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(71) Applicant (for all designated States except US): **THE TRUSTEES OF DARTMOUTH COLLEGE** [US/US];
11 Rope Ferry Road, Hanover, NH 03755 (US).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **SULLIVAN, Charles, R.** [US/US]; 13 Gilson Road, West Lebanon, NH 03784 (US). **NIGAM, Mitushi** [IN/US]; 124 Sycamore Street, Apt 2, Somerville, MA 02145 (US).

(74) Agent: **VOCK, Curtis, A.**; Lathrop & Gage LLP, 4845 Pearl East Circle, Suite 201, Boulder, CO 80301 (US).

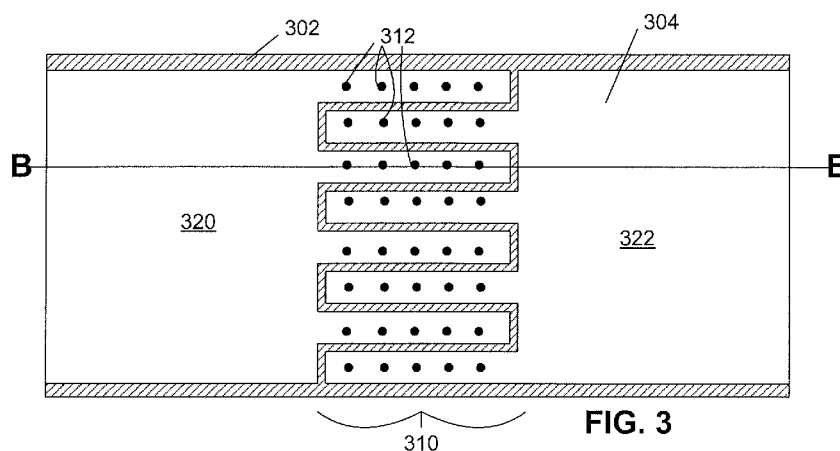
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(54) Title: MULTILAYER FOIL-WOUND INDUCTORS HAVING ALTERNATING LAYERS



(57) Abstract: A multilayer foil winding in a foil-wound magnetic circuit component (200) has conductors (202, 204, 402, 408) that alternate at various points such that the conductors share current more effectively than multiple non-alternating conductors. AC resistance of the multilayer winding is therefore decreased relative to a single, thicker, layer of foil conductor or a multilayer winding that does not alternate layer positions.

MULTILAYER FOIL-WOUND INDUCTORS HAVING ALTERNATING LAYERS

RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Application No. 61/030,016, filed 20 February 2008, and is incorporated herein by reference.

FIELD

[0002] This document pertains to the field of magnetic circuit elements such as electrical inductors and transformers.

BACKGROUND

Skin Effect

[0003] The “skin effect” tends to confine AC currents in solid wire to a layer, of depth equal to the “skin depth” near the surface of the wire. The skin depth decreases with frequency, becoming shallower proportional to the reciprocal of the square root of frequency. Skin depth also varies with resistivity and permittivity of the material of which the wire is made, aluminum having a skin depth about 23% greater than that of copper.

[0004] Skin depth can be noticeable at higher audio frequencies as well as radio frequencies. For example, beyond 2600 Hz a 10-gauge solid copper wire will have a skin depth sufficiently shallow that there will be little current at the center of the wire. Similarly, the center of a 20-gauge copper wire will carry little current above 27 kHz, and the center of a 30 gauge wire will carry little current above 270 kHz. Skin depth δ versus frequency f can be calculated from the equation:

$$\delta \equiv \frac{1}{\sqrt{\pi f \mu \sigma}}$$

where f is the frequency of the current, μ is the permeability of the conductor and σ the conductivity of the conductor.

Proximity Effect

[0005] Proximity effect, a phenomenon well known in the art, is the tendency for current to flow in a conductor in undesirable patterns, i.e. loops or

concentrated distributions, due to the presence of magnetic fields generated by nearby conductors having an AC current. The changing current flowing in a first conductor induces a magnetic field around that conductor and, if a second conductor is near by, the magnetic field causes a current to be induced in the second conductor which opposes the magnetic field from the first conductor. The induced current in the second conductor tends to crowd. This phenomenon causes uneven sharing of the current across the bulk of the conductor, resulting in an increased AC resistance. In one example, a first conductor carries an AC current and is placed in close proximity to a second conductor which is open circuited, eddy-currents are induced in the second conductor by the current flowing in first conductor. The current induced in the second conductor opposes the magnetic field of the first conductor. If the second conductor is open circuited, the net current within the second conductor must be zero and hence a balancing current flows in the second conductor on the side farthest from the first conductor. Similar effects occur in parallel conductors, and depending on the current direction, the surfaces facing each other may have denser current while the concentration of current may be lower far from the other conductor.

[0006] As with skin effect, the proximity effect causes current flow to concentrate in only a portion of the total conductor thickness.

Configurations to Reduce Skin-Effect and Proximity-Effect Losses

[0007] Since skin effects and proximity effects cause increased power losses, it can be desirable to use conformations that mitigate these effects.

[0008] Stranded wire, a bundle of thin, round, uninsulated, conductors, has similar skin-effect issues to solid wire because currents tend to migrate to those strands close to the surface of the bundle.

[0009] Litz wire, a bundle of thin, round, individual conductors insulated from each other and twisted or woven in special patterns such that each strand tends to reside near the surface for an approximately equal fraction of the length of the conductor, is known in the art. Each conductor of litz wire tends to share current more equally than strands of stranded wire, thereby more effectively overcoming skin effect. Litz wire can, however, be expensive and awkward to use since contact must

be made to each strand at the ends of the conductor and the density of copper in the finished winding (the “packing factor”) can be low.

Foil Windings

[0010] Conductors of rectangular cross section have more surface area per unit volume than round conductors, for a given cross-sectional area. Inductors and other magnetic circuit elements like transformers have been wound from thin metal foil conductors; these are known as foil-wound circuit elements. Since the skin effect effectively confines current to the surface, these foil-wound circuit elements tend to require less volume of metal for a given AC current-handling capability.

[0011] Foil-wound magnetic circuit elements such as chokes, coils, transformers, and inductors are used in a wide variety of audio, switching power supply, and radio frequency devices. Such foil-wound magnetic circuit elements may have air, laminated-iron, powdered-metal, ferrite, or other core materials. Such foil-wound magnetic devices are particularly useful in magnetic elements of high-efficiency switching power supplies operating at frequencies from below 20 kHz to above 1 MHz, including those within personal computers.

[0012] Even though the AC resistance of foil windings can be less than that of round-wire, it is not zero – AC resistance of windings represents a significant source of power losses in high frequency, high power, magnetic devices.

[0013] When very AC high current capacity is desired in a foil winding, foil conductor thickness can be increased. Increases in thickness of foil conductor beyond twice the skin depth, however, will not significantly decrease AC resistance of the winding. In multi-layer windings, the optimum thickness can be even smaller than twice the skin depth. An alternative is to increase the width of foil conductor; however, wide foil conductors may require a larger magnetic core, increasing cost, weight, and size. Two or more layers of foil conductor connected in parallel do not always lead to proportional reduction in AC resistance because one layer tends to hog the current, and in some cases eddy currents circulate between the layers.

[0014] It is desirable to find a way to reduce losses and handle higher AC currents in foil windings.

SUMMARY OF THE INVENTION

[0015] It has been found that two or more layers of foil conductors in a foil-wound magnetic circuit component will share current more effectively, thereby decreasing AC resistance, if the foil conductors exchange layer positions one or more times through the winding.

[0016] A layered winding for a magnetic circuit element having at least two windings, made up of long, parallel conductors with their width being much greater than their thickness, one end of the conductors electrically coupled together and to one terminal, a second end of the conductors electrically coupled together and to a second terminal, the conductors otherwise being insulated from one another, and the conductors exchanging layer positions at least once within the winding.

[0017] A transformer having a core, a middle winding, a inner winding, and a outer winding, the three windings being coaxial upon the core, the middle winding being a multilayer foil winding with N number of turns, the inner and outer winding having an approximately equal number of turns, where the inner and outer windings are electrically coupled together and electrically isolated from the middle winding.

BRIEF DESCRIPTION OF THE FIGURES

[0018] FIG. 1 is a schematic cross section of a two-layer foil-wound inductor with two parallel foil conductors as known in the art.

[0019] FIG. 2 is a schematic cross section of a two-layer foil-wound inductor of the present invention.

[0020] FIG. 3 is a view of a top surface of a laminate having two layers of foil conductor on a flexible insulating substrate, the view taken at a swap point.

[0021] FIG. 4 is a cross-sectional view at B-B of the embodiment of FIG. 3

[0022] FIG. 5 is a view of two layers of foil conductor having notches for alternating layer positions.

[0023] FIG. 6 is a view of the layers of foil conductor of FIG. 5 assembled to swap layer positions.

[0024] FIG. 7 is a cross-sectional view of the assembled two-layer structure of FIG. 6 taken at C-C in FIG. 6.

[0025] FIG. 8 is a cross-sectional view of a transformer having a two-layer foil winding having alternations and a split winding.

[0026] FIG. 9 is a cross sectional view of a four-layer winding having alternations.

[0027] FIG. 10 is a cross sectional view of a four-layer winding having a different crossover pattern than that of FIG. 9.

[0028] FIG. 11 is a view of two layers of foil conductor with notches and trimmed for a torroidal winding.

[0029] FIG. 12 is a view of a torroidal foil-wound torroidal inductor having a single crossover.

[0030] FIG. 13 shows a perspective view of a six sided toroidal inductor.

[0031] FIG. 14 shows a perspective view of the two layer foil of FIG. 13.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0032] FIG. 1 illustrates a prior art, two-layer foil-wound inductor 100, having a first conductor 102 and a second conductor 104 wound about a core 106. The conductor 102 and 104 connect together at a first feed point 108 and a second feed point 110. Experiment shows that, because of uneven current sharing in the conductors, at high frequencies where skin effect is significant, the effective AC resistance is in some cases only slightly reduced from that of a single conductor and in other cases it is increased.

[0033] An embodiment of the present magnetic circuit element 200 is schematically illustrated in FIG. 2. In this embodiment, there are a first foil conductor, 202 and a second foil conductor 204 wound about a core 206. Core 206 may be an air core, a ferrite core, a laminated iron core, or another core as known in the art of magnetic materials. A significant difference between the present magnetic circuit element 200 and prior inductor 100 is that the first conductor 202 and second conductor 204 swap layer positions at one or more crossover points 208 within the winding. The conductor 202 and 204 connect together at a first feed point, first termination 212 and a second feed point, second termination 214. The conductors

202 and 204 are wound into a coaxial spiral. These parallel-connected, concentric, foil windings provide an AC resistance significantly reduced when compared to that of a single foil conductor. The first conductor 202 and second conductor 204 are prevented from electrically contacting each other except at the feed points 212, 214 by a dielectric material (not shown) or an insulating coating material as known in the art.

[0034] The number of points at which the conductors change layer positions is typically one fewer than the number of layers. For example, in FIG. 2, there are two layers, and one crossover point. With three layers, two crossover points are needed; with four layers, three crossover points. While a greater number of crossover points may be used in some embodiments, the narrowed foil conductor illustrated in FIG. 5, or the narrowed foil conductor and feedthroughs of FIGs. 3 and 4, at crossover points have AC and DC resistance associated with them. In order to minimize this extra resistance, it is preferred that the number of crossover points not greatly exceed one fewer than the number of layers.

[0035] It is preferred that the crossover points be positioned such that each foil conductor couples the same amount of magnetic flux linkage as each other foil conductor in the winding; such positioning will minimize eddy currents and optimize current sharing between the foil conductors. In a torroidal winding having a single layer of turns, where each turn has multiple foil conductors, but each turn is adjacent to rather than on top of the previous turns, this may be accomplished by having the same length of each foil conductor at each layer position in the winding – for two foil conductors in a torroidal coil the crossover should be at the center of the winding. In a coaxial spiral winding, coupling the same flux linkage to each foil conductor requires a configuration that may vary with core design, and often may require that there be fewer inner turns before alternations than outer turns.

[0036] In order to achieve total flux of zero in a four-layer winding in an interleaved transformer with a balanced MMF configuration, for example as shown in FIG. 8, interchanges were placed at distances of:

$$l_1 = \frac{N}{2(2N-1)} l_t \quad \text{and} \quad l_2 = 4l_t - l_1$$

from one of the ends, where l is the length of each turn and N is the number of turns in the winding. These equations hold true for four layers of winding and assume that the

length of each turn is equal. A calculated AC resistance for a four-layer foil winding is roughly half that of a single-layer winding when the thicknesses of the foil conductors have been chosen to minimize ac resistance. The ac resistance reduction may represent a significant power savings in many applications.

[0037] With transformers having two concentric windings the turns closest to the other winding in many cases will be exposed to the highest flux density, with turns further from the other winding being exposed to lower flux density.

[0038] In a transformer 500 having two concentric windings, as illustrated in FIG. 8, the magnitude of flux at opposite ends of a first multilayer foil winding 502 can be partially equalized by splitting the second winding into two sections 504, 506 having approximately equal turns, and one of these sections 504 is wound under the first winding 502 and the second section 506 is wound over the first winding. Sections 504, 506 of the split winding are electrically coupled together in series or parallel such that each section 504, 506 generates approximately equal flux.

[0039] In the illustration of FIG. 8, the split second winding sections 504, 506, are wound with round wire because the transformer 500 has a high turns ratio; in other embodiments, including many of those having turns ratios closer to one, the split second winding may be also be a foil winding. The transformer 500 of FIG. 8 may be wound on an E-core 508 or on a pot-core as known in the art. Where the flux is equal on both sides of a two-layer foil winding, for example, if the current is zero in the two-layer foil winding, layer position alternation may occur near the center of the winding as measured in turns; in cases where the configuration results in flux linkage differences between the sides of the winding, layer position alternation should occur at a point such that each layer of multilayer foil first winding 502 links equal flux.

[0040] In the case of transformer 500, as illustrated in FIG. 8, with a split second winding with one section inside and the other section outside of a first multilayer foil winding, the number of points at which the conductors change layer positions may in some cases be reduced to two fewer than the number of layers while still resulting in an equal flux linkage for each conductor.

[0041] FIGs. 3 and 4 illustrate a section of a flexible laminate suitable for winding a magnetic circuit element at a crossover point such as periodic crossover point 208 of FIG. 2. In this embodiment, a thin, flexible, dielectric material 302 is

laminated with a top foil conductor 304 and a bottom foil conductor 306. In a crossover zone 310, a gap is etched or otherwise cut in each foil conductor 304, 306 to separate each foil conductor 304, 306 into two conductors 320, 322 having interdigitated fingers, and multiple plated-through vias 312 are used to connect the first conductor of the first layer position to the first conductor of the second layer position, and similarly multiple plated-through vias 312 are used to connect the second conductor of the first layer position to the second conductor of the second layer position. The effect of this zone is to swap a foil conductor from top to bottom layer position. The top and/or bottom foil conductors 304, 306 are then coated with a dielectric and the laminate is wound into a winding of the magnetic circuit element 200.

[0042] In an alternative embodiment, as illustrated in FIG. 5, a first foil conductor 402 is notched with one or more notches 404 along a first edge 406 of the foil conductor 402, each notch cutting through approximately half of the width of the foil conductor. A second foil conductor 408 is also notched with notches 410 of similar dimensions along an edge 412 of second foil conductor 408, such that each notch 412 of the second foil conductor 408 aligns with a notch 404 of the first foil conductor 402. The foil conductors 402 and 408 having been previously coated with a dielectric (not shown). Foil conductors 402 and 408 are then brought together, with appropriate deflection of one or both foil conductors, such that they overlap with tab portion 420 of the first foil conductor 402 are above, and tab portions 422 and 424 of the first foil 402 are below corresponding areas of second foil 408, in the manner illustrated in FIG. 6. As can be seen in FIG. 7, once assembled into the two-layer structure illustrated in FIG. 6, first foil conductor 402 has a wide side parallel and adjacent (save for dielectric, not shown) to a wide side of second foil conductor 408 at all points except at the crossover. The foil conductors also have narrow edges that are adjacent only at the aligned notches of a crossover. Further, at each point along the assembled two-layer structure, a centerline of the foil conductor in a first layer position is parallel to a centerline of the foil conductor in a second layer position.

[0043] Although FIG. 5 shows two notches in each foil conductor to create two interchange locations, a two-layer winding ordinarily only needs one interchange location. However, two are shown in FIG. 5 to help illustrate how the concept can be

extended to more interchanges as needed with more layers. Using more than one interchange for two layers, as shown in FIG. 5 may be useful in some cases, for example at very high frequency where capacitive coupling between the foil conductors can provide a path for circulation currents, or when necessary to keep the distance between interchanges from approaching a significant fraction of an electromagnetic wavelength in the dielectric medium separating the conductors.

[0044] Where more than two foil conductors are used, a given foil conductor will often need notches in both sides in order to mesh with other conductors to provide a particular configuration of interchanges.

[0045] While square notches may be used, sharp corners may make the foil conductors harder to handle. Further, currents at a narrowed notch 410 point in a foil conductor, such as foil conductor 408, will not expand instantaneously into a wider zone of foil conductor, but spread over a finite distance into the wider zone. For these reasons, and a slight saving in material, each notch in an embodiment is cut at an angle A (FIG. 6) of approximately twenty to thirty degrees from the perpendicular; such a notch is referred to herein as a tapered notch.

[0046] Once stacked with desired alternations, the foil conductors of the embodiment of FIG. 5 and 6 are wound into the coils of the magnetic circuit elements. This construction is applicable to inductors as well as to transformers.

[0047] Where more than two layers of foil conductor are desired, the construction of FIG. 3 and FIG. 4 may be expanded to use three, four, or more, layers. Any two foil conductors may be swapped at a point between alternations of the other two, non-alternating, conductors by using through-drilled vias and etching or otherwise making small openings around the vias on the non-alternating conductors; as known in the art of flexible printed circuits.

[0048] FIG. 9 illustrates a cross section of a first, second, third, and fourth foil conductor 602, 604, 606, 608 with similar notched construction, but some foil conductors must be notched on one edge at one crossover, and at a second edge at another crossover. This embodiment is preferably assembled as a first pair of conductors 602, 604, and a second pair of conductor 606, 608, with alternations 620, 624. These pairs are then assembled into a four layer structure with crossover 622. This embodiment succeeds in having each foil conductor in every layer position of the

winding for at least part of the winding, as is often needed to achieve equal flux linkage for each layer. The embodiment of FIG. 10, with first, second, third and fourth foil conductors 612, 614, 616, 618, also has each foil conductor in every layer position of the winding for at least part of the winding, with rotational alternations 628.

[0049] The embodiments in FIGs. 9 and 10 may be extended to larger numbers of layers. The rotational alternations in FIG. 10 is a possible embodiment for any number of layers. The number of rotation locations is preferred to be the number of layers per turn minus one. The position swapping configuration shown in FIG. 9 is a preferred embodiment for numbers of layers equal to a power of two. For a number of layers $n = 2^J$, a first interchange I_1 622 divides the winding into two segments. In the case of equal flux density along the length of the winding, I_1 622 is located in the center of the winding; locations for interchanges for other cases are discussed below. At I_1 , 622 the top $n/2$ conductors are moved to become the bottom $n/2$ conductors. Each of a set of two interchange locations I_2 620, 624 then divides each of the remaining segments into two. At locations I_2 620, 624 the top $n/4$ conductors exchange layer positions with the next down $n/4$ conductors.

Independently, but at the same location, the bottom $n/4$ conductors exchange layer positions with the next up $n/4$ conductors. This pattern continues: for index $k = 1$ to J , there are 2^{k-1} I_k locations, each I_k location divides the segments defined by the I_{k-1} interchange into two new segments. A portion of a first and second foil conductor 702, 704 are illustrated in FIG. 11. These conductors are notched 706, 708 so they may be assembled into a two-layer structure in the manner of FIG. 6, where the conductors exchange layer position at the notches. Foil conductors 702, 704 are shaped having narrow portions 710 and wide portions 712, separated by tapered portions 714. The crossover point at the notches is preferably in a wide portion to avoid current crowding. The ends of foil conductors 702, 704, are insulated from each other except at the ends, are connected together and to tabs 806 (see FIG. 12), and wound as helical winding around a torroidal core to form an approximately torroidal winding as illustrated in FIG. 12. The torroidal core of FIG. 12 is an eight sided polygonal core with rectangular cross-section. The number of turns in the winding of the inductor equals the number of sides to the polygon. For example,

inductor 800 has eight turns in the winding, giving inductor 800 eight sides. The greater the number of turns in the winding, the closer the inductor approximates a circular shape, reducing loss due to the polygonal shape. The wide portions become outer surfaces 802 of the winding, the tapered portions become top 804 and bottom (not shown) surfaces, and narrow portions become central surfaces. Tabs 806 are flattened onto the plane of the bottom surface and become terminals for attaching the inductor to a circuit board. The crossover 810 is at approximately the midpoint of the winding.

[0050] FIG. 13 shows a perspective view of a six sided toroidal inductor 900 which includes an outer surface 914. Outer layer 902 of foil conductor 904 and outer layer 906 of foil conductor 908 are shown. Foil conductor 904 and foil conductor 908 exchange layer positions at crossover location 910. FIG. 14 shows a perspective view of outer surface 914 of FIG. 13, labeled outer surface 1000. Outer surface 1000 is elongated to enhance clarity. Outer surface 1000 is assembled into a two-layer structure in the manner of FIG. 6. Outer surface 1000 illustrates foil conductors 904 and 908 exchanging layer positions at crossover location 910. Outer layer 902 becomes inner layer 904, and inner layer 1004 becomes outer layer 1002. Crossover location 910 is at approximately the midpoint of the winding.

[0051] In an alternative embodiment, the polygonal toroidal core has a circular cross-section. Having a circular cross section results in foil conductors which do not need any folding at the edges of the core and have substantially continuous, smooth boundaries when unwound.

[0052] It has been found that in a multilayer foil winding as herein described having conductors that alternate at various points in a coaxial spiral, the winding shares current more effectively between conductors than when multiple non-alternating conductors are used. AC resistance of the multilayer winding is therefore decreased relative to a multilayer foil winding that does not alternate layer positions. Because of the skin effect and the proximity effect, AC resistance of the multilayer winding may also be reduced relative to a single layer of thicker foil conductor if the conductor thicknesses are chosen to minimize loss as described in M.E. Dale and C.R. Sullivan "Comparison of Loss in Single-Layer and Multi-Layer Windings with a DC Component." IEEE Industry Applications Society Annual Meeting, Oct. 2006 and in

M.E. Dale and C.R. Sullivan. "Comparison of Single-Layer and Multi-Layer Windings with Physical Constraints or Strong Harmonics." IEEE International Symposium on Industrial Electronics, July 2006.

[0053] While the forgoing has been particularly shown and described with reference to particular embodiments thereof, it will be understood by those skilled in the art that various other changes in the form and details may be made without departing from the spirit and hereof. It is to be understood that various changes may be made in adapting the description to different embodiments without departing from the broader concepts disclosed herein and comprehended by the claims that follow.

CLAIMS

What is claimed is:

1. A winding for a magnetic circuit element (200) comprising:
a first foil conductor (202, 402, 702),
a second foil conductor (204, 408, 704),
wherein a first end of the first foil conductor and the second foil conductor are attached to a first termination (212), and a second end of the first foil conductor and the second foil conductor are attached to a second termination (214), the first foil conductor and the second foil conductor being otherwise insulated from each other;
the first and second foil conductor disposed parallel to each other and such that a wide side of the first foil conductor is parallel to a wide side of the second foil conductor for at least a portion of the first and second conductors;
wherein the first foil conductor and the second foil conductor are wound into the winding; and
wherein the first foil conductor and the second foil conductor exchange positions at least once within the winding.
2. The winding for a magnetic circuit element of claim 1 wherein the first foil conductor and the second foil conductor are notched (404, 410, 706, 708) through approximately half a width of the foil conductors, the alternation of first and second foil conductors being accomplished by aligning notches, deflecting a foil conductor, and sliding the foil conductors together.
3. The winding for a magnetic circuit element of claim 2 wherein the notches in the first foil conductor are tapered notches.
4. The winding for a magnetic circuit element of claim 2 wherein the winding is a coaxial spiral winding.

5. The winding for a magnetic circuit element of claim 4 wherein the alternation (208, 620, 624) of the first and second foil conductors is positioned in the winding such that a total flux linkage of the first foil conductor is approximately equal to a total flux linkage of the second foil conductor.

6. The winding for a magnetic circuit element of claim 1 further comprising:

a third and a fourth foil conductor (606, 608), the third and fourth foil conductor being electrically insulated from each other and from the first and second foil conductor (602, 604) except at the first and second termination;

wherein the third and fourth foil conductors are electrically coupled to the first and second termination;

wherein the third and fourth foil conductor disposed parallel to each other and such that a wide side of the third foil conductor is parallel to a wide side of the fourth foil conductor for at least a portion of a length of the third and fourth conductors;

wherein the third and fourth foil conductors are wound coaxially with the first and second foil conductor; and

wherein the third and fourth foil conductor alternate layer positions at least once within the coaxial spiral winding.

7. The winding for a magnetic circuit element of claim 6 wherein alternation (620, 624) of the third and fourth foil conductors is positioned in the winding such that a total flux linkage of the third foil conductor is approximately equal to a total flux linkage of the fourth foil conductor.

8. The winding for a magnetic circuit element of claim 7 wherein the first and second foil conductor alternate as pairs (622) with the third and fourth foil conductor at least one point in the winding.

9. The winding for a magnetic circuit element of claim 7 wherein at least the first foil and the second foil conductor are notched through approximately half a width of the foil, the alternation of first and second foil conductor is accomplished by

aligning notches, deflecting a foil conductor between notches, and sliding the foil conductors together.

10. The winding for a magnetic circuit element of claim 1 wherein the first foil conductor and the second foil conductor comprise conductive foil laminated on opposing sides of a flexible dielectric material (302), wherein the first and second foil conductors are alternated by conductive vias through the flexible dielectric material at a point where the conductive foils forming the first and the second foil conductor are interdigitated.

11. The winding for a magnetic circuit element of claim 1 wherein at least part of the first foil conductor and the second foil conductor are wound into a helical winding about at least part of a torroidal core.

12. The winding for a magnetic circuit element of claim 11 wherein the first foil conductor and the second foil conductor are notched through approximately half a width of the foil conductor, the alternation of first and second foil conductors is accomplished by aligning notches, deflecting a foil conductor between notches, and sliding the foil conductors together.

13. The winding for a magnetic circuit element of claim 11 wherein the notches in at least the first foil conductor are tapered notches.

14. The winding for a magnetic circuit element of claim 11 wherein alternation of the first and second foil conductors is positioned in the winding such that a total flux linkage of the first foil conductor is approximately equal to a total flux linkage of the second foil conductor.

15. The winding for a magnetic circuit element of claim 14 further comprising a third and a fourth foil conductor, the third and fourth foil conductor being electrically insulated from each other, wherein the third and fourth foil conductors are attached to the first and second termination and wound in the winding with a wide side of the first foil conductor is adjacent and parallel to a wide side of the third foil conductor for at least part of the winding, and wherein a wide side of the third foil conductor is adjacent and parallel to a wide side of the fourth foil conductor

for at least part of the winding, and wherein the third and fourth foil conductor alternate layer positions within the winding at least once in the winding.

16. A transformer (500) comprising a core (508), a first winding (502), a second winding (504), and a third winding (506), the first winding being a multilayer foil winding with N number of turns, the second and third winding having an approximately equal number of turns, the first, second, and third windings being coaxial upon the core, the first winding being disposed between the second and third windings with the second winding within the first winding and the third winding outside the first winding, where the second and third windings are electrically coupled together.

17. The transformer of claim 16 wherein the first winding comprises a first conductor and a second conductor, and the first conductor and second conductor exchange layer positions at least once in the first winding.

18. The winding of claim 1 further comprising at least a third foil conductor, and wherein:

at a first point in the winding the first conductor is on a first layer position, the second conductor is on a second layer position, and the third conductor is on a third layer position;

wherein at a second point in the winding the first conductor is on the second layer position, the second conductor is on the third layer position, and the third conductor is on the first layer position; and

wherein at a third point in the winding the first conductor is on the third layer position, the second conductor is on the first layer position, and the third conductor is on the second layer position.

19. A winding for a magnetic circuit element comprising:

N foil conductors, N being an integer at least three, where each foil conductor has a first wide side, a second wide side, a first narrow edge, and a second narrow edge;

wherein a first end of each foil conductor is attached to a first termination, and a second end of each foil conductor is attached to a second termination, the foil conductors being otherwise insulated from each other;

wherein each foil conductor is disposed parallel to the other foil conductors such that wide sides of the foil conductors are parallel for at least a portion of the winding, each foil conductor situated at a layer position within the winding;

wherein the foil conductors are wound into the winding; and

wherein at least two of the foil conductors change layer positions at least at N-2 points within the winding.

20. The winding of claim 19 wherein at least two of the foil conductors change layer positions at least at N-1 points within the winding.

21. The winding for a magnetic circuit element of claim 19 wherein a first and a second foil conductor of the foil conductors are notched through approximately half a width of the foil conductor, a changing of layer positions of the first and second foil conductors being accomplished by aligning notches and sliding the foil conductors together.

22. The winding for a magnetic circuit element of claim 21 wherein the winding is a coaxial spiral winding.

23. The winding for a magnetic circuit element of claim 21 wherein the winding is a helical winding wound about a torroidal core.

24. The winding for a magnetic circuit element of claim 23 wherein the foil conductors are shaped with wide portions (712, 802) and narrow portions (710) such that at least part of the wide portions are outside of the torroidal core and at least part of the narrow portions are inside the torroidal core, and the notches (706, 708) in the first and second foil conductor are in a wide portion.

25. The winding of claim 19 wherein an order of the at least three foil conductors at a first location in the winding comprises a first conductor, a second conductor, and a third conductor; wherein an order of the foil conductors at a second

location in the winding comprises second conductor, third conductor, first conductor, and an order of the foil conductors at a third location in the winding comprises third conductor, first conductor, second conductor.

26. The winding of claim 19 wherein an order of the foil conductors at a first location in the winding comprises a first conductor, a second conductor, and a third conductor; wherein an order of the foil conductors at a second location in the winding comprises second conductor, first conductor, third conductor, and an order of the foil conductors at a third location in the winding comprises third conductor, second conductor, first conductor.

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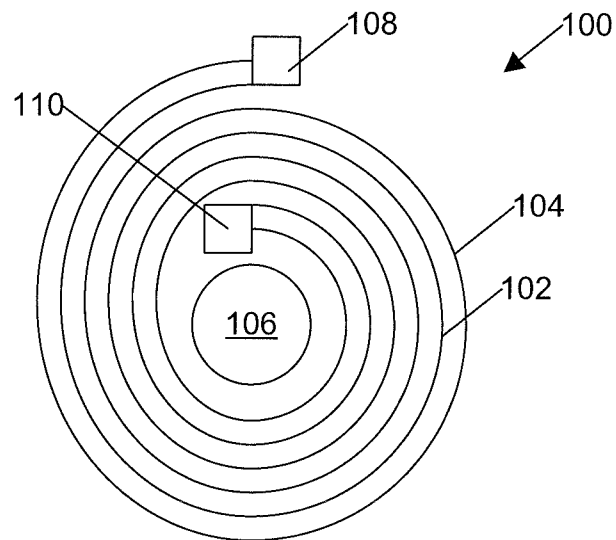


FIG. 1

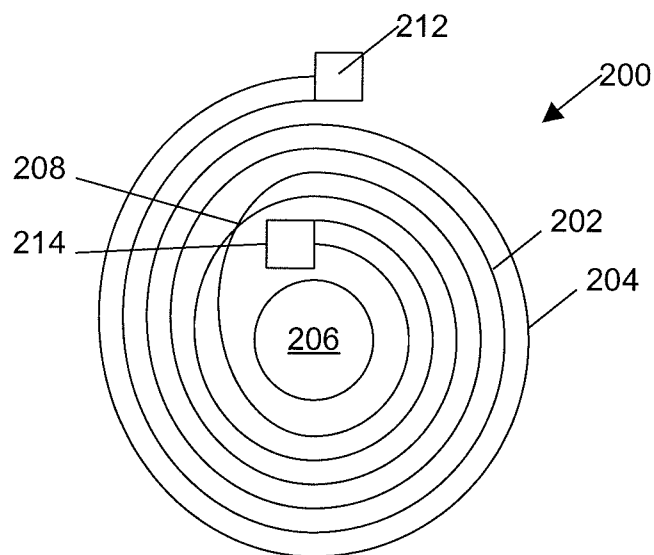
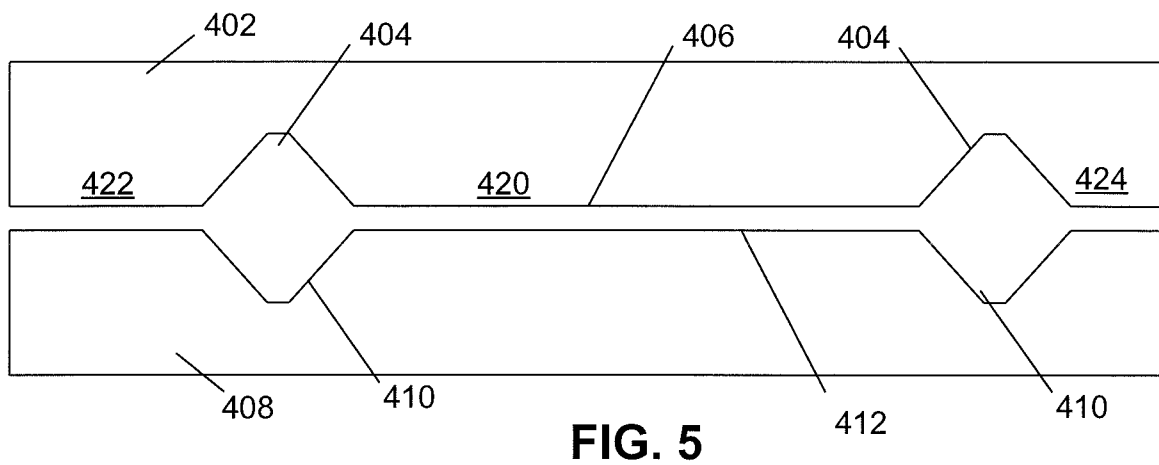
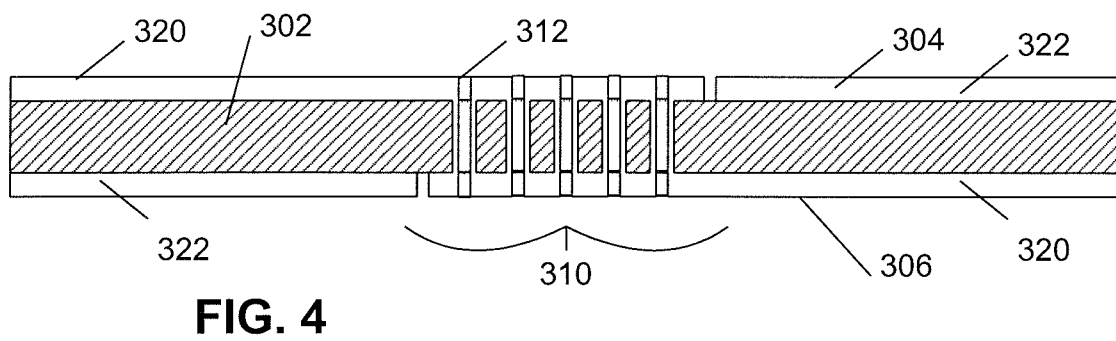
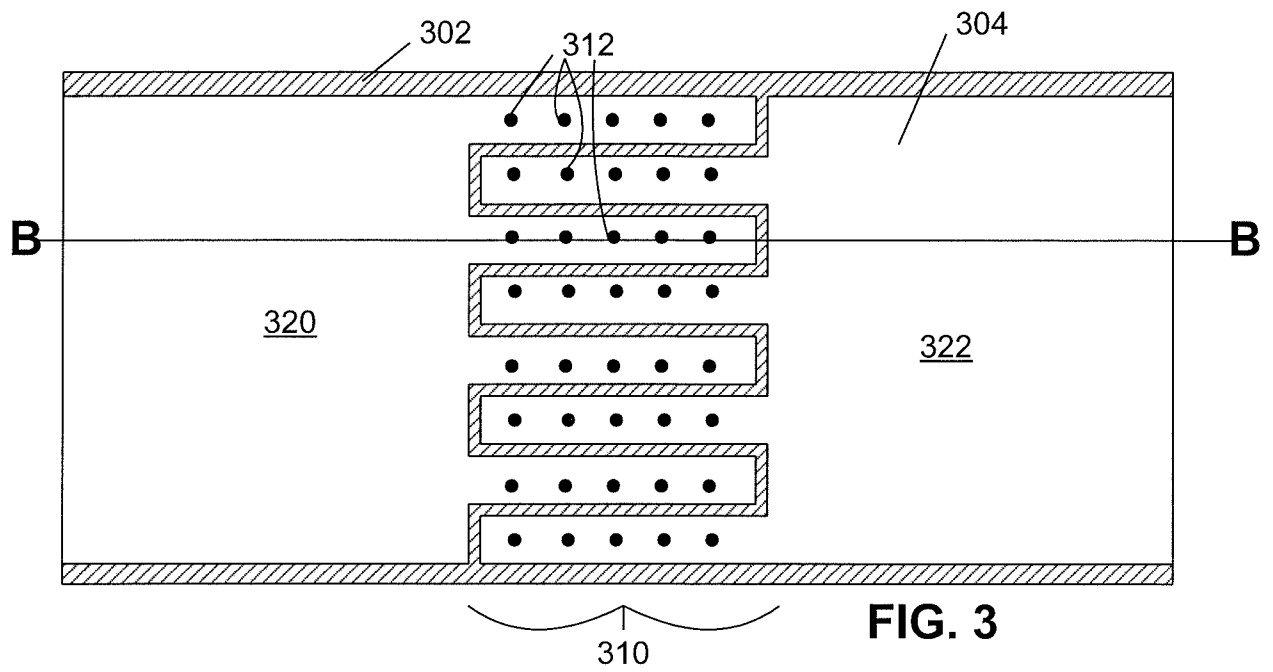


FIG. 2

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FIG. 6

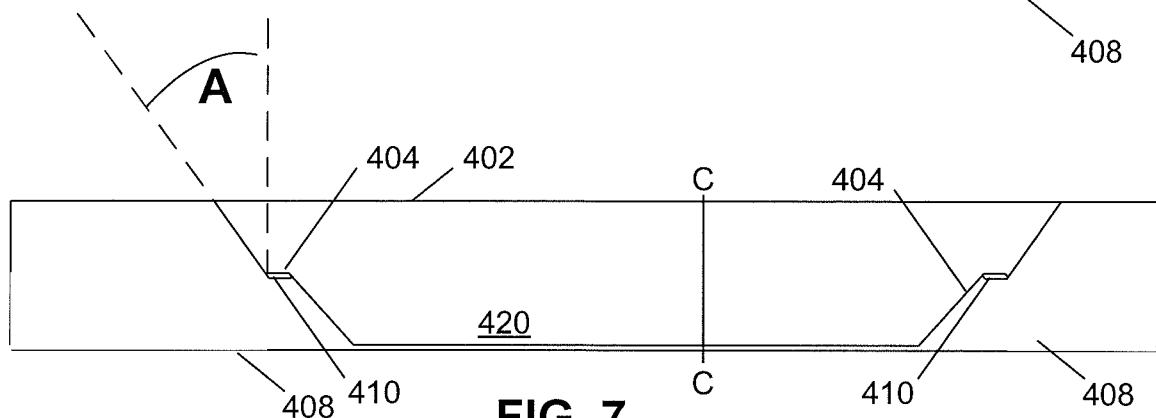
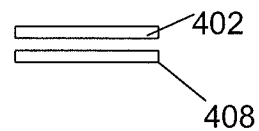


FIG. 7

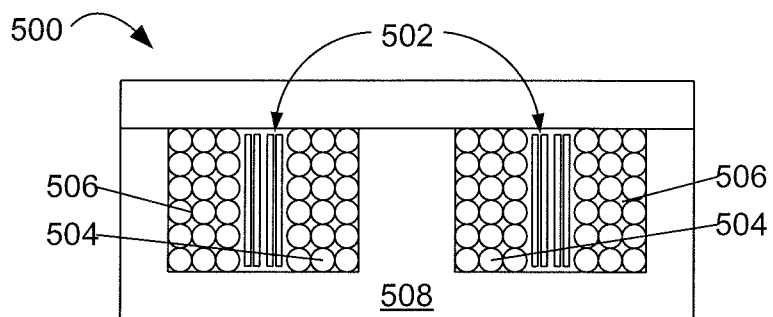


FIG. 8

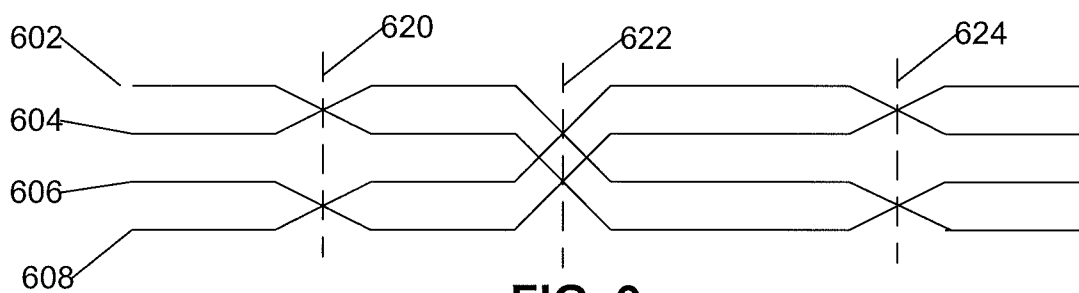


FIG. 9

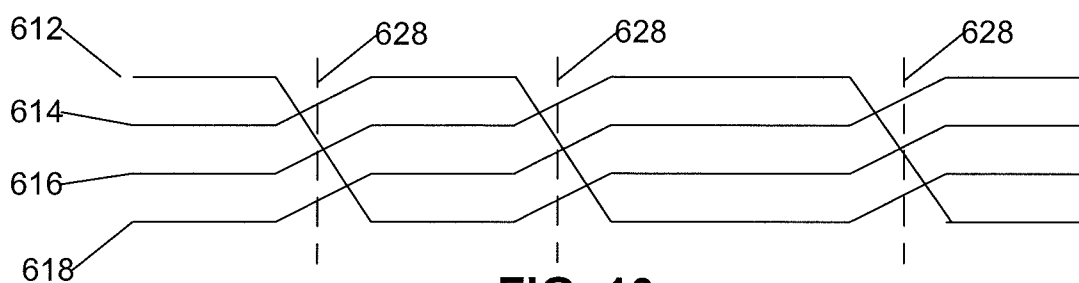


FIG. 10

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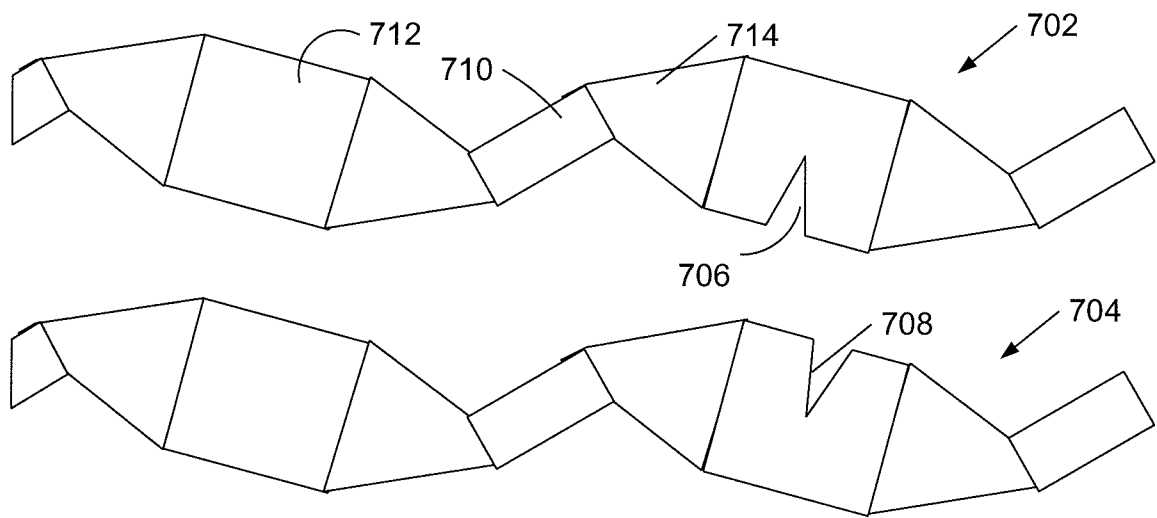


FIG. 11

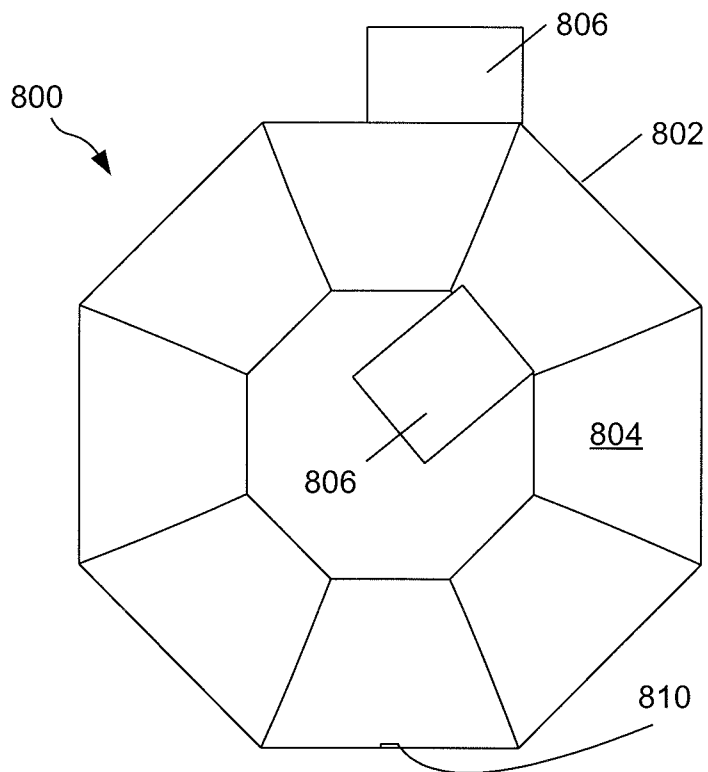


FIG. 12

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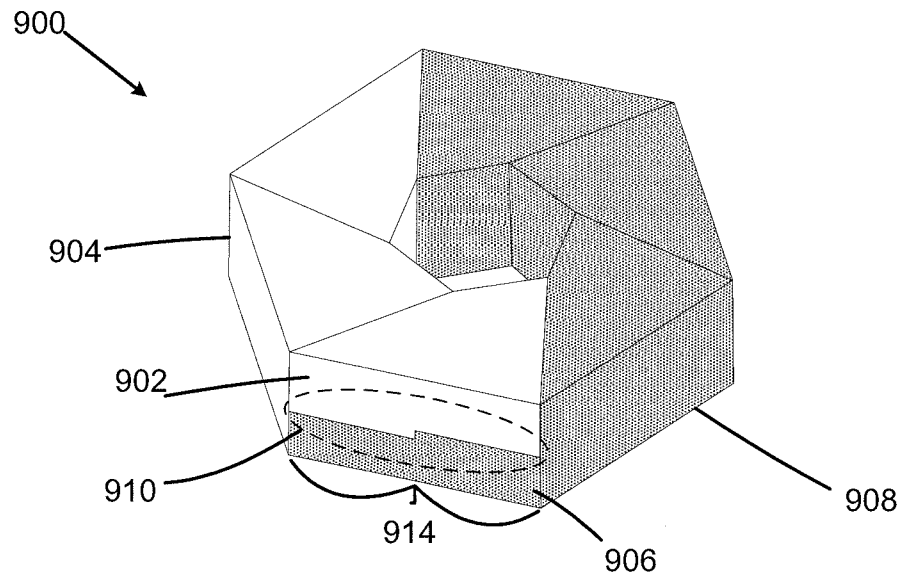


FIG. 13

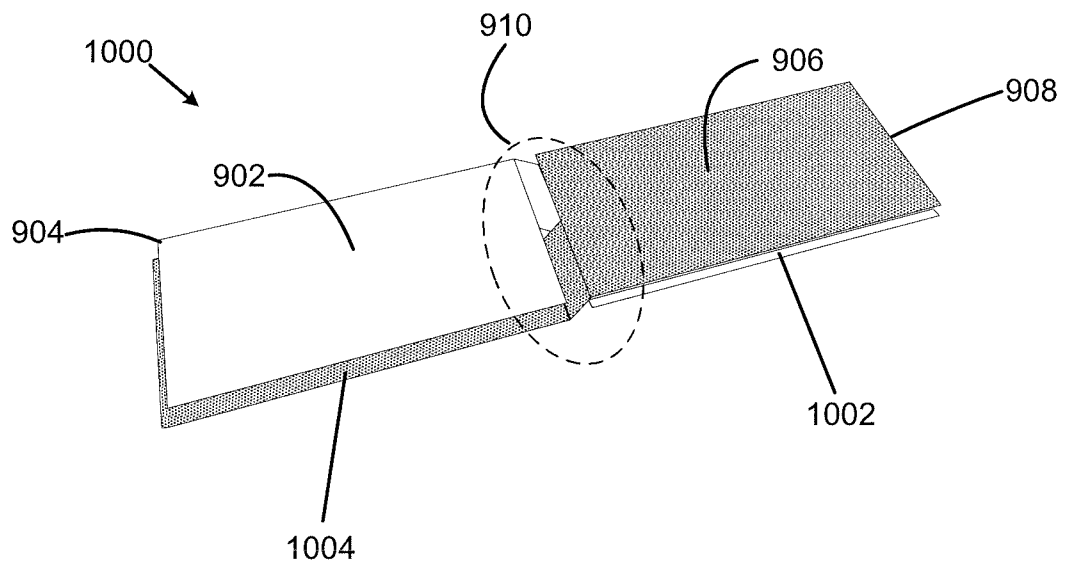


FIG. 14

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2009/034729

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01F27/28 H01F27/30

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)
H01F H02K

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 practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 3 633 272 A (BENKE FRANK W ET AL) 11 January 1972 (1972-01-11) the whole document	1-9, 16-22, 25, 26
X	DE 102 03 246 A1 (BOMBARDIER TRANSP GMBH [DE]) 21 August 2003 (2003-08-21) abstract paragraphs [0002], [0027], [0062], [0063] claims 18-20 figure 12	1-4, 16, 17
X	GB 129 788 A (JAN ARTHUR KUYSER; BRITISH WESTINGHOUSE ELECTRIC) 15 July 1919 (1919-07-15) pages 3,4 figures 6-8	1-3, 6, 19, 20, 25
-/--		

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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Date of the actual completion of the international search

7 May 2009

Date of mailing of the international search report

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NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
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INTERNATIONAL SEARCH REPORT

International application No

PCT/US2009/034729

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4 395 693 A (MARINESCU MARLENE [DE]) 26 July 1983 (1983-07-26) abstract column 2, line 57 - column 4, line 12; figure 1 figures 1-5 figures 1-5 -----	1-26

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Information on patent family members

International application No

PCT/US2009/034729

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		WO 03065388 A1	07-08-2003
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