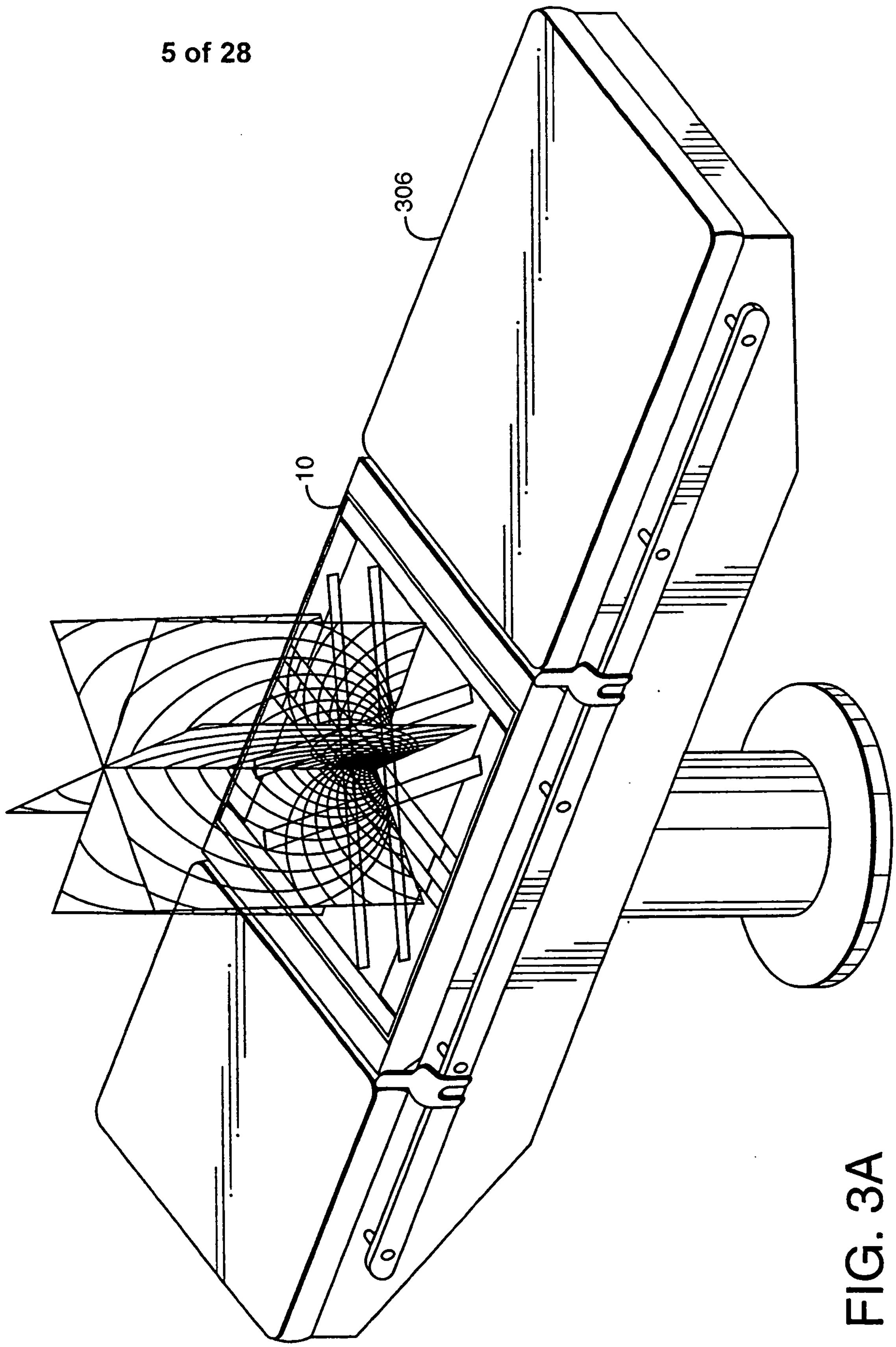

FIG. 3A

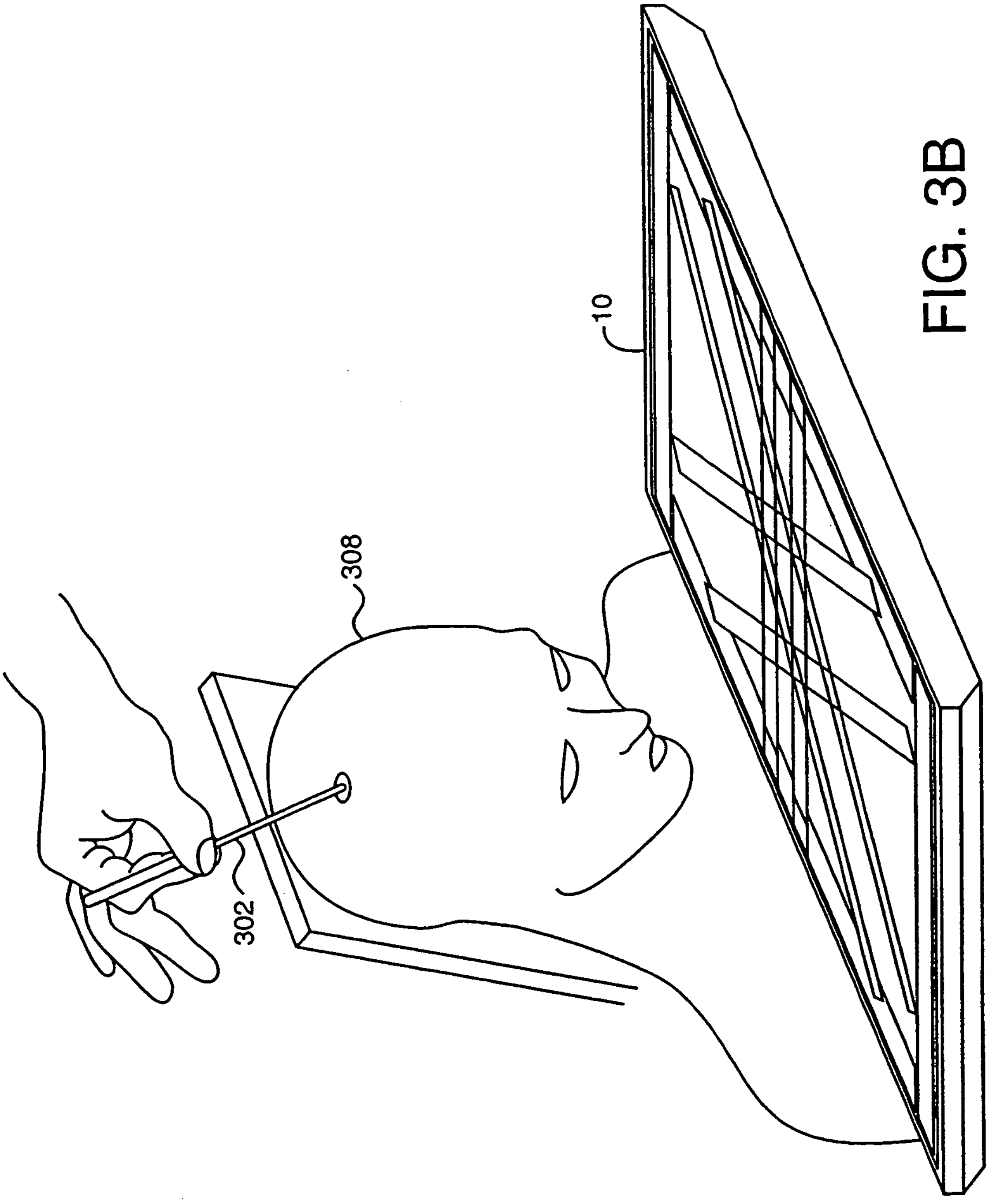

FIG. 3B

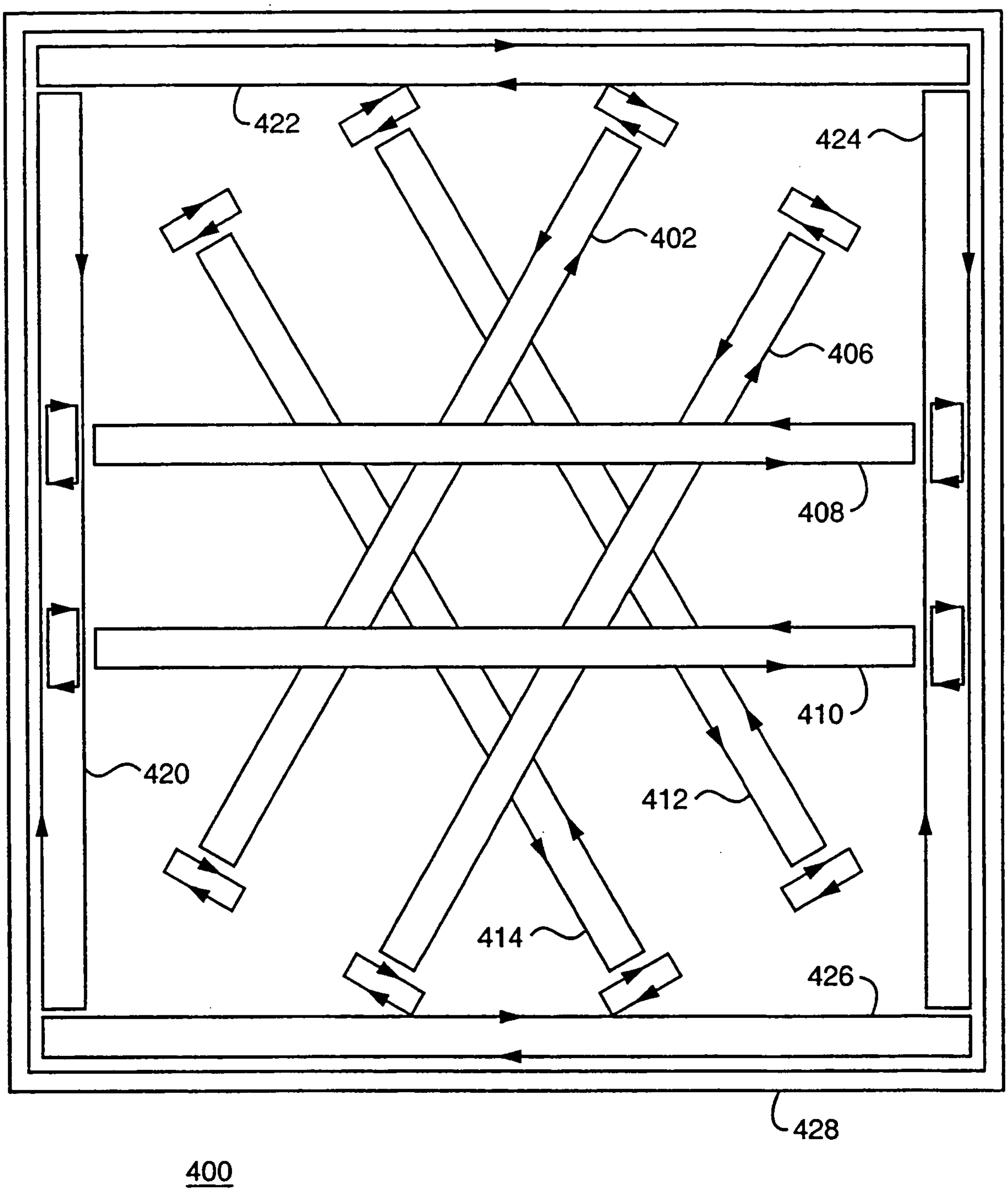

FIG. 4

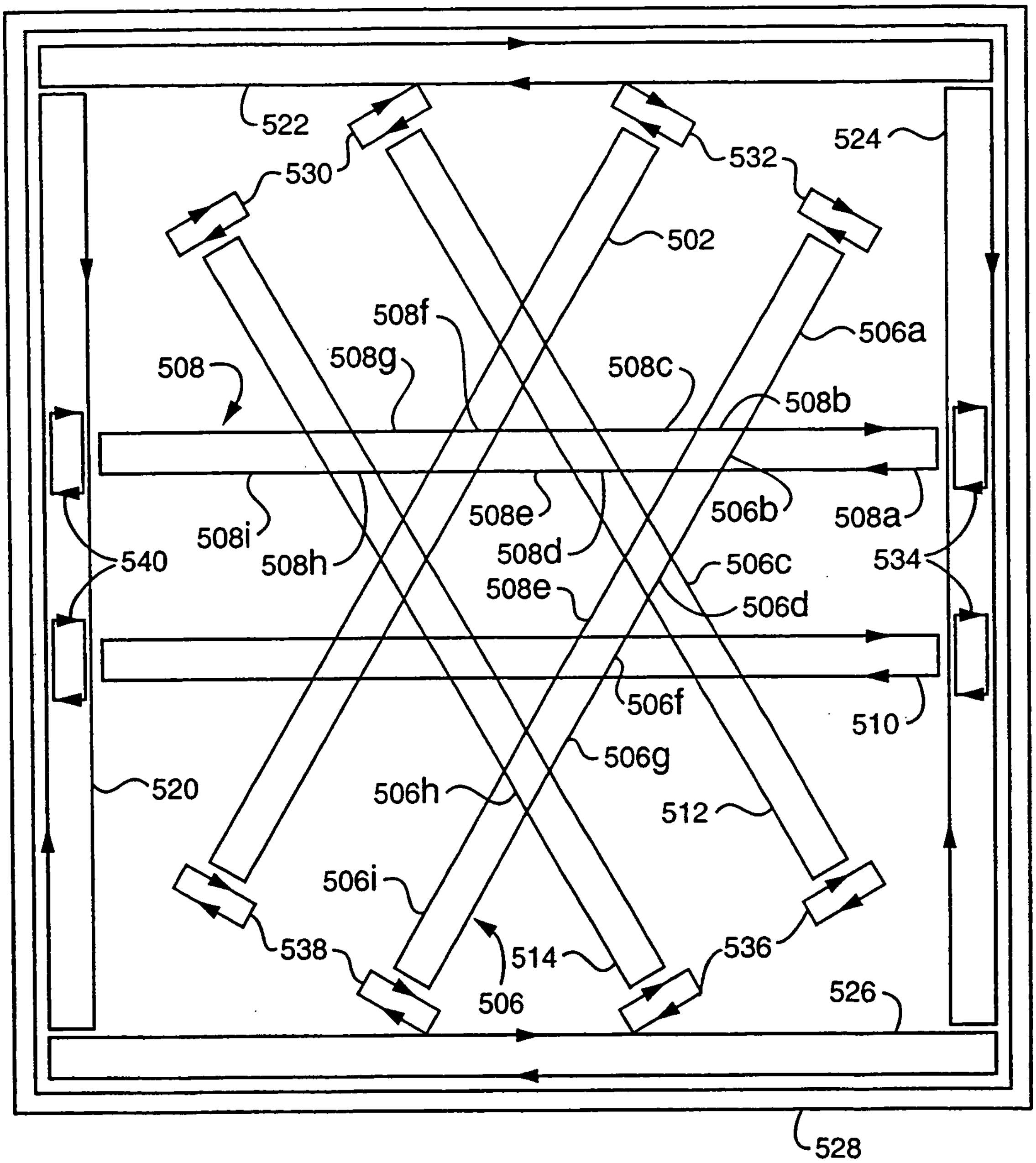
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FIG. 5

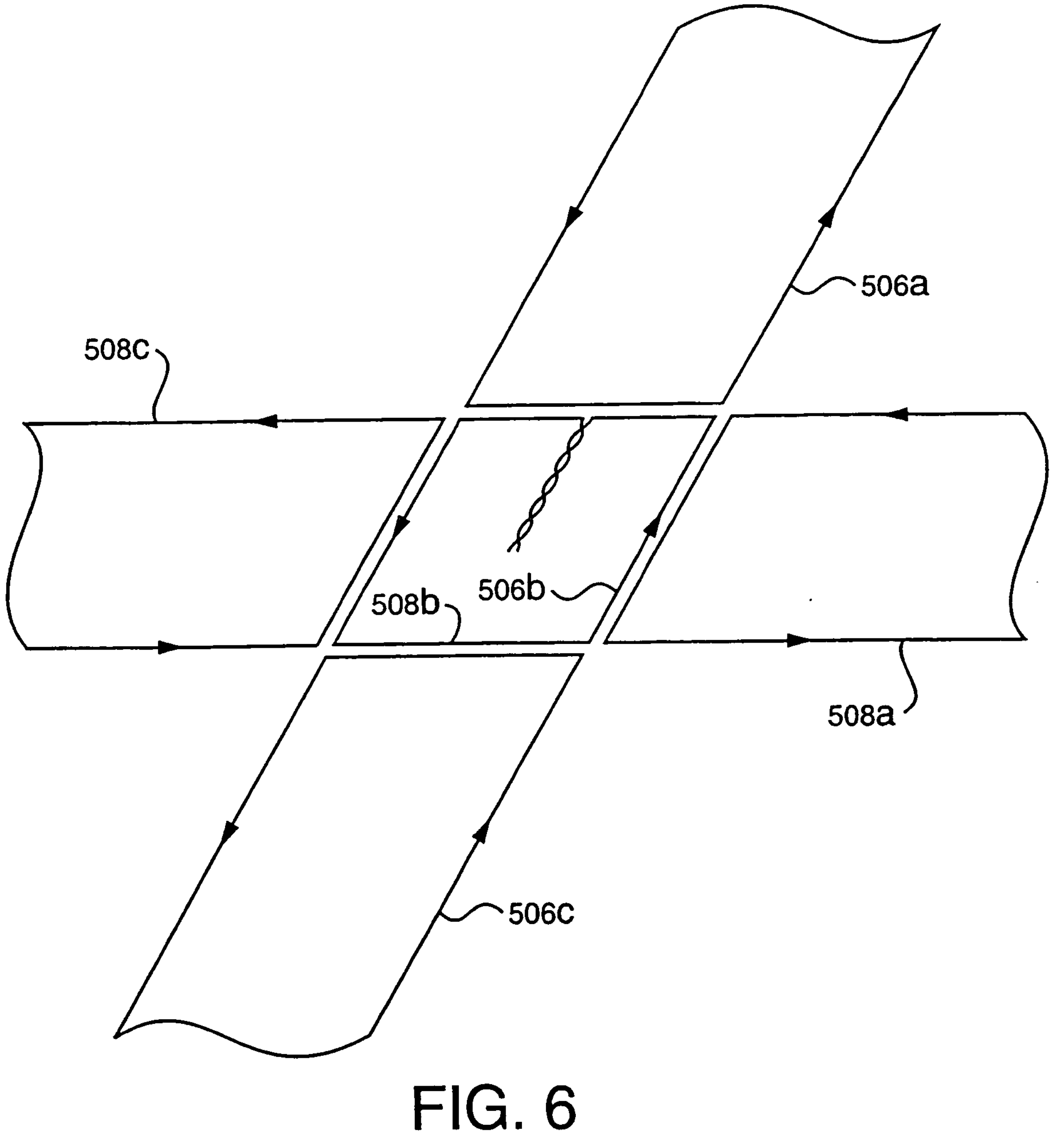

FIG. 6

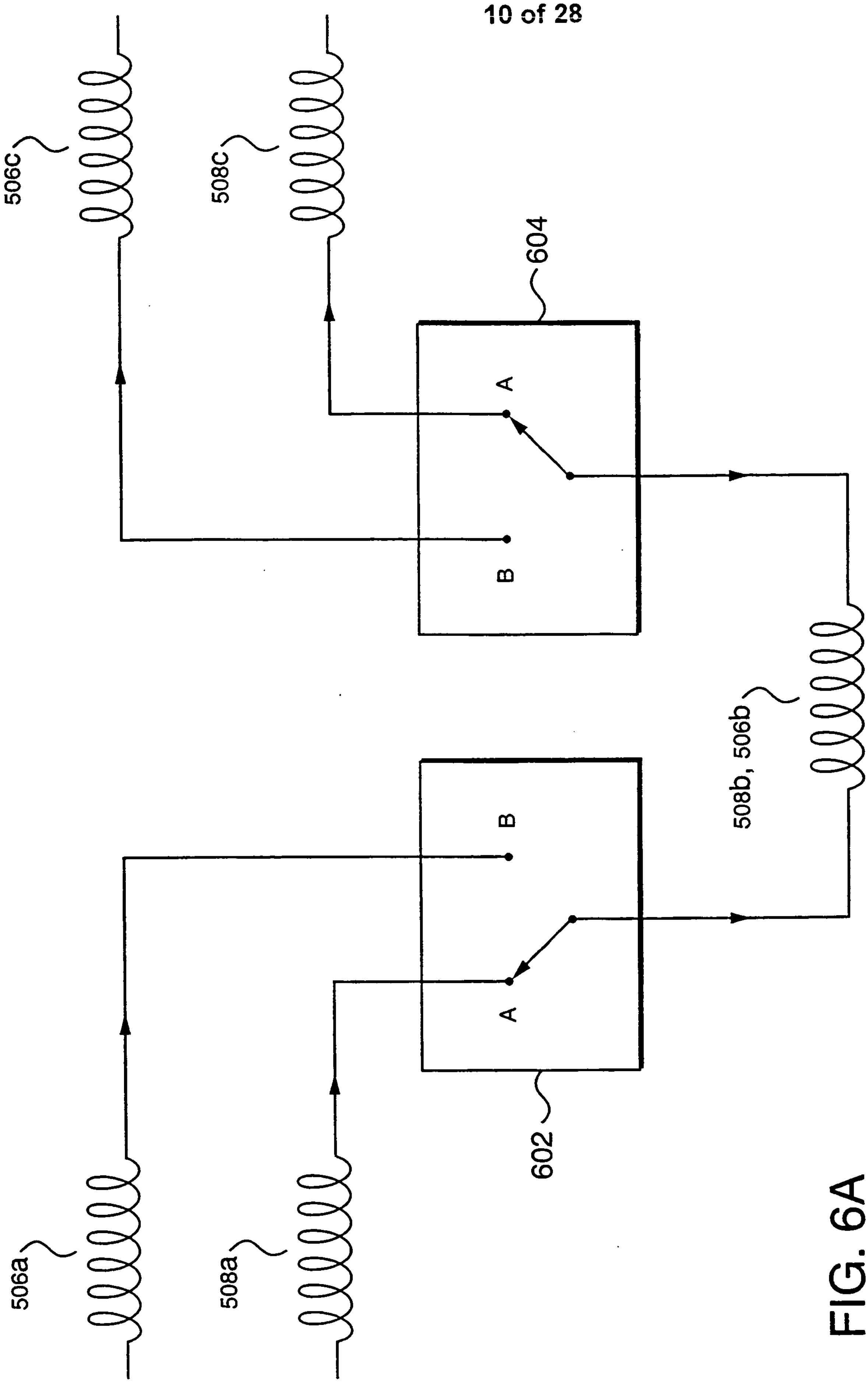

FIG. 6A

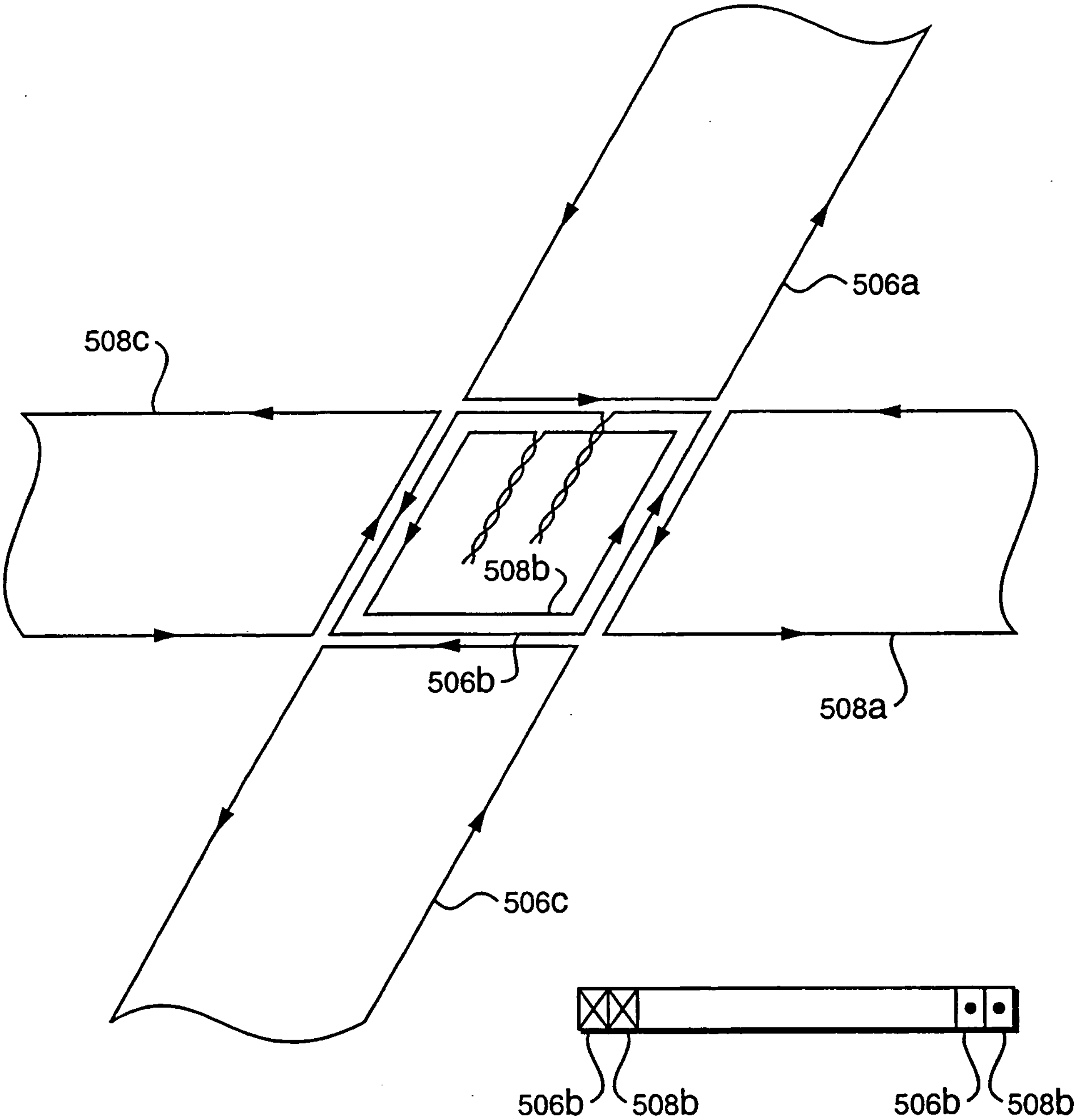

FIG. 7

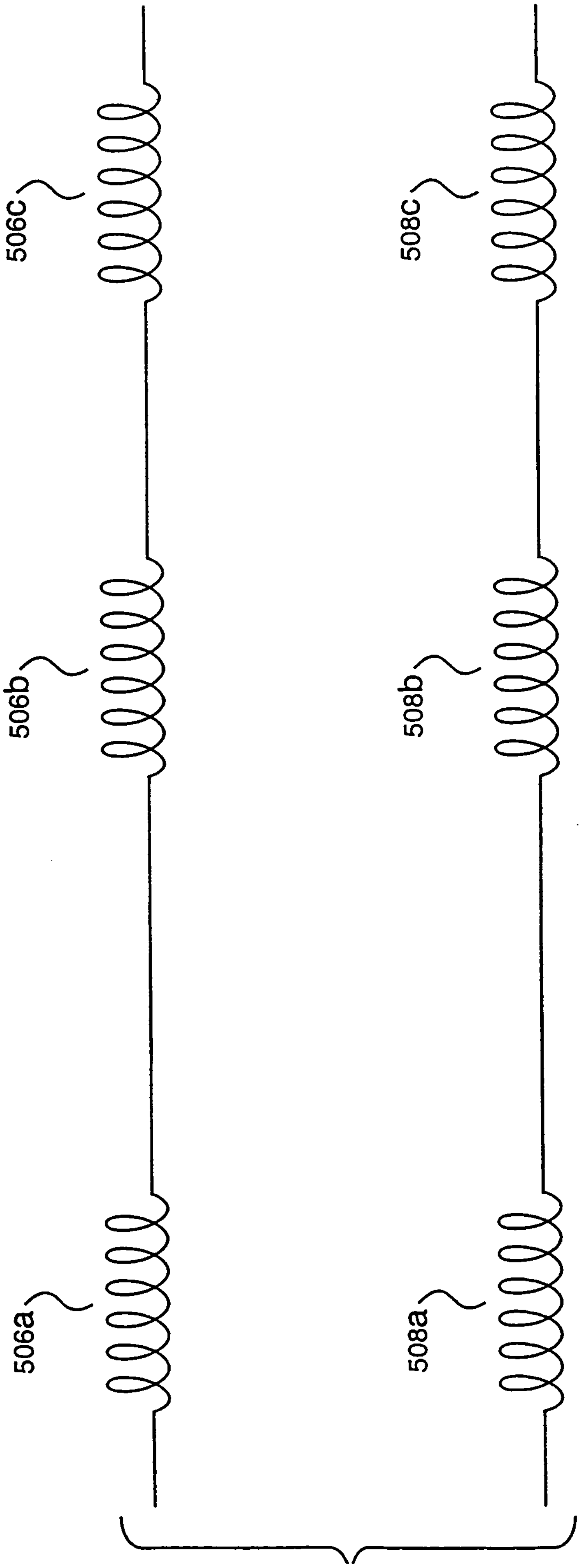

FIG. 7A

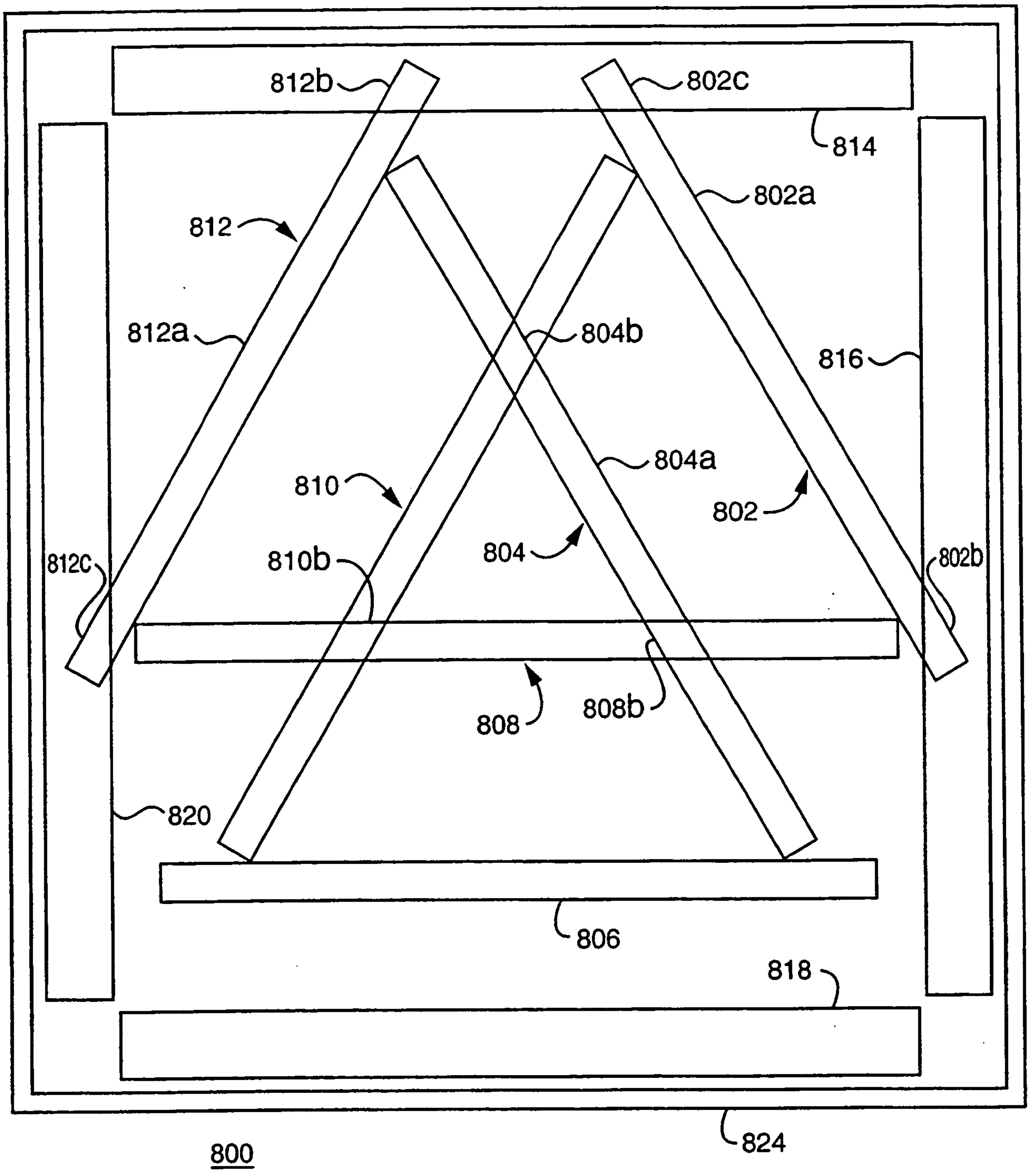
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FIG. 8

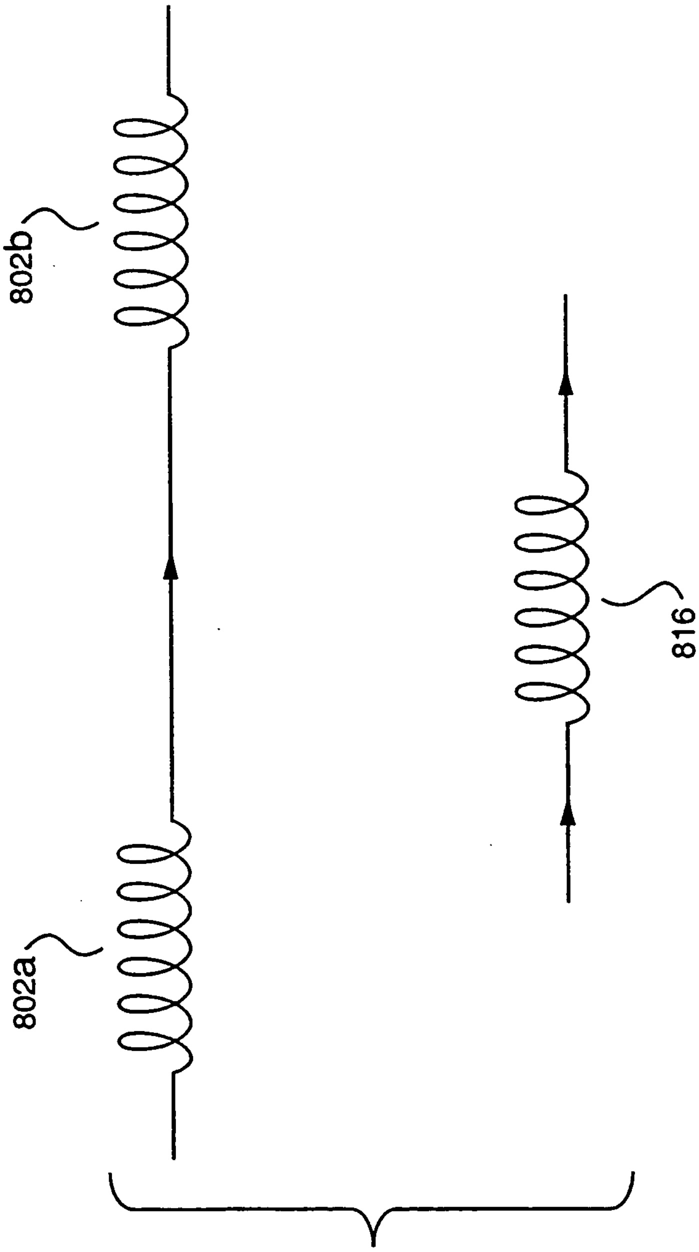

FIG. 8A

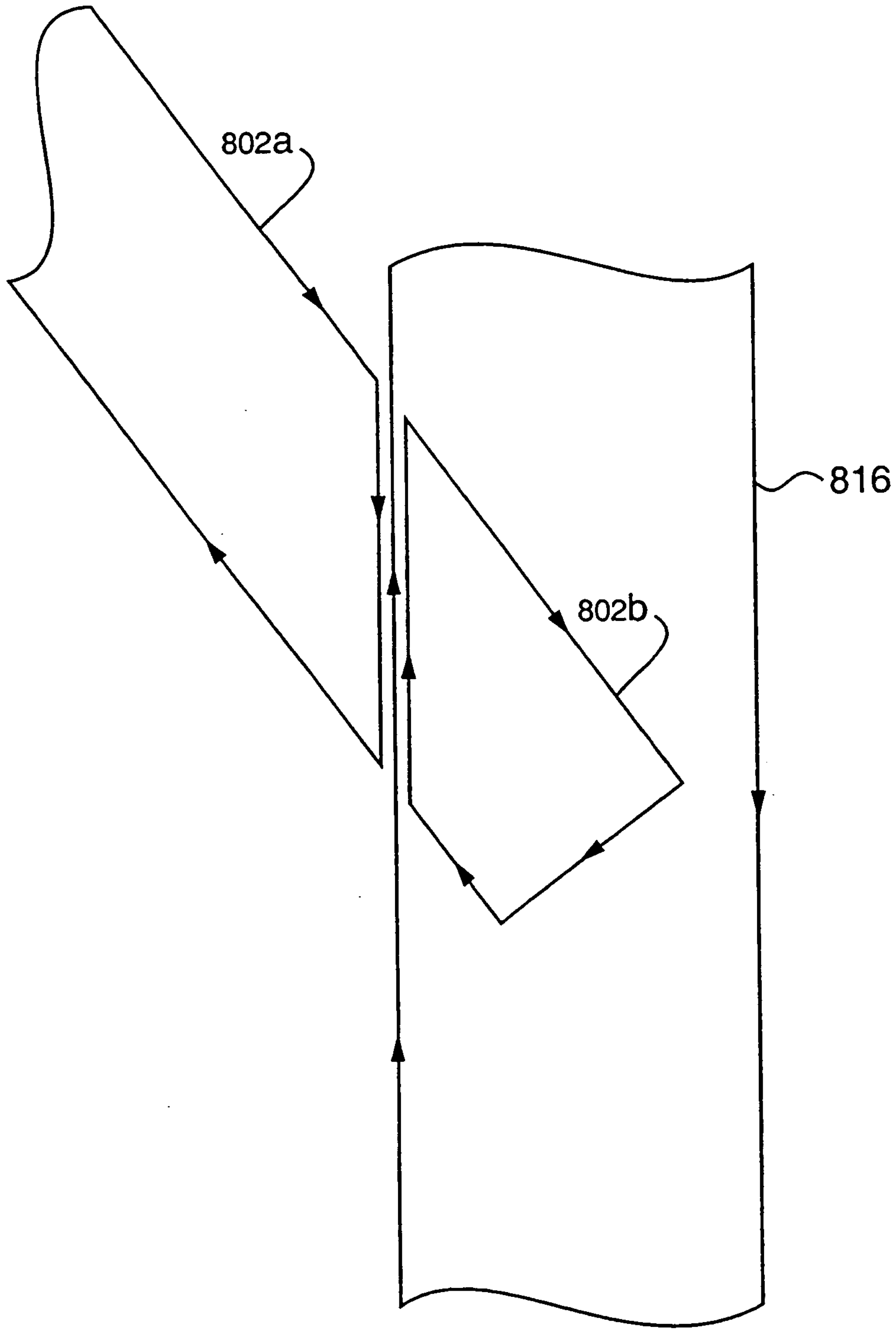

FIG. 9

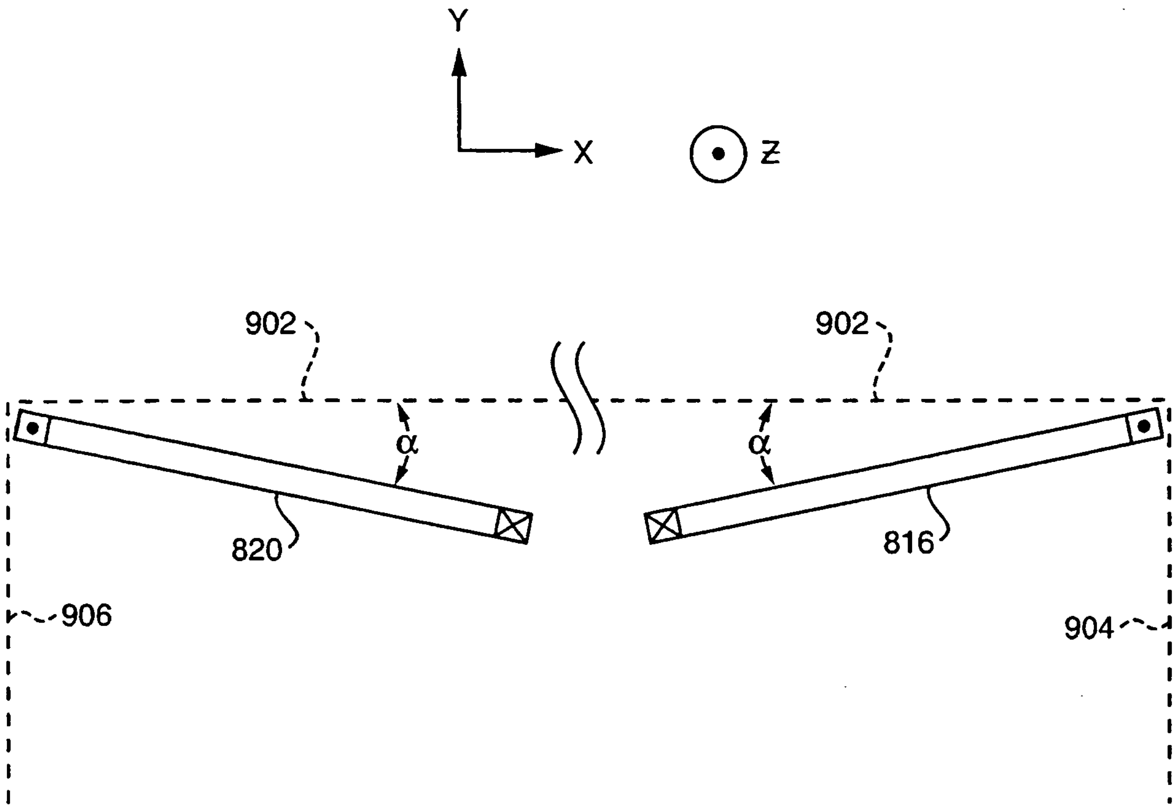

FIG. 9A

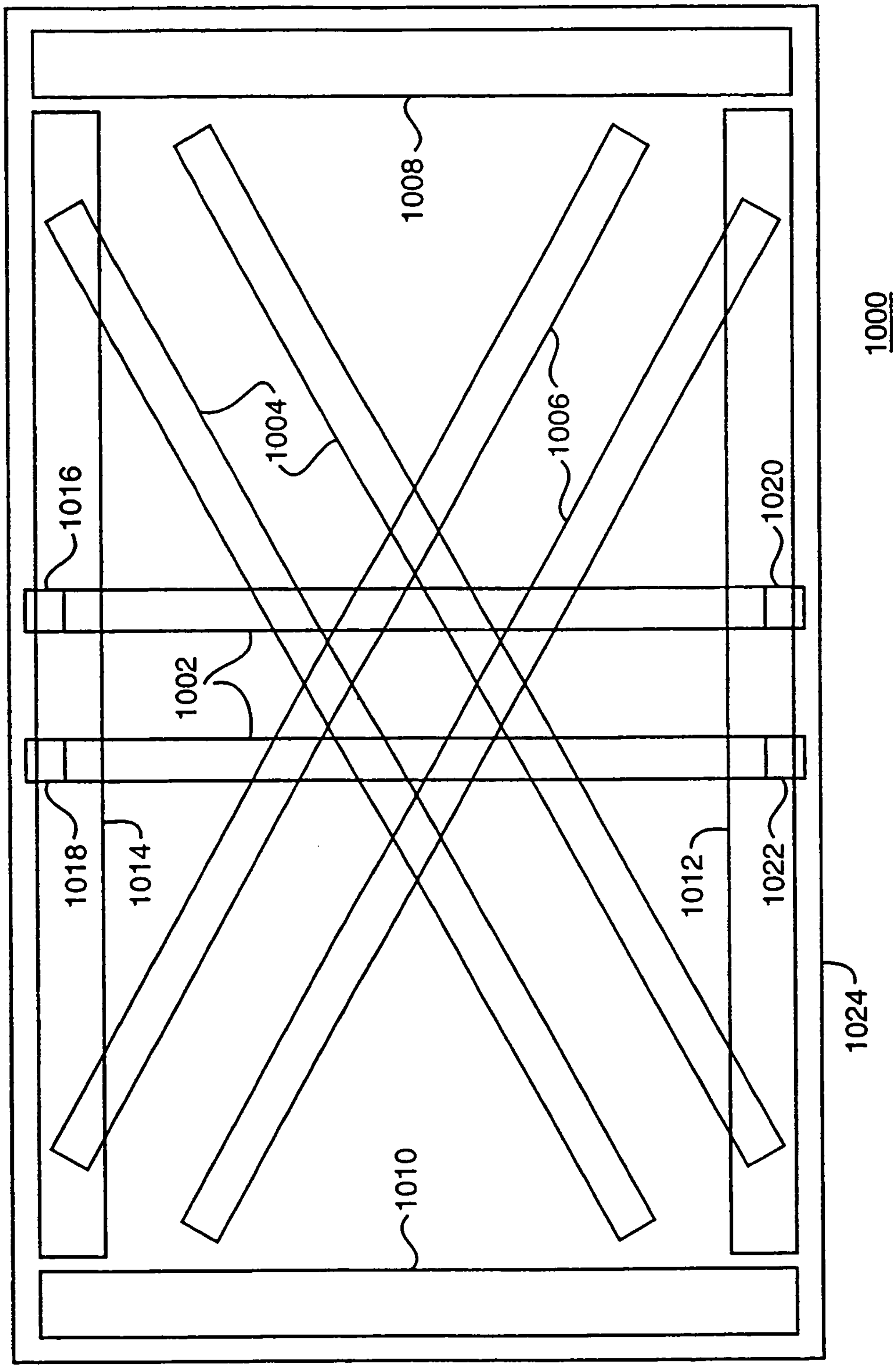
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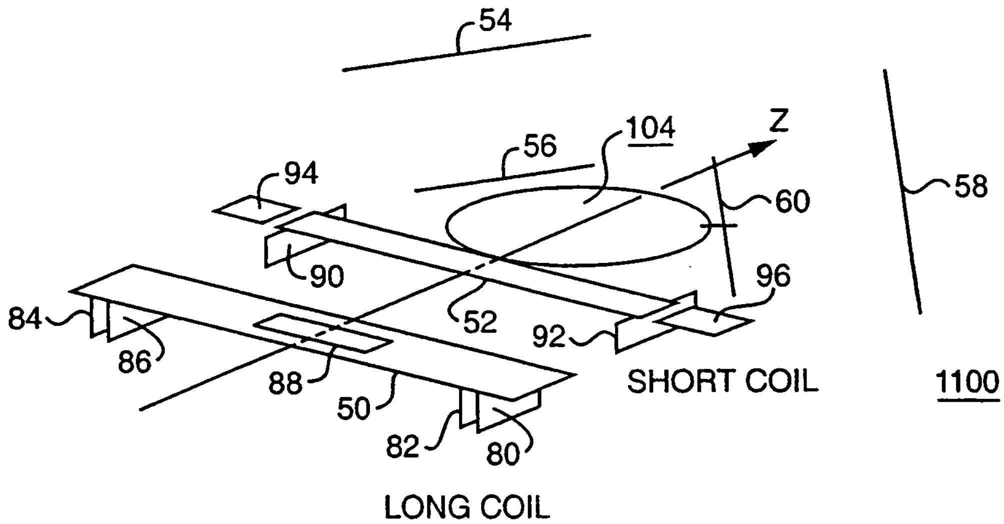
FIG. 10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LONG COIL

FIG. 11

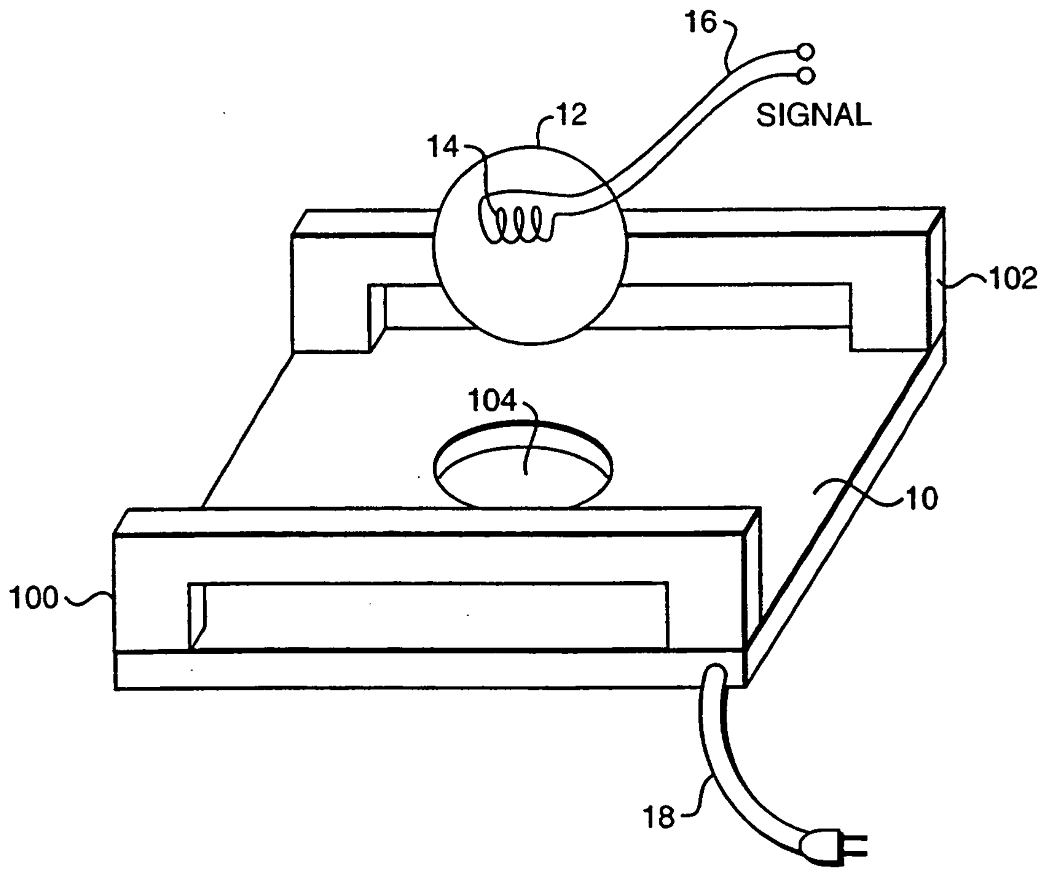
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FIG. 12

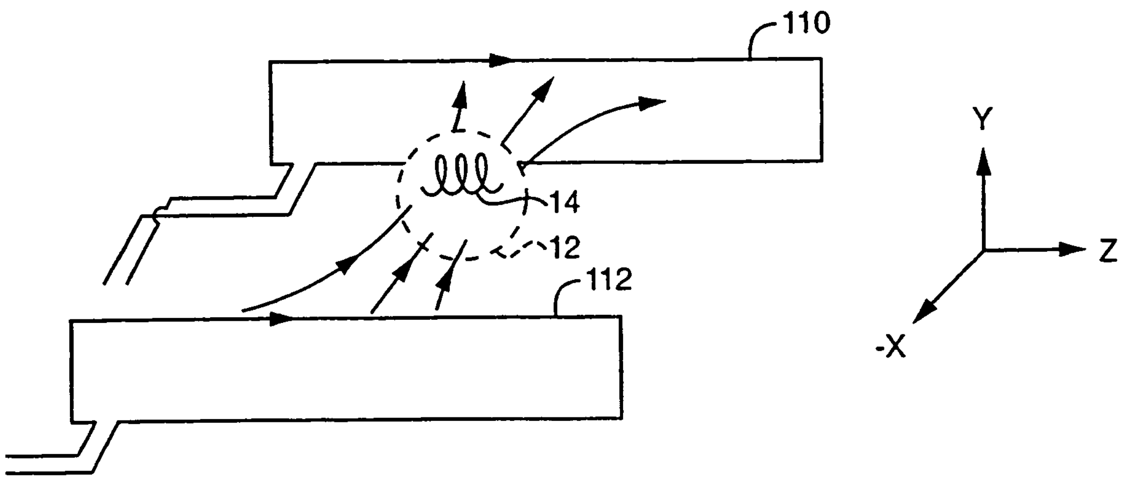


FIG. 13A

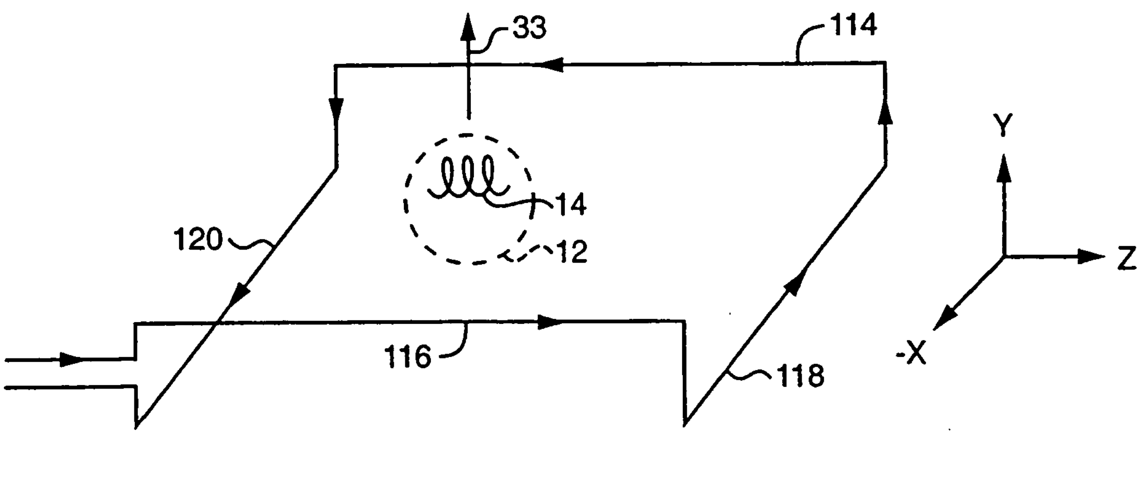


FIG. 13B

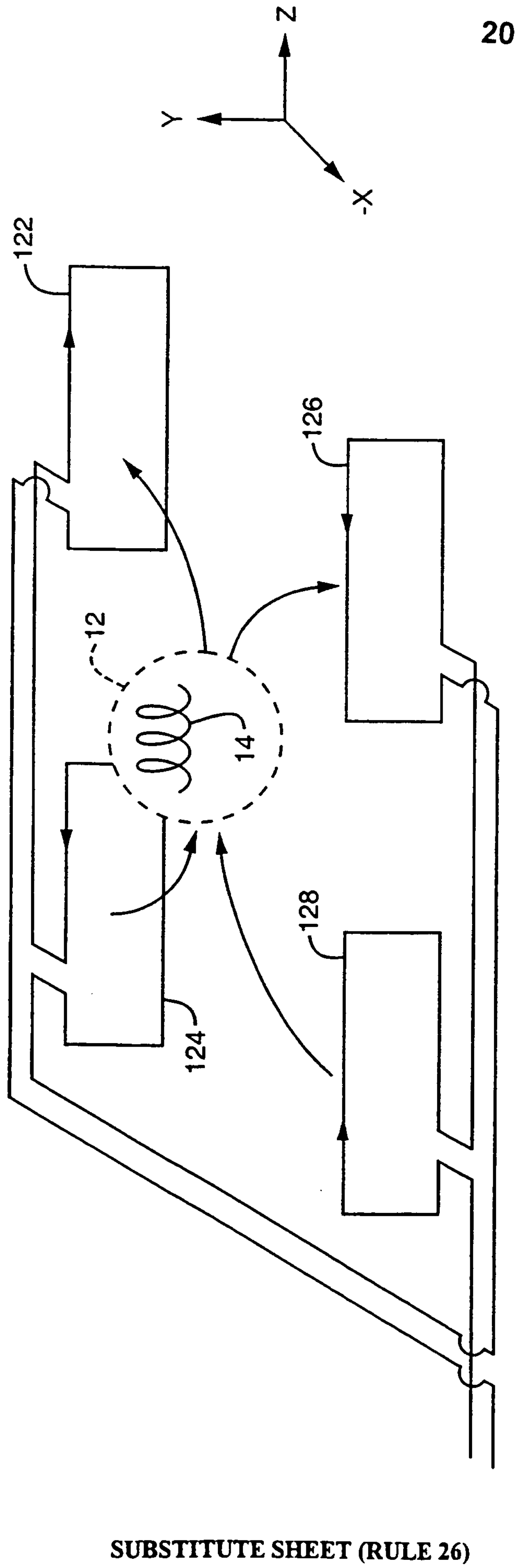


FIG. 13C

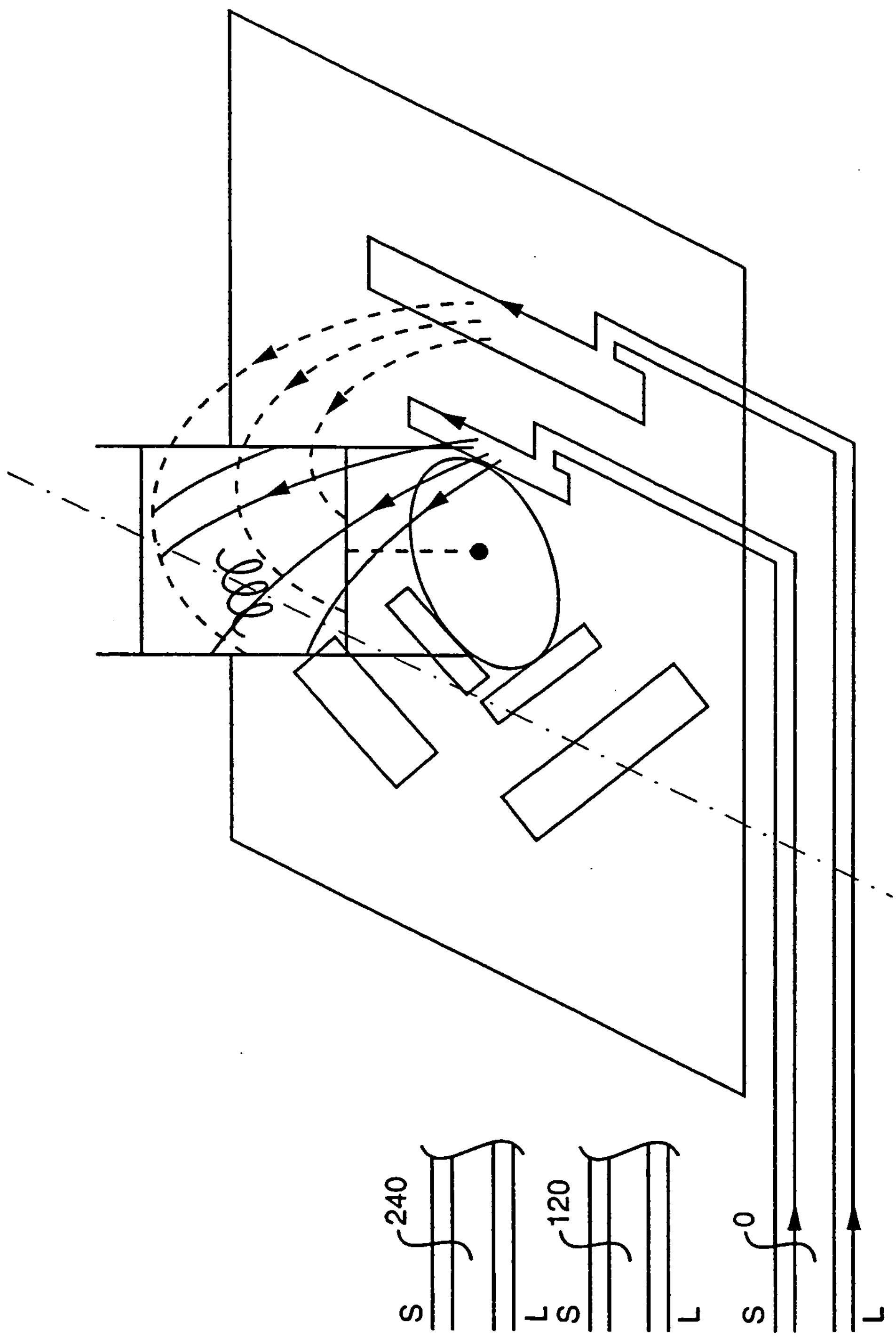


FIG. 13D

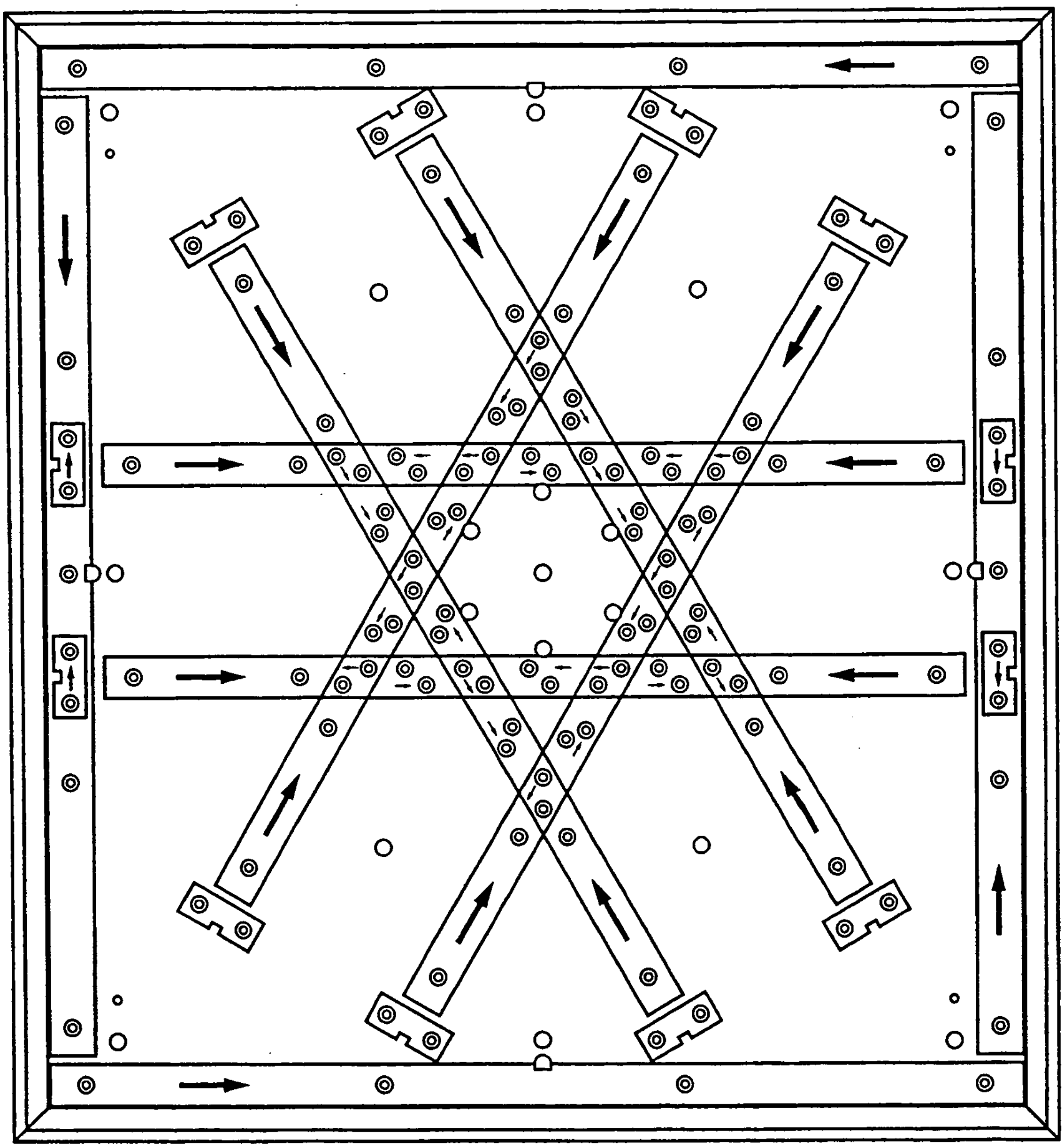


FIG. 14

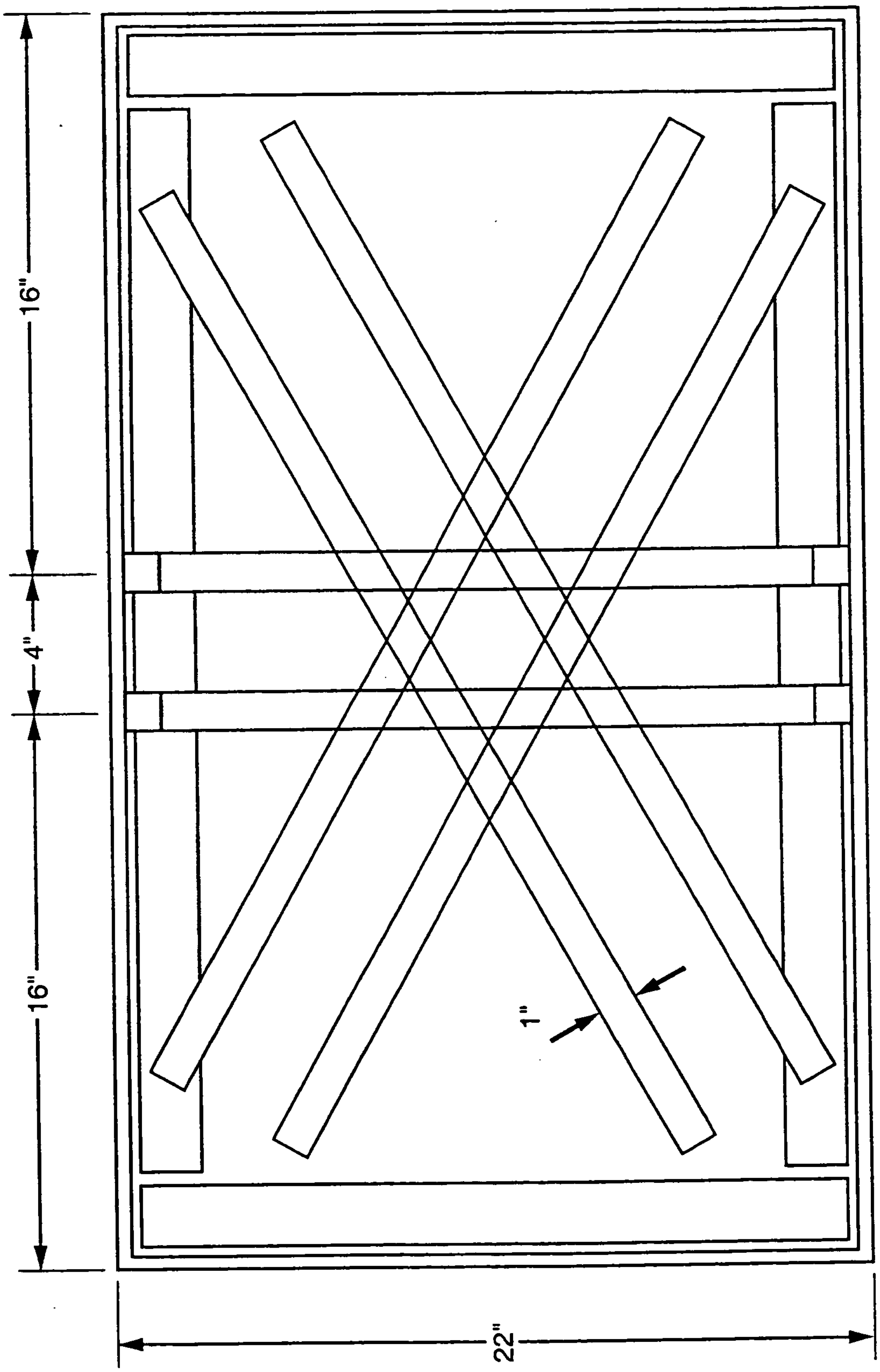


FIG. 15

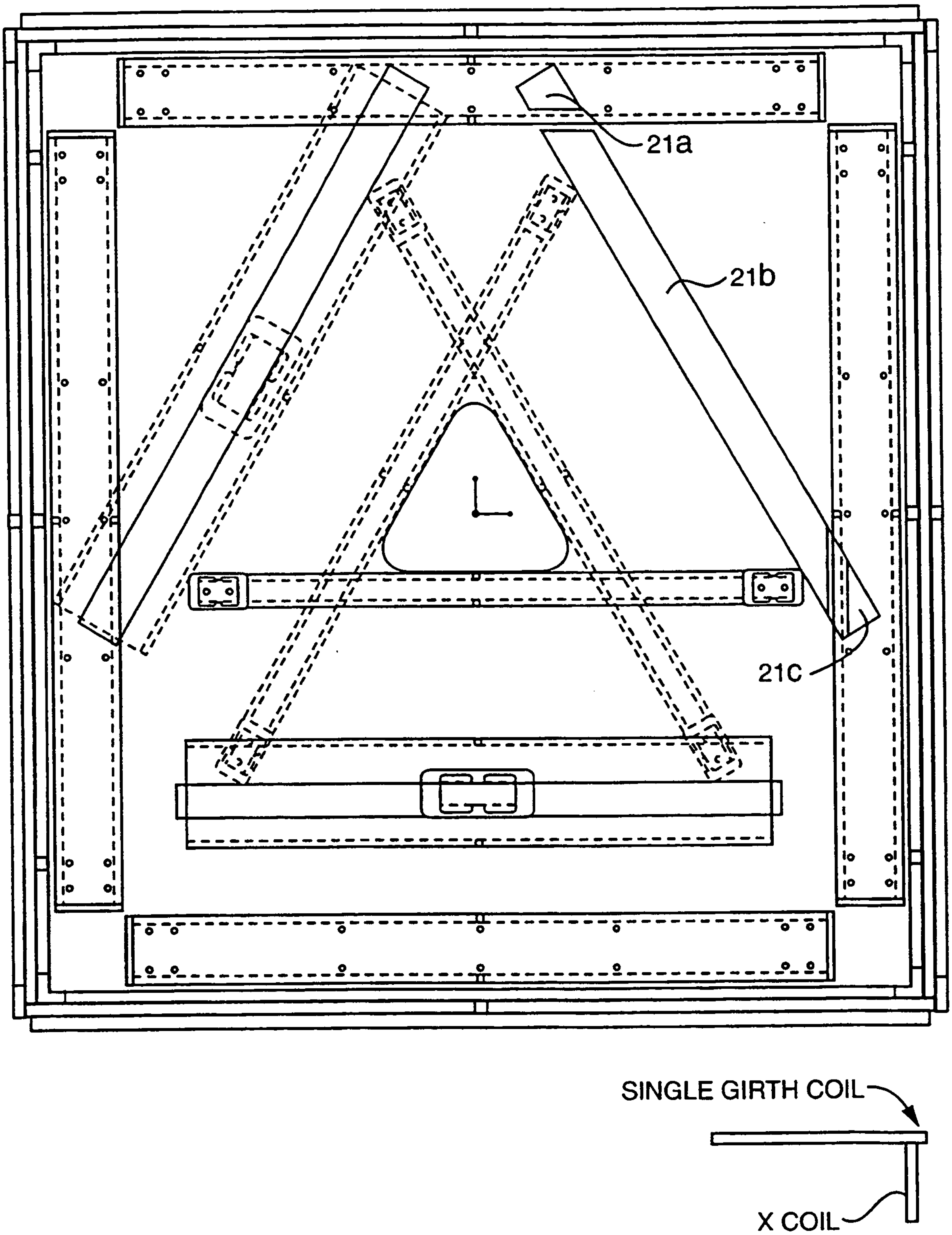
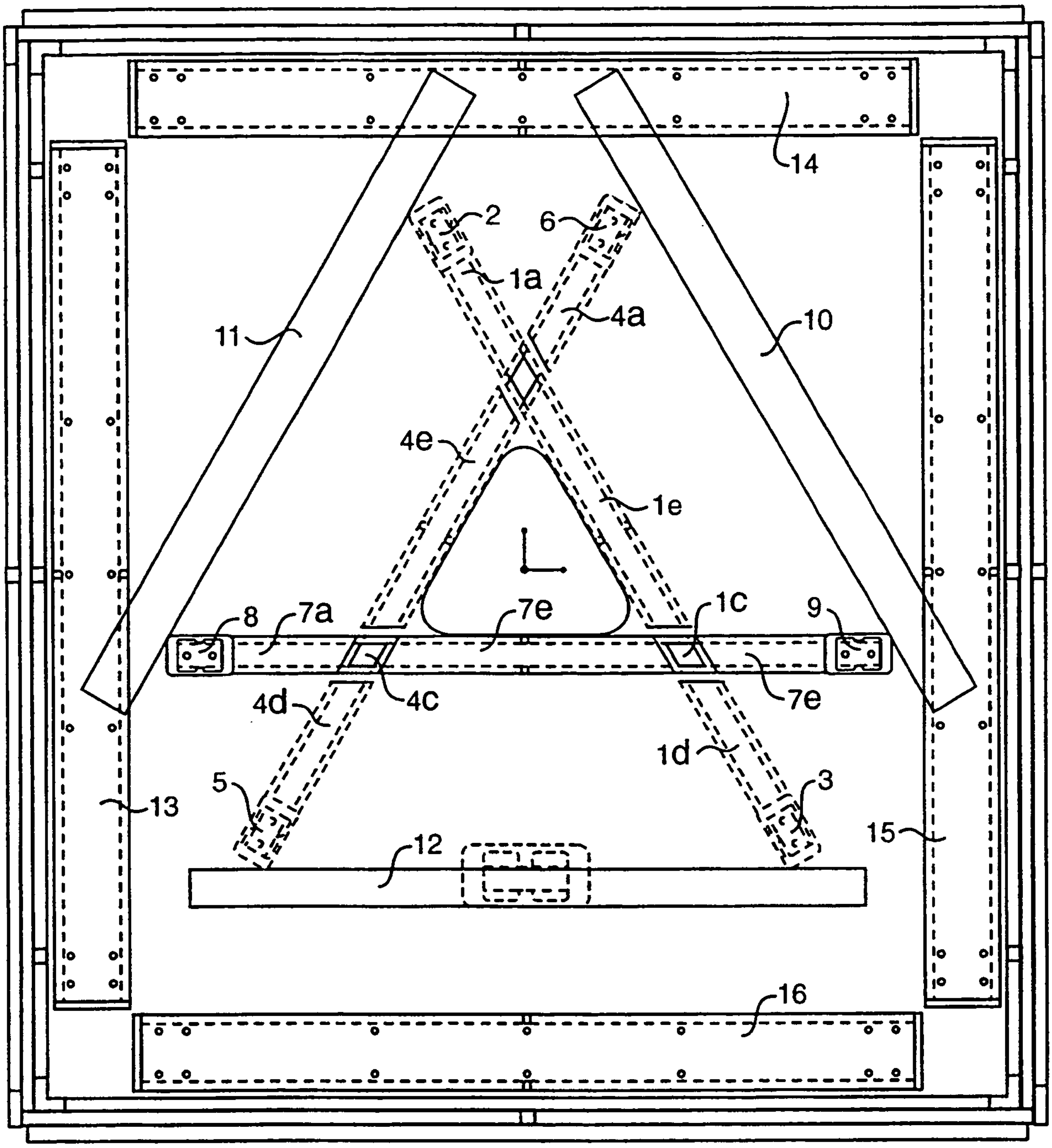


FIG. 16



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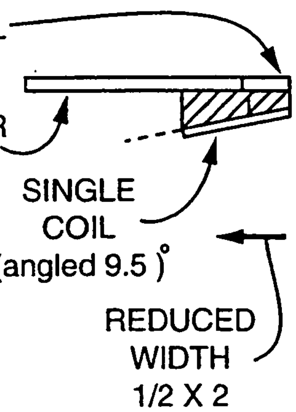

SINGLE GIRTH COIL
ALL OTHER COILS
SINGLE COIL (angled 9.5°)
REDUCED WIDTH 1/2 X 2

FIG. 17

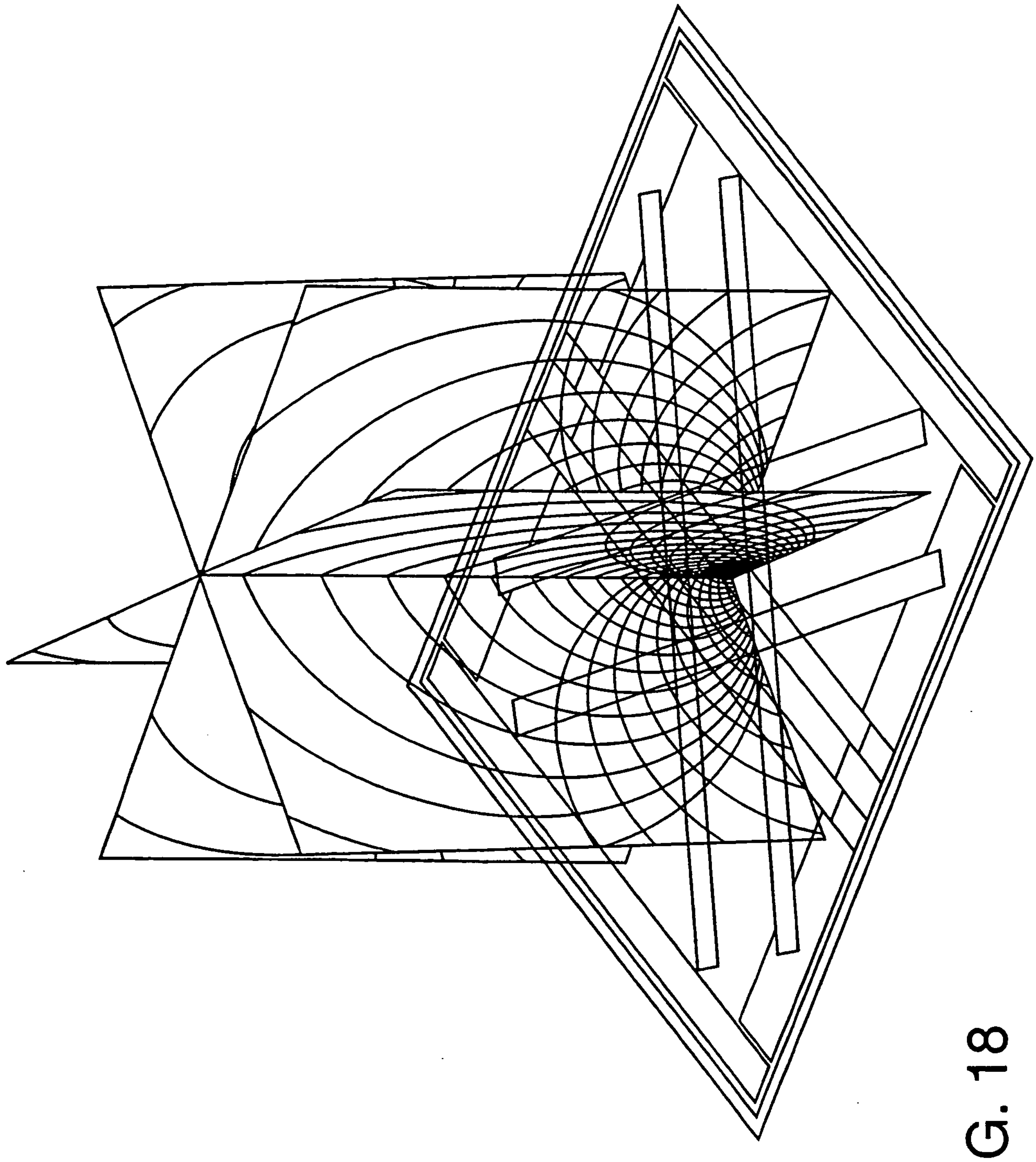

FIG. 18

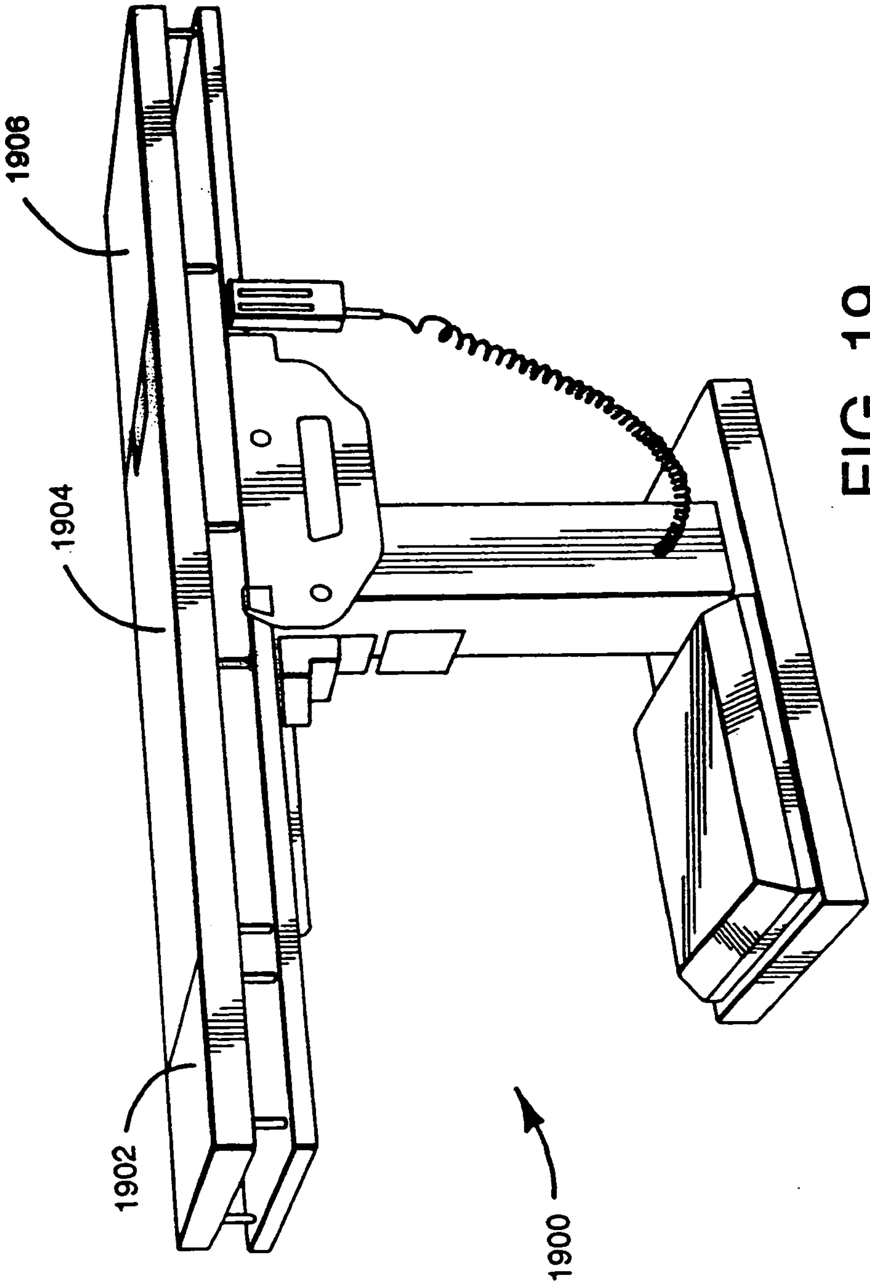

FIG. 19

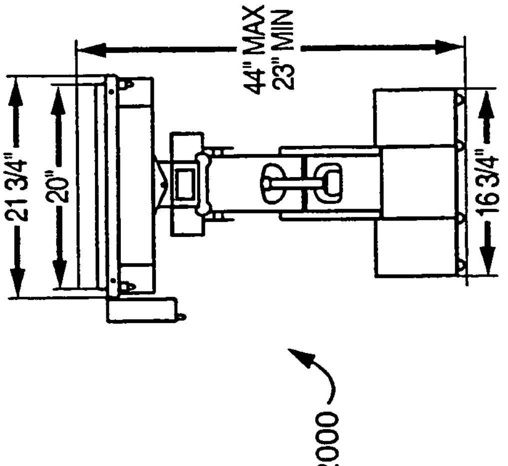

FIG. 20C

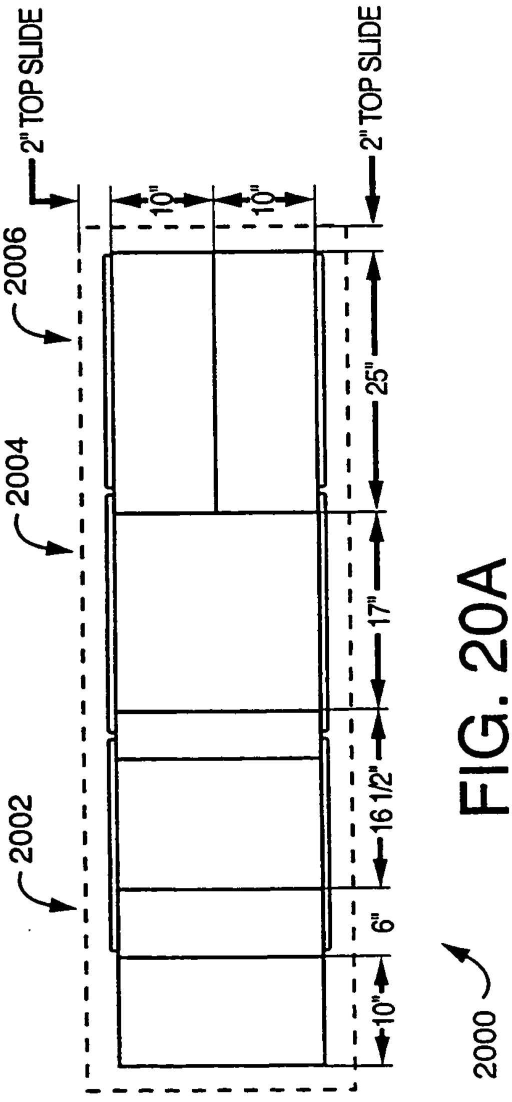

FIG. 20A

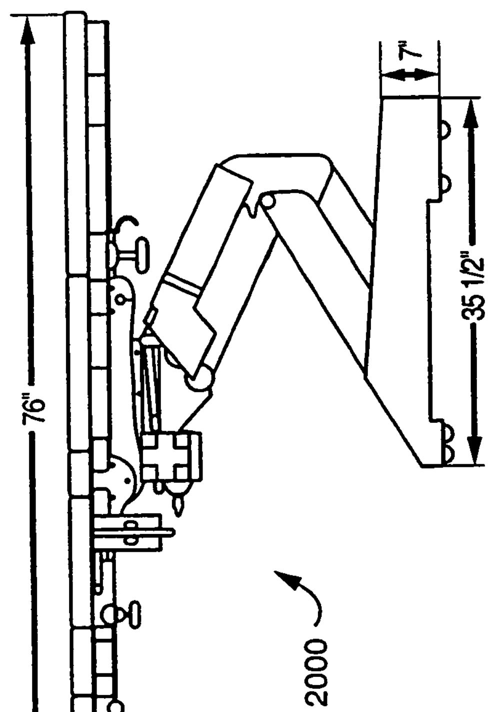

FIG. 20B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/29733

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :G06F 15/00; A61B 19/00
US CL :702/152; 128/899; 324/207.13, 228.
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 702/150, 151, 152, 153; 128/899; 600/409, 410, 424; 324/207.13, 207.16, 207.22, 228.

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EAST

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y --- A	US 5,592,939 A (MARTINELLI) 14 January 1997 (14.01.1997), col. 3, line 57 to col. 7, line 64.	1-2, 4, 15-19, 21-22 ---------- 3, 5-14, 20
Y --- A	US 5,211,165 A (DUMOULIN et al) 18 May 1993 (18.05.1993), col. 2, line 60 to col. 6, line 58.	1-2, 4, 15-19, 21-22 ----------- 3, 5-14, 20
Y --- A	US 4,821,731 A (MARTINELLI et al) 18 April 1989 (18.04.1989) col.4, line 27 to col. 9, line 35.	1-2, 4, 15-19, 21-22 ----------- 3, 5-14, 20
A	US 4,173,228 A (VAN STEENWYK et al) 06 November 1979 (06.11.1979), col. 2, line 62 to col. 5, line 50.	1-22

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
15 FEBRUARY 2001	04 APR 2001

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	BRYAN BUI
Facsimile No. (703) 305-3230	Telephone No. (703) 305-4490