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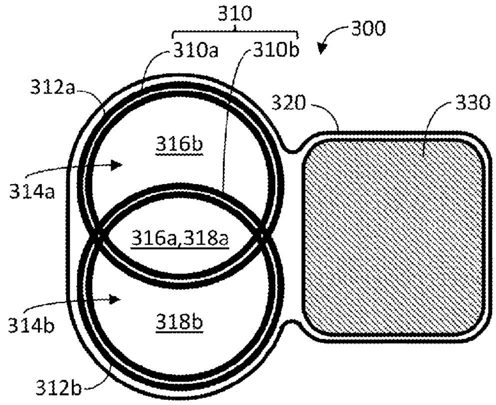
— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

(54) Title: MULTI-COIL ARRAY FOR MEDICAL IMPLANT

FIG. 2A:



(57) Abstract: An apparatus includes at least a first MI antenna and a second MI antenna. The first MI antenna includes an electrically conductive and substantially planar first coil extending around and substantially orthogonal to a first antenna axis. The second MI antenna includes an electrically conductive and substantially planar second coil extending around and substantially orthogonal to a second antenna axis. The second antenna axis is substantially parallel to the first antenna axis. The second coil in series electrical connection with the first coil. The first and second MI antennas have a mutual coupling coefficient that is substantially

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MULTI-COIL ARRAY FOR MEDICAL IMPLANT

BACKGROUND

Field

[0001] The present application relates generally to systems and methods for wirelessly communicating data to and/or from a device implanted on or within a recipient's body.

Description of the Related Art

[0002] Medical devices have provided a wide range of therapeutic benefits to recipients over recent decades. Medical devices can include internal or implantable components/devices, external or wearable components/devices, or combinations thereof (e.g., a device having an external component communicating with an implantable component). Medical devices, such as traditional hearing aids, partially or fully-implantable hearing prostheses (e.g., bone conduction devices, mechanical stimulators, cochlear implants, etc.), pacemakers, defibrillators, functional electrical stimulation devices, and other medical devices, have been successful in performing lifesaving and/or lifestyle enhancement functions and/or recipient monitoring for a number of years.

[0003] The types of medical devices and the ranges of functions performed thereby have increased over the years. For example, many medical devices, sometimes referred to as "implantable medical devices," now often include one or more instruments, apparatus, sensors, processors, controllers or other functional mechanical or electrical components that are permanently or temporarily implanted in a recipient. These functional devices are typically used to diagnose, prevent, monitor, treat, or manage a disease/injury or symptom thereof, or to investigate, replace or modify the anatomy or a physiological process. Many of these functional devices utilize power and/or data received from external devices that are part of, or operate in conjunction with, implantable components.

SUMMARY

[0004] In one aspect disclosed herein, an apparatus comprises an array of magnetic induction (MI) antennas. The array comprises at least a first MI antenna and a second MI antenna. The first MI antenna comprises an electrically conductive and substantially planar first coil extending around and substantially orthogonal to a first antenna axis. The second MI antenna comprises an electrically conductive and substantially planar second coil extending around and substantially orthogonal to a second antenna axis. The second antenna axis is substantially parallel to the first antenna axis. The second coil in series electrical connection with the first coil. The first and second MI antennas have a mutual coupling coefficient that is substantially equal to zero.

[0005] In another aspect disclosed herein, a method comprises bending a first portion of a wire to form a substantially planar first coil comprising a first number of coil turns. The method further comprises bending a second portion of the wire to form a substantially planar second coil comprising a second number of coil turns. The second coil is in series electrical connection with the first coil. The first coil is between an elongate first section of the wire and an elongate second section of the wire. The second coil is between the second section of the wire and an elongate third section of the wire. The method further comprises positioning an elongate first portion of the first section relative to the second section such that the first portion and the second section have substantially zero magnetic inductive coupling to the first and second coils. The method further comprises positioning an elongate second portion of the first section relative to the third section such that the second portion and the third section have substantially zero magnetic inductive coupling to the first and second coils.

[0006] In another aspect disclosed herein, an apparatus comprises a plurality of electrically conductive and substantially planar first coil loops that are substantially parallel to one another and in series electrical communication with one another. The apparatus further comprises a plurality of electrically conductive and substantially planar second coil loops that are substantially parallel to one another and in series electrical communication with one another. The plurality of second coil loops are substantially parallel and in series electrical communication with the plurality of first coil loops. The plurality of second coil loops have substantially zero magnetic inductive coupling with the plurality of first coil loops.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Implementations are described herein in conjunction with the accompanying drawings, in which:

[0008] FIG. 1A is a perspective view of an example cochlear implant auditory prosthesis implanted in a recipient in accordance with certain implementations described herein;

[0009] FIG. 1B is a perspective view of an example fully implantable middle ear implant auditory prosthesis implanted in a recipient in accordance with certain implementations described herein;

[0010] FIG. 2A schematically illustrates a top view of an example apparatus in accordance with certain implementations described herein;

[0011] FIG. 2B schematically illustrates a cross-sectional view of the example apparatus in accordance with certain implementations described herein and a device external to the recipient's body;

[0012] FIG. 2C schematically illustrates another example array of MI antennas in accordance with certain implementations described herein;

[0013] FIG. 2D schematically illustrates another example array of MI antennas in accordance with certain implementations described herein;

[0014] FIGs. 3A-3C schematically illustrate example arrays of MI antennas with more than two coils in accordance with certain implementations described herein;

[0015] FIG. 4 is a schematic plot of the mutual coupling coefficient k as a function of the normalized displacement d/R for example first and second coils in accordance with certain implementations described herein;

[0016] FIG. 5A is a plot of an example coupling between a single coil of the array of MI antennas and at least one external coil as a function of lateral displacement between the single coil and the at least one external coil in accordance with certain implementations described herein.

[0017] FIG. 5B is a plot of an example coupling between a series of three coils of the array of MI antennas and at least one external coil as a function of lateral displacement between the center coil and the at least one external coil in accordance with certain implementations described herein;

[0018] FIGs. 6A-6E are example contour plots of the aggregate coupling between the multiple substantially circular coils and a substantially circular external coil as a function of the lateral displacement of the external coil in accordance with certain implementations described herein;

[0019] FIG. 7 is a flow diagram of an example method in accordance with certain implementations described herein;

[0020] FIGs. 8A-8E schematically illustrate various stages of the fabrication method for a wound-wire array of MI antennas in accordance with certain implementations described herein;

[0021] FIGs. 9A-9C schematically illustrate various stages of fabrication of an array of MI antennas comprising five coils in two groups in accordance with certain implementations described herein;

[0022] FIG. 10 schematically illustrates another intermediate stage of the fabrication of an array of MI antennas in accordance with certain implementations described herein;

[0023] FIGs. 11A and 11B schematically illustrate two example arrays of MI antennas with substantially circular coils and substantially reniform coils, respectively, in accordance with certain implementations described herein; and

[0024] FIGs. 12A and 12B schematically illustrate two example devices with multiple external coils in accordance with certain implementations described herein.

DETAILED DESCRIPTION

[0025] Certain implementations described herein provide an implantable portion of a medical system (e.g., a sensory prosthesis system) comprising an array of magnetic induction antenna coils configured to form a wireless and transcutaneous communication link with an external portion of the medical system. The array comprises substantially planar coil loops that are parallel to one another, in series electrical communication with one another, and have substantially zero mutual inductance with one another. The array can extend over a larger area than does a single coil while providing sufficient coupling strength and stability to the external portion despite large misalignments and/or movements of the external portion relative to an optimal position (e.g., misalignments/movements that can be expected for a magnet-free configuration). For example, the array can provide a significantly improved range of power transfer efficiencies for a magnet-free link (e.g., 20% to 30% over a wide range of misalignments/movements) as compared to that of a single coil.

[0026] The teachings detailed herein are applicable, in at least some implementations, to any type of implantable or non-implantable stimulation system or device (e.g., implantable or non-implantable auditory prosthesis device or system). Implementations can include any type of medical device that can utilize the teachings detailed herein and/or variations thereof. Furthermore, while certain implementations are described herein in the context of auditory prosthesis devices, certain other implementations are compatible in the context of other types of devices or systems.

[0027] Merely for ease of description, apparatus and methods disclosed herein are primarily described with reference to an illustrative medical device, namely an implantable transducer assembly including but not limited to: electro-acoustic electrical/acoustic systems, cochlear implant devices, implantable hearing aid devices, middle ear implant devices, bone conduction devices (e.g., active bone conduction devices; passive bone conduction devices, percutaneous bone conduction devices; transcutaneous bone conduction devices), Direct Acoustic Cochlear Implant (DACI), middle ear transducer (MET), electro-acoustic implant devices, other types of auditory prosthesis devices, and/or combinations or variations thereof, or any other suitable hearing prosthesis system with or without one or more external components. Implementations can include any type of auditory prosthesis that can utilize the teachings detailed herein and/or variations thereof. Certain such implementations can be referred to as “partially implantable,” “semi-implantable,” “mostly implantable,” “fully implantable,” or “totally implantable” auditory prostheses. In some implementations, the teachings detailed herein and/or variations thereof can be utilized in other types of prostheses beyond auditory prostheses.

[0028] While certain implementations are described herein in the context of auditory prosthesis devices, certain other implementations are compatible in the context of other types of sensory prosthesis systems that are configured to evoke other types of neural or sensory (e.g., sight, tactile, smell, taste) percepts are compatible with certain implementations described herein, including but are not limited to: vestibular devices (e.g., vestibular implants), visual devices (e.g., bionic eyes), visual prostheses (e.g., retinal implants), somatosensory implants, and chemosensory implants. Certain other implementations are compatible with other types of medical devices that can utilize the teachings detailed herein and/or variations thereof to provide a wide range of therapeutic benefits to recipients, patients, or other users (e.g., epilepsy monitoring systems; pain control systems; bladder control systems; neurostimulators; pacemakers; other medical implants comprising an implanted power source).

[0029] FIG. 1A is a perspective view of an example cochlear implant auditory prosthesis 100 implanted in a recipient in accordance with certain implementations described herein. The example auditory prosthesis 100 is shown in FIG. 1A as comprising an implanted stimulator unit 120 and a microphone assembly 124 that is external to the recipient (e.g., a partially implantable cochlear implant). An example auditory prosthesis 100 (e.g., a totally implantable cochlear implant; a mostly implantable cochlear implant) in accordance with certain implementations described herein can replace the external microphone assembly 124 shown in FIG. 1A with a subcutaneously implantable microphone assembly, as described more fully herein.

[0030] As shown in FIG. 1A, the recipient has an outer ear 101, a middle ear 105, and an inner ear 107. In a fully functional ear, the outer ear 101 comprises an auricle 110 and an ear canal 102. An acoustic pressure or sound wave 103 is collected by the auricle 110 and is channeled into and through the ear canal 102. Disposed across the distal end of the ear canal 102 is a tympanic membrane 104 which vibrates in response to the sound wave 103. This vibration is coupled to oval window or fenestra ovalis 112 through three bones of middle ear 105, collectively referred to as the ossicles 106 and comprising the malleus 108, the incus 109, and the stapes 111. The bones 108, 109, and 111 of the middle ear 105 serve to filter and amplify the sound wave 103, causing the oval window 112 to articulate, or vibrate in response to vibration of the tympanic membrane 104. This vibration sets up waves of fluid motion of the perilymph within cochlea 140. Such fluid motion, in turn, activates tiny hair cells (not shown) inside the cochlea 140. Activation of the hair cells causes appropriate nerve impulses to be generated and transferred through the spiral ganglion cells (not shown) and auditory nerve 114 to the brain (also not shown) where they are perceived as sound.

[0031] As shown in FIG. 1A, the example auditory prosthesis 100 comprises one or more components which are temporarily or permanently implanted in the recipient. The example auditory prosthesis 100 is shown in FIG. 1A with an external component 142 which is directly or indirectly attached to the recipient's body, and an internal component 144 which is temporarily or permanently implanted in the recipient (e.g., positioned in a recess of the temporal bone adjacent auricle 110 of the recipient). The external component 142 typically comprises one or more sound input elements (e.g., an external microphone 124) for detecting sound, a sound processing unit 126 (e.g., disposed in a Behind-The-Ear unit), a power source (not shown), and an external transmitter unit 128. In the illustrative implementations of FIG. 1A, the external transmitter unit 128 comprises an external coil 130 (e.g., a wire antenna coil comprising multiple turns of electrically insulated single-strand or multi-strand platinum or gold wire) and, preferably, a magnet (not shown) secured directly or indirectly to the external coil 130. The external coil 130 of the external transmitter unit 128 is part of an inductive radio frequency (RF) communication link with the internal component 144. The sound processing unit 126 processes the output of the microphone 124 that is positioned externally to the recipient's body, in the depicted implementation, by the recipient's auricle 110. The sound processing unit 126 processes the output of the microphone 124 and generates encoded signals, sometimes referred to herein as encoded data signals, which are provided to the external transmitter unit 128 (e.g., via a cable). As will be appreciated, the sound processing unit 126 can utilize digital processing techniques to provide frequency shaping, amplification, compression, and other signal conditioning, including conditioning based on recipient-specific fitting parameters.

[0032] The power source of the external component 142 is configured to provide power to the auditory prosthesis 100, where the auditory prosthesis 100 includes a battery (e.g., located in the internal component 144, or disposed in a separate implanted location) that is recharged by the power provided from the external component 142 (e.g., via a transcutaneous energy transfer link). The transcutaneous energy transfer link is used to transfer power and/or data to the internal component 144 of the auditory prosthesis 100. Various types of energy transfer, such as infrared (IR), electromagnetic, capacitive, and inductive transfer, may be used to transfer the power and/or data from the external component 142 to the internal component 144. During operation of the auditory prosthesis 100, the power stored by the rechargeable battery is distributed to the various other implanted components as needed.

[0033] The internal component 144 comprises an internal receiver unit 132, a stimulator unit 120, and an elongate electrode assembly 118. In some implementations, the internal receiver unit 132 and the stimulator unit 120 are hermetically sealed within a biocompatible housing. The internal receiver unit 132 comprises an internal coil 136 (e.g., a wire antenna coil comprising multiple turns of electrically insulated single-strand or multi-strand platinum or gold wire), and preferably, a magnet (also not shown) fixed relative to the internal coil 136. The internal receiver unit 132 and the stimulator unit 120 are hermetically sealed within a biocompatible housing, sometimes collectively referred to as a stimulator/receiver unit. The internal coil 136 receives power and/or data signals from the external coil 130 via a transcutaneous energy transfer link (e.g., an inductive RF link). The stimulator unit 120 generates electrical stimulation signals based on the data signals, and the stimulation signals are delivered to the recipient via the elongate electrode assembly 118.

[0034] The elongate electrode assembly 118 has a proximal end connected to the stimulator unit 120, and a distal end implanted in the cochlea 140. The electrode assembly 118 extends from the stimulator unit 120 to the cochlea 140 through the mastoid bone 119. In some implementations, the electrode assembly 118 may be implanted at least in the basal region 116, and sometimes further. For example, the electrode assembly 118 may extend towards apical end of cochlea 140, referred to as cochlea apex 134. In certain circumstances, the electrode assembly 118 may be inserted into the cochlea 140 via a cochleostomy 122. In other circumstances, a cochleostomy may be formed through the round window 121, the oval window 112, the promontory 123, or through an apical turn 147 of the cochlea 140.

[0035] The elongate electrode assembly 118 comprises a longitudinally aligned and distally extending array 146 of electrodes or contacts 148, sometimes referred to as electrode or contact array 146 herein, disposed along a length thereof. Although the electrode array 146 can be disposed on the electrode assembly 118, in most practical applications, the electrode array 146 is integrated into the electrode assembly 118 (e.g., the electrode array 146 is disposed in the electrode assembly 118). As noted, the stimulator unit 120 generates stimulation signals which are applied by the electrodes 148 to the cochlea 140, thereby stimulating the auditory nerve 114.

[0036] While FIG. 1A schematically illustrates an auditory prosthesis 100 utilizing an external component 142 comprising an external microphone 124, an external sound processing unit 126, and an external power source, in certain other implementations, one or more of the microphone 124, sound processing unit 126, and power source are implantable on or within the recipient (e.g., within the internal component 144). For example, the auditory prosthesis 100 can have each of the microphone 124, sound processing unit 126, and power source implantable on or within the recipient (e.g., encapsulated within a biocompatible assembly located subcutaneously), and can be referred to as a totally implantable cochlear implant ("TICI"). For another example, the auditory prosthesis 100 can have most components of the cochlear implant (e.g., excluding the microphone, which can be an in-the-ear-canal microphone) implantable on or within the recipient, and can be referred to as a mostly implantable cochlear implant ("MICI").

[0037] FIG. 1B schematically illustrates a perspective view of an example fully implantable auditory prosthesis 200 (e.g., fully implantable middle ear implant or totally implantable acoustic system), implanted in a recipient, utilizing an acoustic actuator in accordance with certain implementations described herein. The example auditory prosthesis 200 of FIG. 1B comprises a biocompatible implantable assembly 202 (e.g., comprising an implantable capsule) located subcutaneously (e.g., beneath the recipient's skin and on a recipient's skull). While FIG. 1B schematically illustrates an example implantable assembly 202 comprising a microphone, in other example auditory prostheses 200, a pendant microphone can be used (e.g., connected to the implantable assembly 202 by a cable). The implantable assembly 202 includes a signal receiver 204 (e.g., comprising a coil element) and an acoustic transducer 206 (e.g., a microphone comprising a diaphragm and an electret or piezoelectric transducer) that is positioned to receive acoustic signals through the recipient's overlying tissue. The implantable assembly 202 may further be utilized to house a number of components of the fully implantable auditory prosthesis 200. For example, the implantable assembly 202 can include an energy storage device and a signal processor (e.g., a sound processing unit). Various additional processing logic and/or circuitry components can also be included in the implantable assembly 202 as a matter of design choice.

[0038] For the example auditory prosthesis 200 shown in FIG. 1B, the signal processor of the implantable assembly 202 is in operative communication (e.g., electrically interconnected via a wire 208) with an actuator 210 (e.g., comprising a transducer configured to generate mechanical vibrations in response to electrical signals from the signal processor). In certain implementations, the example auditory prosthesis 100, 200 shown in FIGs. 1A and 1B can comprise an implantable microphone assembly, such as the microphone assembly 206 shown in FIG. 1B. For such an example auditory prosthesis 100, the signal processor of the implantable assembly 202 can be in operative communication (e.g., electrically interconnected via a wire) with the microphone assembly 206 and the stimulator unit of the main implantable component 120. In certain implementations, at least one of the microphone assembly 206 and the signal processor (e.g., a sound processing unit) is implanted on or within the recipient.

[0039] The actuator 210 of the example auditory prosthesis 200 shown in FIG. 1B is supportably connected to a positioning system 212, which in turn, is connected to a bone anchor 214 mounted within the recipient's mastoid process (e.g., via a hole drilled through the skull). The actuator 210 includes a connection apparatus 216 for connecting the actuator 210 to the ossicles 106 of the recipient. In a connected state, the connection apparatus 216 provides a communication path for acoustic stimulation of the ossicles 106 (e.g., through transmission of vibrations from the actuator 210 to the incus 109).

[0040] During normal operation, ambient acoustic signals (e.g., ambient sound) impinge on the recipient's tissue and are received transcutaneously at the microphone assembly 206. Upon receipt of the transcutaneous signals, a signal processor within the implantable assembly 202 processes the signals to provide a processed audio drive signal via wire 208 to the actuator 210. As will be appreciated, the signal processor may utilize digital processing techniques to provide frequency shaping, amplification, compression, and other signal conditioning, including conditioning based on recipient-specific fitting parameters. The audio drive signal causes the actuator 210 to transmit vibrations at acoustic frequencies to the connection apparatus 216 to affect the desired sound sensation via mechanical stimulation of the incus 109 of the recipient.

[0041] The subcutaneously implantable microphone assembly 202 is configured to respond to auditory signals (e.g., sound; pressure variations in an audible frequency range) by generating output signals (e.g., electrical signals; optical signals; electromagnetic signals) indicative of the auditory signals received by the microphone assembly 202, and these output signals are used by the auditory prosthesis 100, 200 to generate stimulation signals which are provided to the recipient's auditory system. To compensate for the decreased acoustic signal strength reaching the microphone assembly 202 by virtue of being implanted, the diaphragm of an implantable microphone assembly 202 can be configured to provide higher sensitivity than are external non-implantable microphone assemblies. For example, the diaphragm of an implantable microphone assembly 202 can be configured to be more robust and/or larger than diaphragms for external non-implantable microphone assemblies.

[0042] The example auditory prostheses 100 shown in FIG. 1A utilizes an external microphone 124 and the auditory prosthesis 200 shown in FIG. 1B utilizes an implantable microphone assembly 206 comprising a subcutaneously implantable acoustic transducer. In certain implementations described herein, the auditory prosthesis 100 utilizes one or more implanted microphone assemblies on or within the recipient. In certain implementations described herein, the auditory prosthesis 200 utilizes one or more microphone assemblies that are positioned external to the recipient and/or that are implanted on or within the recipient, and utilizes one or more acoustic transducers (e.g., actuator 210) that are implanted on or within the recipient. In certain implementations, an external microphone assembly can be used to supplement an implantable microphone assembly of the auditory prosthesis 100, 200. Thus, the teachings detailed herein and/or variations thereof can be utilized with any type of external or implantable microphone arrangement, and the acoustic transducers shown in FIGs. 1A and 1B are merely illustrative.

[0043] Magnetic links between an implanted portion of a medical system (e.g., sensory prosthesis system) and an external portion of the medical system can be used to generate an attractive magnetic force that holds the external portion in place relative to the implanted portion to facilitate a sufficiently strong and consistent magnetic induction (MI) communication channel between the two across the maximum skin-flap separation. In contrast, magnet-free links can have highly variable misalignments between the external portion and the implanted portion, resulting in highly variable coil coupling coefficients (e.g., ranging from $k = 0.1$ to 0.02 or less). Thus, sufficiently strong and consistent power transfer efficiency can be difficult to achieve in view of substantial misalignments of the coils of the external portion relative to the implanted portion. In addition, for auditory prosthesis systems, the anatomy of the concha can be a source of additional variability, resulting in a wide range of behind-the-ear placements, subsequent day-to-day variations, and variability due to activity (e.g., running) by the recipient. Certain implementations described herein are configured to provide sufficiently strong and consistent MI communications between the implanted portion and the external portion despite the positional variability of a magnet-free link.

[0044] FIG. 2A schematically illustrates a top view of an example apparatus 300 in accordance with certain implementations described herein. FIG. 2B schematically illustrates a cross-sectional view of the example apparatus 300 in accordance with certain implementations described herein and a device 400 external to the recipient's body. The apparatus 300 comprises an array of magnetic induction (MI) antennas 310, the array comprising at least a first MI antenna 310a and a second MI antenna 310b. The first MI antenna 310a comprises an electrically conductive and substantially planar first coil 312a extending around and substantially orthogonal to a first antenna axis (not shown). The second MI antenna 310b comprises an electrically conductive and substantially planar second coil 312b extending around and substantially orthogonal to a second antenna axis (not shown). The second antenna axis is substantially parallel to the first antenna axis, and the second coil 312b in series electrical connection with the first coil 312a. The first and second MI antennas 310a,b have a mutual coupling coefficient that is substantially equal to zero.

[0045] In certain implementations, the apparatus 300 is part of a transcutaneous system (e.g., auditory prosthesis system) comprising the apparatus 300 (e.g., an implanted portion of an acoustic prosthesis system) and the device 400 (e.g., an external portion of the acoustic prosthesis system). For example, the apparatus 300 can be configured to be implanted on and substantially parallel to a bone surface 510 (e.g., a surface of a portion of the skull 520; a surface of the mastoid bone 119) within a recipient and the external device 400 can be configured to be worn on the recipient's skin 530 over the apparatus 300 (e.g., on and/or behind a concha of the recipient). The device 400 can comprise a housing 410 (e.g., biocompatible; skin-friendly) and at least one external MI antenna 420 comprising at least one electrically conductive coil 422 configured to provide power and/or data to the apparatus 300 and/or to receive data from the apparatus 300 via magnetic induction with the array of MI antennas 310 of the apparatus 300. The array of MI antennas 310 can be configured to wirelessly transmit signals to and/or receive signals from the at least one external MI antenna 420 of the device 400 positioned outside the recipient's skin 530 and over the array of MI antennas 310 (e.g., to inductively receive power, data, and/or control signals transmitted transcutaneously from the device 400 and/or to transcutaneously transmit data and/or control signals to the device 400). In certain implementations, the array of MI antennas 310 bounds a substantially planar region through which magnetic flux from the at least one external MI antenna 420 extends in a direction non-parallel to the region.

[0046] In certain implementations, the first coil 312a can comprise a first electrically conductive wire wound around and substantially orthogonal to the first antenna axis and the second coil 312b can comprise a second electrically conductive wire wound around and substantially orthogonal to the second antenna axis. In certain implementations, the first coil 312a comprises a first portion of an electrically conductive wire and the second coil 312b comprises a second portion of the electrically conductive wire (e.g., the coils 312 of the array of MI antennas 310 formed from a single length of wire as described herein), while in certain other implementations, the first coil 312a and the second coil 312b comprise portions of different electrically conductive wires that are placed in series electrical connection with one another.

[0047] The first and second coils 312a,b can each comprise a planar electrically conductive wire portion (e.g., platinum, gold, copper, or other metal; electrically insulated single-strand or multi-strand) with multiple windings and can each have a substantially circular, rectangular, spiral, oval, obround, fabiform, reniform, or other shape. For another example, the first and second coils 312a,b can each comprise metal traces on an printed circuit board that run (e.g., wind) around a corresponding antenna axis. The first and second coils 312a,b can each have a diameter, length, and/or width (e.g., along a lateral direction substantially parallel to the bone surface 510) less than or equal to 100 millimeters (e.g., in a range of 15 millimeters to 40 millimeters; in a range of 25 millimeters to 50 millimeters; in a range of less than 30 millimeters; in a range of 20 millimeters to 60 millimeters; in a range greater than 60 millimeters). The first coil 312a and the second coil 312b can be substantially co-planar with one another or can be substantially parallel to one another. The first and second coils 312a,b can be configured to inductively receive power, data, and/or control signals from the device 400 external to the recipient's body and/or to inductively transmit data signals and/or control signals to the device 400.

[0048] In the example array of MI antennas 310 shown by FIG. 2A, the first coil 312a comprises a plurality of first loops (e.g., 2, 3, 4, or more) having substantially equal widths and the second coil 312b comprises a plurality of second loops (e.g., 2, 3, 4, or more) having substantially equal widths. The width of the first loops can be substantially equal to the width of the second loops (see, e.g., FIG. 2A) or the width of the first loops can be substantially different from the width of the second loops. FIG. 2C schematically illustrates another example array of MI antennas 310 in accordance with certain implementations described herein. The first coil 312a of FIG. 2C has a first spiral shape and the second coil 312b of FIG. 2C has a second spiral shape. The width of the first spiral shape can be substantially equal to the width of the second spiral shape (see, e.g., FIG. 2C) or the width of the first spiral shape can be substantially different from the width of the second spiral shape.

[0049] In certain implementations, the first coil 312a bounds a first area 314a and the second coil 312b bounds a second area 314b, with the first area 314a having a first portion 316a overlapping the second area 314b and a second portion 316b not overlapping the second area 314b, and with the second area 314b having a first portion 318a overlapping the first area 314a and a second portion 318b not overlapping the first area 314a. For example, as shown in FIG. 2A, an outer perimeter of the first loops of the first coil 312a bounds a substantially circular first area 314a and an outer perimeter of the second loops of the second coil 312b bounds a substantially circular second area 314b, with the first and second areas 314a,b partially (e.g., not completely) overlapping one another. For another example, as shown in FIG. 2C, an outer perimeter of the first spiral-shaped first coil 312a bounds a substantially circular first area 314a and an outer perimeter of the second spiral-shaped second coil 312b bounds a substantially circular second area 314b, with the first and second areas 314a,b partially (e.g., not completely) overlapping one another.

[0050] While FIGs. 2A and 2C show the array of MI antennas 310 comprising two substantially circularly shaped coils 312, other shapes are also compatible with certain implementations described herein. For example, FIG. 2D schematically illustrates another example array of MI antennas 310 in accordance with certain implementations described herein. The first coil 312a of FIG. 2D has a first reniform (e.g., kidney-shaped) shape and the second coil 312b of FIG. 2D has a second reniform shape. The reniform shape of the coils 312 can be configured to account for expected misalignments (e.g., radial and angular misalignments) of the at least one external coil 422 relative to the center of the array of MI antennas 310. The dimensions of the first and second reniform shapes can be substantially equal to one another or substantially different from one another. Certain implementations with reniform coils 312 are particularly suited for use in magnet-free inductive links between the array of MI antennas 310 and the at least one external coil 422 of the device 400, since the reniform coils 312 can substantially match the curvature of the device 400 while positioned behind the concha (e.g., auricle 110) of the ear.

[0051] While FIGs. 2A, 2C, and 2D show the array of MI antennas 310 comprising two coils 312, other numbers of coils and other arrangements are also compatible with certain implementations described herein. For example, the array of MI antennas 310 can comprise more than two coils 312 (e.g., three coils; four coils; five coils) in various configurations in accordance with certain implementations described herein. FIGs. 3A-3C schematically illustrate example arrays of MI antennas 310 with more than two coils 312 in accordance with certain implementations described herein. The arrays of MI antennas 310 of FIGs. 3A-3B each comprise a third MI antenna 310c comprising an electrically conductive and substantially planar third coil 312c extending around and substantially orthogonal to a third antenna axis (not shown), the third antenna axis substantially parallel to the first and second antenna axes, and the third coil 312c in series electrical connection with the first and second coils 312a,b. The third coil 312c can have a third spiral shape (e.g., the same or different from the first and second spiral shapes) or can comprise a plurality of third loops having substantially equal widths (e.g., the same or different from the loop widths of the first and second coils 312a,b). The third MI antenna 310c can have a second coupling coefficient with the first MI antenna 310a that is substantially equal to zero and a third coupling coefficient with the second MI antenna 310b that is substantially equal to zero. The array of MI antennas 310 of FIG. 3C comprises fourth and fifth MI antennas 310d,e each comprising an electrically conductive and substantially planar fourth and fifth coil 312d,e, respectively, extending around and substantially orthogonal to corresponding antenna axes (not shown) that are substantially parallel to the other antenna axes. As described herein, the coils 312 can be in series electrical communication with one another and the coupling between adjacent (e.g., overlapping) coils 312 can be substantially equal to zero. While each of the coils 312 of FIGs. 3A-3C has a reniform shape (e.g., kidney-shaped), other shapes are also compatible with certain implementations described herein.

[0052] As shown in FIGs. 3A and 3B, the first coil 312a can bound a first area, the second coil 312b can bound a second area, and the third coil 312c can bound a third area. As shown in FIG. 3A, the first area can have a first portion overlapping the second area and the third area, a second portion overlapping the second area and not overlapping the third area, a third area overlapping the third area and not the second area, and a fourth portion not overlapping the second or third areas. The second area can have a first portion overlapping the first area and the third area, a second portion overlapping the first area and not overlapping the third area, a third portion overlapping the third area and not the first area, and a fourth portion not overlapping the first and third areas. The third area can have a first portion overlapping the first area and the second area, a second portion overlapping the first area and not overlapping the second area, a third portion overlapping the second area and not the first area, and a fourth portion not overlapping the first and second areas.

[0053] As shown in FIG. 3B, the first area can have a first portion overlapping the second area and not the third area and a second portion not overlapping the second area and the third area. The second area can have a first portion overlapping the first area and not the third area, a second portion not overlapping the first area and the third area, and a third portion overlapping the third area and not the first area. The third area can have a first portion overlapping the second area and not the first area and a second portion not overlapping the second area and the first area. Other configurations of the first, second, and third coils 312a,b,c are also compatible with certain implementations described herein.

[0054] In certain implementations, the multiple coils 312 of the configurations of FIGs. 3A-3C increase the extent of the array of MI antennas 310 to provide sufficient coupling to the at least one external coil 422 of the device 400 (e.g., a Behind-The-Ear unit) beyond that provided by a single coil 312 (e.g., to provide sufficient coupling over substantially an entire range of positions of the at least one external coil 422). In FIG. 3A, three reniform coils 312a,b,c extend over a larger range of displacements of the at least one external coil 422 in a radial direction (denoted by an arrow in FIG. 3A) than does a single coil 312, and the three coils 312a,b,c are arranged with each coil 312 overlapping the other two coils 312. In FIG. 3B, three reniform coils 312a,b,c extend over a larger range of displacements of the at least one external coil 422 in an angular direction (denoted by an double-headed arrow in FIG. 3A) perpendicular to the radial direction than does a single coil 312, and are arranged (e.g., along an angular axis in polar coordinates) such that the first and second coils 312a,b overlap one another and the second and third coils 312b,c overlap one another, with the first coil 312a not overlapping the third coil 312c. In FIG. 3C, five reniform coils 312a-e extend over a larger range of displacements of the at least one external coil 422 in both the radial and angular directions than does a single coil 312.

[0055] In certain implementations, the coils 312 of the array of MI antennas 310 are in series electrical communication with one another, have substantially the same shape or geometry as one another, substantially the same number of coil turns as one another, and substantially the same coil type (e.g., loop-type; spiral-type) as one another. While having the coils 312 substantially identical to one another can simplify the overall design of the array of

MI antennas 310 and can be easier to model the performance of the array of MI antennas 310, in certain other implementations, the coils 312 of the array of MI antennas 310 have substantial variations in shape or geometry, type, and/or number of turns. For example, the size, shape, and/or number of coil turns can vary across the array of MI antennas 310 (e.g., to increase aggregate coupling in predetermined locations by having more coil turns in the nearby coils 312). For polar array distributions (e.g., for magnet-free links), the coils 312 at larger radii can have larger lengths such that the coils 312 cover the same angle of arc. Certain such implementations can improve coil overlapping while maintaining substantially zero magnetic inductive coupling between the coils 312.

[0056] By having the coils 312 of the array of MI antennas 310 in series electrical connection with one another, certain implementations utilize only a single pair of electrical conduits (e.g., of a hermetically sealed feedthrough) to provide electrical communications between the array of MI antennas 310 and other circuitry 330 of the apparatus 300. In certain implementations, the entire array of MI antennas 310 comprising wire-wound coils 312 can be formed from a single long wire, as described herein. In addition, the series electrical connection of the coils 312 can have the entire array of MI antennas 310 function electrically as a single coil (e.g., avoiding system complexity which can be a safety consideration for implantable devices). The coils 312 can be in series electrical connection with one another in any order, and a connection order that minimizes the total length of connecting wires between the coils 312 can be utilized to minimize electrical resistance of the array of MI antennas 310, thereby reducing concomitant power losses.

[0057] In certain implementations, the coils 312 are positioned relative to one another such that the electric current flowing through each coil 312 is in the same direction (e.g., all clockwise; all counterclockwise). Having an identical current flow direction for the coils 312 of the array of MI antennas 310 can reinforce the magnetic flux coupling of the array of MI antennas 310 to the at least one external coil 422 of the external device 400.

[0058] In certain implementations, the coils 312 of the array of MI antennas 310 are series electrical communication with one another via electrical conduits (e.g., wire portions) that are arranged to run in closely coupled complementary pairs (e.g., pairs of wires in series electrical connection with two coils 312, extending substantially parallel to one another, having electrical currents flowing in opposite directions to one another, and having substantially zero magnetic inductive coupling to the at least one external coil 422 and to the two coils 312). In this way, the stray magnetic couplings of these electrical conduits to the coils 312 of the array of MI antennas 310 and to the at least one external coil 422 of the device 400 can be reduced (e.g., minimized), thereby reducing concomitant degradation of the electrical performance of the array of MI antennas 310. For example, for an array of MI antennas 310 comprising coils 312 on an implantable flexible PCB, the electrical conduits can comprise minimally-spaced conductor trace pairs. For another example, for an array of MI antennas 310 comprising wound-wire coils 312 can have the electrical conduit pairs arranged (e.g., twisted) with one another as described herein.

[0059] In certain implementations, the apparatus 300 further comprises a casing 320 (e.g., housing) configured to be implanted on or within a recipient's body and circuitry 330 in electrical communication with the array of MI antennas 310. The casing 320 can comprise an electrically insulative and biocompatible material (e.g., silicone rubber; polymer; polyether-etherketone (PEEK); ceramic; titanium oxide; glass; glycerine). The casing 320 can contain the array of MI antennas 310 and can be configured to be affixed to a bone surface 510 within the recipient (e.g., with the first and second antenna axes substantially perpendicular to the bone surface 510). For example, the casing 320 can be configured to be positioned beneath the skin 530 and other tissue (e.g., fat and/or muscular 408 layers) and above and on the bone surface 510 in a portion of the recipient's body (e.g., the head). The casing 320 can be substantially parallel to the bone surface 510 (e.g., schematically illustrated in FIG. 2B). In certain implementations, the casing 320 can be bent to be compatible with (e.g., conforms to; follows) a curvature of the bone surface 510, while in certain other implementations, the bone surface 510 can be altered (e.g., machined) to provide a portion with which the casing 320 is compatible. In certain implementations, the casing 320 can be configured to be affixed to the bone surface 510 using at least one biocompatible anchor, screw, or adhesive. The casing 320 of certain implementations is configured to hermetically seal the array of MI antennas 310 from an environment surrounding the casing 320. The casing 320 can also be substantially transparent to the electromagnetic or magnetic fields between the apparatus 300 and the device 400 (e.g., such that the casing 320 does not substantially interfere with power transmission from the device 400 to the apparatus 300 and/or data transmission to and/or from the apparatus 300).

[0060] The circuitry 330 can be configured to receive power from the array of MI antennas 310 and to receive and/or transmit data signals via the array of MI antennas 310. For example, the circuitry 330 can comprise one or more active elements (e.g., stimulator unit 120; assembly 202; vibrating actuator) configured to deliver stimuli (e.g., stimulation signals) to a portion of the recipient's body and/or to detect an attribute or condition of the recipient's body. The circuitry 330 can be in electrical communication with the portion of the recipient's body via electrical conduits 332 (e.g., electrode assembly 118; return electrode) in electrical communication with the circuitry 330 and extending from the casing 320 to a region of the recipient's body. In certain implementations, the circuitry 330 and the array of MI antennas 310 are within the same casing 320 (see, e.g., FIGs. 2A-2B), while in certain other implementations, the circuitry 330 and the array of MI antennas 310 are in two casings that are attached to one another (e.g., electrically connected by at least one electrical conductor).

[0061] The circuitry 330 can comprise one or more microprocessors (e.g., application-specific integrated circuits; generalized integrated circuits programmed by software with computer executable instructions; microelectronic circuitry; microcontrollers) and at least one storage device (e.g., at least one tangible or non-transitory computer readable storage medium; read only memory; random access memory; flash memory) configured to store information (e.g., data; commands) accessed by the one or more microprocessors during operation. The at least one storage device can be encoded with software (e.g., a computer program downloaded as an application) comprising computer executable instructions for instructing the one or more microprocessors (e.g., executable data access logic, evaluation logic, and/or information outputting logic). In certain implementations, the one or more microprocessors execute the instructions of the software to provide functionality as described herein. The circuitry 330 can be configured to receive power signals, data signals, and/or control signals wirelessly communicated from the device 400 via the at least one external coil 422 and the array of MI antennas 310.

[0062] In certain implementations, as shown in FIGs. 2A-2B, the apparatus 300 does not comprise a magnetic element within the casing 320 that is configured to generate a magnetic force with the device 400 to hold the device 400 on the recipient's body. In certain other implementations, the apparatus 300 does comprise a magnetic element within the casing 320 (e.g., the magnetic element hermetically sealed within the casing 320). For example, the magnetic element can comprise at least one magnetic material (e.g., ferromagnetic; ferrimagnetic; permanent magnet; diamagnetic magnet) and can have a substantially planar shape (e.g., disk; plate; substantially circular, oval, or rectangular). The magnetic element can be configured to generate a magnetic force with sufficient strength to hold the device 400 on or over the skin 530 of the recipient above the apparatus 300 such that the coil 320 is in operative wireless communication with the array of MI antennas 310 to wirelessly and transcutaneously transfer energy from the device 400 to the apparatus 300 (e.g., via magnetic induction; via a radio-frequency or RF link).

[0063] In certain implementations, the coils 312 of the array of MI antennas 310 are arranged to overlap one another while covering a total area larger than an area covered by a single coil 312. With the larger total area of the coils 312 of the array of MI antennas 310, the apparatus 300 can tolerate larger movements and/or misalignments of the at least one external coil 422 of the external device 400 than can be tolerated using a single coil 312. For example, at least some of the coils 312 of the array of MI antennas 310 can provide sufficient coupling with the at least one external coil 422 of the external device 400 to produce an operable wireless transcutaneous communication link between the apparatus 300 and the external device 400 in view of a movement and/or misalignment of the at least one external coil 422 with a single coil 312. In addition, the coils 312 of the array of MI antennas 310 in certain implementations are arranged to have small (e.g., substantially equal to zero) mutual coupling coefficients. With the small mutual coupling coefficients among the coils 312 of the array of MI antennas 310, the coupling of the at least one external coil 422 of the external device 400 to the array of MI antennas 310 is substantially equal to the sum of the couplings to the individual coils 312 of the array of MI antennas 310.

[0064] As described herein, the coils 312 of certain implementations are positioned relative to one another such that adjacent coils 312 partially overlap one another with a mutual inductance (e.g., coupling coefficient) that is substantially equal to zero. In certain implementations, the first and second MI antennas 310a,b have a mutual coupling coefficient k that is substantially equal to zero. The substantially zero coupling corresponds to substantially no magnetic flux from one of the first and second coils 312a,b coupled to the other of the first and second coils 312a,b. FIG. 4 is a schematic plot of the mutual coupling coefficient k as a function of the normalized displacement d/R for example first and second coils 312a,b in accordance with certain implementations described herein. The example first and second coils 312a,b of FIG. 4 each comprises a plurality of substantially circular loops with an outer perimeter radius *R* and have centers 311a,b (e.g., at first and second antenna axes 313a,b) offset from one another by a distance *d*.

[0065] The mutual coupling coefficient *k* shown in FIG. 4 has the following characteristics:

- When the first and second coils 312a,b are exactly on top of each other (e.g., $d/R = 0$), the mutual coupling coefficient *k* is at a maximum.
- When the first and second coils 312a,b are laterally offset from one another (e.g., $0 < d/R < 2$), the mutual coupling coefficient *k* is reduced monotonically through zero to small and negative values. In particular, when the first and second coils 312a,b do not overlap one another (e.g., $d/R \sim 2$), the mutual coupling coefficient *k* is small and becomes smaller as the first and second coils 312a,b are further displaced (e.g., $d/R > 2$).
- When the first and second coils 312a,b are relatively far apart (e.g., $d/R >> 1$), the coupling coefficient *k* is negative, because the flux linkage is in the opposite sense as when the coils are relatively close together (e.g., $d/R << 1$). Furthermore, as the first and second coils 312a,b are further laterally offset from one another (e.g., $d/R \rightarrow \infty$), the mutual coupling coefficient *k* approaches zero asymptotically from the negative side.
- Since the mutual coupling coefficient *k* is positive at relatively small values of *d/R* and is negative at relatively large values of *d/R*, and there cannot be discontinuities in the magnetic flux coupling, the mutual coupling coefficient *k* is substantially equal to zero for a value of *d/R* which corresponds to the first and second coils 312a,b being approximately half-overlapped with one another.

While FIG. 4 shows the mutual coupling coefficient *k* as a function of *d/R* for two example circular, loop-type coils 312a,b, the mutual coupling coefficient *k* for other types of coils (e.g., spirals) and other shapes (e.g., kidney-shaped) have the same general characteristics described above and shown in FIG. 4, though the specific values of the mutual coupling coefficient *k* as a function of *d/R* and the value of *d/R* at which the mutual coupling coefficient *k* is substantially equal to zero can be different than those in FIG. 4. For any pair of coplanar coils 312 of any shape (e.g., same shapes as one another; different shapes as one another), the substantially coplanar coils 312 can be configured to have substantially zero mutual coupling, which is a result of the absence of magnetic monopoles ($\nabla \cdot B = 0$).

[0066] In certain implementations in which the array of MI antennas 310 comprises more than two coils (see, e.g., FIG. 2D), pairs of two coils 312 overlapping (e.g., adjacent to) one another are laterally displaced from one another such that the coupling coefficient between the two coils 312 of the pair is substantially equal to zero. As shown in FIG. 4, other coils 312 that are not overlapping (e.g., non-adjacent to) one another have relatively low coupling coefficients.

[0067] In certain implementations, the overlapping coils 312 of the array of MI antennas 310 have sufficiently low mutual inductances (e.g., coupling coefficients) such that the at least one external coil 422 of the device 400 can be positioned to couple to multiple overlapping coils 312 of the array of MI antennas 310, with the cumulative coupling of the at least one external coil 422 to the multiple overlapping coils 312 substantially equal to the sum of the couplings to the individual coils 312 (e.g., as if the at least one external coil 422 was coupled more strongly to a single coil 312). The mutual inductances can also be sufficiently low to simplify tuning of the at least one external coil 422 to the array of MI antennas 310.

[0068] FIG. 5A is a plot of an example coupling between a single coil 312 of the array of MI antennas 310 and at least one external coil 422 as a function of lateral displacement between the single coil 312 and the at least one external coil 422 in accordance with certain implementations described herein. FIG. 5B is a plot of an example coupling between a series of three coils 312a,b,c of the array of MI antennas 310 and at least one external coil 422 as a function of lateral displacement between the center coil 312b and the at least one external coil 422 in accordance with certain implementations described herein. The three coils 312a,b,c of FIG. 5B are in series electrical connection and arranged in a linear configuration with one another, and are spaced such that overlapping coils 312 have a mutual coupling coefficient that is substantially equal to zero. In FIGs. 5A and 5B, the at least one external coil 422 is spaced from the coils 312 by a gap in a direction perpendicular to the coils 312,422. While FIGs. 5A and 5B correspond to substantially circular coils 312,422 having substantially the same radius, the plots of FIGs. 5A and 5B have the same general features for the coils 312,422 having different radii or different shapes.

[0069] As shown in FIG. 5A, the coupling between the single coil 312 and the at least one external coil 422 is at a maximum when the coils 312,422 are exactly laterally aligned with one another. For increasing lateral displacements of the at least one external coil 422, the coupling initially reduces substantially, passing through zero to become small and negative, and then asymptotically approaching zero (e.g., similar to the characteristics shown in FIG. 4). As shown in FIG. 5B, with the three coils 312a,b,c connected in series with one another and have mutual inductance coupling coefficients that are substantially equal to zero, the aggregate coupling of the at least one external coil 422 (denoted by the solid line) is substantially equal to the sum of the couplings of the at least one external coil 422 to each of the individual coils 312 (denoted by dashed lines). A range of positions of the at least one external coil 422 for which the coupling between the at least one external coil 422 and the multiple coils 312 (shown in FIG. 5B) is at least one-half a maximum coupling value is substantially wider than the equivalent range of positions for a single coil 312 (shown in FIG. 5A). In addition, the coupling to the multiple coils 312 of FIG. 5B is substantially constant over a wider range of positions of the at least one external coil 422 than the coupling to the single coil 312 of FIG. 5A. In this way, the array of MI antennas 310 comprising multiple coils 312 can provide sufficiently strong coupling to the at least one external coil 422 despite significant misalignments and/or movements of the at least one external coil 422 (e.g., the electrical performance of the wireless communication link between the apparatus 300 and the device 400 is substantially insensitive to a range of misalignments/movements).

[0070] FIGs. 6A-6E are example contour plots of the aggregate coupling between the multiple substantially circular coils 312 and a substantially circular external coil 422 as a function of the lateral displacement of the external coil 422 in accordance with certain implementations described herein. The lateral displacements in FIGs. 6A-6E are over an area extending over the multiple coils 312 having components in the x-direction and/or in the y-direction perpendicular to the x-direction. For reference, the solid dots denote the positions of the centers of the multiple coils 312 and the dash-dot line in each of FIGs. 6A-6E denotes the one-half maximum coupling contour for the external coil 422 with a single coil at the center of the area. The two solid lines in each of FIGs. 6A-6E denote the one-half maximum aggregate coupling contour (labeled “0.5”) and the zero aggregate coupling contour (labeled

"0") for the external coil 422 with the multiple coils 312. Other configurations of multiple coils 312 with other shapes are also compatible with certain implementations described herein.

[0071] FIG. 6A shows the contour plots for two coils 312a,b with the x-direction extending through the centers of the two coils 312a,b. The one-half maximum aggregate coupling contour (e.g., which can be deemed to bound the usable region of misalignments/movements of the external coil 422 that can be tolerated while maintaining sufficiently strong coupling) extends over a wider area than does the single-coil one-half maximum coupling contour, such that sufficiently strong coupling can be provided for larger misalignments/movements of the external coil 422. While the usable area for the two coils 312a,b is increased along the x-direction, the extent of the usable area along the y-direction is substantially the same as for a single coil.

[0072] FIG. 6B shows the contour plots for three coils 312a,b,c with the centers linearly aligned along the x-direction. The one-half maximum aggregate coupling contour extends over an even wider area than does that of the two coils 312a,b of FIG. 6A, denoting that sufficiently strong coupling can be provided for even larger misalignments/movements of the external coil 422. As with the two coils 312a,b of FIG. 6A, the usable area for the linearly aligned three coils 312a,b,c of FIG. 6B is increased along the x-direction, but the extent of the usable area along the y-direction is substantially the same as for a single coil.

[0073] FIG. 6C shows the contour plots for three coils 312a,b,c with the centers arranged at the corners of an equilateral triangle. The extent of the one-half maximum aggregate coupling contour in all lateral directions (e.g., both the x-direction and in the y-direction) is larger than that of a single coil. In addition, the value of the aggregate coupling at the center is about 30% greater than that for a single coil and the value of the aggregate coupling at the periphery of the dash-dot circle is nearly double that for a single coil. These attributes are indicative of the equilateral triangle configuration of the three coils 312a,b,c being configured to account for misalignments/movements of the external coil 422 in both the x- and y-directions and/or in radial/angular directions.

[0074] FIG. 6D shows the contour plots for five coils 312a-e with three of the centers aligned along a line parallel to the x-direction and two of the centers aligned along another line parallel to the x-direction such that each of the centers is at a corner of an equilateral triangle. While FIG. 6D corresponds to an arrangement of substantially circular coils 312a-e, this non-symmetric arrangement can be used for reniform (e.g., kidney-shaped) coils 312 of the array of MI antennas 310 (see, e.g., FIG. 3C) positioned behind the ear and following the curvature of the concha (e.g., auricle 110).

[0075] FIG. 6E shows the contour plots for seven coils 312a-g in a hexagonal arrangement with three of the centers aligned along the x-direction, two of the centers aligned along a line parallel to the x-direction, and two of the centers aligned along another line parallel to the x-direction, such that each of the centers is at a corner of an equilateral triangle. The arrangement of FIG. 6E is configured to tolerate a wide range of misalignments/movements of the external coil 422 in both the x- and y-directions. Due to the small but negative coupling coefficients for coils 312 far from the center, configurations comprising more than seven coils 312a-g in a hexagonal arrangement can have a “dead zone” in which the aggregate coupling coefficient at a center region of the array of MI antennas 310 or in an annular ring surrounding the center region that is lower than that of a single coil (e.g., less than 0.5) or that is negative.

[0076] Using multiple coils 312 generally entails a penalty in peak power transmission and efficiency as compared to a perfectly aligned single coil. However, certain implementations described herein provide a resilience (e.g., less sensitivity) to misalignments/movements of the external coil 422 from perfect alignment (e.g., sufficiently large aggregate coupling coefficients even with less-than-perfect alignment). This tradeoff of peak power transmission and efficiency for misalignment/movement resilience can facilitate using a device 400 that is not magnetically held in position by a magnet of the implanted portion. In addition, for an array of MI antennas 310 comprising a large number of coils 312 in series electrical communication with one another (e.g., more than seven), the total electrical resistance can result in an unwanted amount of resistive power losses making such configurations less practical for wireless power transfer.

[0077] FIG. 7 is a flow diagram of an example method 700 for fabricating an array of MI antennas 310 in accordance with certain implementations described herein. While the method 700 is described by referring to some of the structures of the example apparatus 300 of FIGs. 2A-2D, 3A-3C, 4, 5A-5B, and 6A-6E, other apparatus and systems with other configurations of components can also be used to perform the method 700 in accordance with certain implementations described herein.

[0078] FIGs. 8A-8E schematically illustrate various stages of the fabrication method 700 for a wound-wire array of MI antennas 310 in accordance with certain implementations described herein. In certain implementations, the array of MI antennas 310 is formed from a single wire 800 (shown in FIG. 8A). The array of MI antennas 310 formed using a single wire can avoid having wire joints between the coils 312 (e.g., outside the enclosure of the circuitry 330), thereby providing enhanced reliability. While FIGs. 8A-8E show the method 700 used to fabricate an array of MI antennas 310 comprising three substantially circular coils 312a,b,c with two loop coil turns each, the method 700 can be used to fabricate arrays of MI antennas 310 with other types of coils 312, shapes of coils 312, and/or coils 312 with other numbers of turns. In addition, while the coils 312 of FIGs. 8A-8E are substantially identical to one another, certain other implementations have at least two of the coils 312 substantially not identical to one another. Other fabrication methods (e.g., printing the array of MI antennas 310 onto a flexible, biocompatible substrate; winding a number of discrete coils 312 and joining them together) are compatible with certain implementations described herein.

[0079] In an operational block 710, the method 700 comprises bending a first portion of the wire 800 to form a substantially planar first coil 312a comprising a first number of coil turns (see, e.g., FIG. 8B). In an operational block 720, the method 700 further comprises bending a second portion of the wire 800 to form a substantially planar second coil 312b comprising a second number of coil turns (see, e.g., FIG. 8C). The second coil 312b is in series electrical connection with the first coil 312a, the first coil 312a is between an elongate first section 810 of the wire 800 and an elongate second section 820 of the wire 800, the second coil 312b is between the second section 820 of the wire 800 and an elongate third section 830 of the wire 800. The first coil 312a can have a first size and shape and the second coil 312b can have a second size and shape substantially equal to the first size and shape, and the second number of coil turns can be equal to the first number of coil turns. As schematically illustrated by FIG. 8D, the method 700 can further comprise bending a third portion of the wire 800 to form a substantially planar third coil 312c comprising a third number of coil turns, the third coil 312c in series electrical connection with the first and second coils 312a,b, the third coil 312c between the third section 830 and an elongate fourth section 840 of the wire 800. The third coil 312c can have a third size and shape that is substantially equal to the first size and shape and/or the second size and shape, and the third number of coil turns can be equal to the first number of coil turns and/or the second number of coil turns. As shown in FIG. 8D, the electric current flow direction in the first section 810 is opposite to the electric current flow directions in the second, third, and fourth sections 820,830,840 (denoted by two arrow heads).

[0080] In an operational block 730, the method 700 further comprises positioning (e.g., twisting) an elongate first portion 850a of the first section 810 relative to the second section 820 such that the first portion 850a and the second section 820 have substantially zero magnetic inductive coupling to the first and second coils 312a,b. For example, as shown in FIG. 8E, the first portion 850a and the second section 820 can be substantially parallel to one another, with substantially equal lengths, configured to have equal and opposite electrical currents flowing therethrough, and coupled (e.g., twisted) together to minimize an area between the first portion 850a and the second section 820 (e.g., closely coupled to one another).

[0081] In an operational block 740, the method 700 further comprises positioning (e.g., twisting) an elongate second portion 850b of the first section 810 relative to the third section 830 such that the second portion 850b and the third section 830 have substantially zero magnetic inductive coupling to the first and second coils 312a,b. For example, as shown in FIG. 8E, the second portion 850b and the third section 830 can be substantially parallel to one another, with substantially equal lengths, configured to have equal and opposite electrical currents flowing therethrough, and coupled (e.g., twisted) together to minimize an area between the second portion 850b and the third section 830 (e.g., closely coupled to one another). In certain implementations, as schematically illustrated by FIG. 8E, the method 700 can further comprise positioning (e.g., twisting) an elongate third portion 850c of the first section 810 relative to the fourth section 840 such that the third portion 850c and the fourth section 840 have substantially zero magnetic inductive coupling to the first and second coils 312a,b. For example, as shown in FIG. 8E, the third portion 850c and the fourth section 840 can be substantially parallel to one another, with substantially equal lengths, configured to have equal and opposite electrical currents flowing therethrough, and coupled (e.g., twisted) together to minimize an area between the third portion 850c and the fourth section 840 (e.g., closely coupled to one another). The array of MI antennas 310 comprises a first pair of electrical conduits 820,850a twisted with one another and in series electrical connection with the first coil 312a and the second coil 312b and a second pair of electrical conduits 830,850b twisted with one another and in series electrical connection with the second coil 312b and the third coil 312c.

[0082] In certain implementations, by having the coils 312 of the array of MI antennas 310 in series electrical communication with one another, the two wire ends 860 of the wire 800 can be electrically coupled to the circuitry 330 via an electrically insulative feedthrough having a pair of electrically conductive connectors (e.g., pins).

[0083] In certain implementations, the method 700 further comprises positioning the second coil 312b relative to the first coil 312a such that electrical current flow through the first coil 312a and electrical current flow through the second coil 312b are in a common direction (e.g., both clockwise; both counterclockwise) as one another and a first region bounded by the first coil 312a partially overlaps a second region bounded by the second coil 312b. Twisting the complementary wire portions/sections with one another can ensure that the complementary wire portions/sections remain together while the coils 312 are being moved into position relative to one another. If the coils 312 are wound in the same direction (e.g., all clockwise; all counterclockwise), positioning the coils 312 relative to one another can only comprise translating and rotating the coils 312 in the array plane (e.g., not flipping any of the coils 312) such that the winding sense of the coils 312 remain the same as one another. For example, the twisting of the complementary wire portions/sections between two coils 312 can have an integer number of 360-degree twists. If at least one of the coils 312 is wound in an opposite direction to the other coils 312, the coils 312 can be flipped during array placement such that all the coils 312 have the same winding sense in the array of MI antennas 310. For example, the twisting of the complementary wire portions/sections between two coils 312 can include an integer number of 360-degree twists and an odd-integer number of 180-degree twists. There are many variations of possible fabrication methods in accordance with certain implementations described herein which can provide the coils 312 in the substantially zero mutual inductance positions and having the same winding sense as one another.

[0084] While FIGs. 8A-8E show the coils 312 wound one after the other with the twisting of the complementary portions/sections performed afterwards, in certain other implementations, the coils 312 are wound in groups and the twisting of the complementary portions/sections performed during and/or after forming the groups of coils 312. For example, FIGs. 9A-9C schematically illustrate various stages of fabrication of an array of MI antennas

310 comprising five coils 312a-e in two groups 870a,b in accordance with certain implementations described herein. After forming the two groups 870a,b (see, e.g., FIG. 9A), the complementary portions/sections in the first group 870a can be twisted together and the complementary portions/sections in the second group 870b can be twisted together (see, e.g., FIG. 9B), and then the remaining complementary portions/sections can be twisted together (see, e.g., FIG. 9C). Other variations are also compatible with certain implementations described herein.

[0085] FIG. 10 schematically illustrates another intermediate stage of the fabrication of an array of MI antennas 310 in accordance with certain implementations described herein. Each of the coils 312 can have a pair of wire portions 880 that are coupled (e.g., twisted) together to reduce (e.g., minimize) an area bounded by the pair of wire portions 880 (e.g., the pair of wire portions 880 closely coupled to one another). For example, FIG. 10 shows three coils 312a-c, each formed from a corresponding single wire, and the remaining portions of the single wire twisted along much of their length to form the corresponding pairs of wire portions 880a-c. End portions 882 of the pairs of wire portions 880 can be positioned within a casing 320 comprising the circuitry 330 and the end portions 882 can connected to the circuitry 330 such that the coils 312 are in series electrical communication with one another. For example, each of the end portions 882 can be affixed to a corresponding pair of PCB solder pads 884, the pairs of solder pads 884 connected in series by PCB electrically conductive traces 886. The coils 312 can be positioned in the zero-coupling arrangement either before or after the end portions 882 are connected to the circuitry 330. As compared to the method of FIGs. 8A-8E and 9A-9C, the method of FIG. 10 utilizes more electrical feedthroughs to connect the coils 312 to the circuitry 330, and can result in higher resistive losses (e.g., doubling the resistive losses for a two-coil or three-coil array) due to longer twisted pair wire lengths.

[0086] FIGs. 11A and 11B schematically illustrate two example arrays of MI antennas 310 with substantially circular coils 312 and substantially reniform coils 312, respectively, in accordance with certain implementations described herein. Because the complementary wire portions/sections are not inductively coupled to the coils 312 or to the at least one external coil 422, the locations of the complementary wire portions/sections do not substantially affect the coupling between the array of MI antennas 310 and the at least one external coil 422. For example, the complementary wire portions/sections can extend out of the plane of the coils 312, and can be positioned in any way such that the coils 312 are appropriately positioned and the complementary wire portions/sections remain closely coupled along their route.

[0087] In certain implementations, two or more overlapping coils 312 of the array of MI antennas 310 have a non-zero mutual coupling coefficient, with the two or more overlapping coils 312 separately in electrical communication with the circuitry 330. While certain such implementations can achieve a denser packing of the coils 312 (e.g., increasing the probability of the at least one external coil 422 maximally coupling to one of the coils 312), the array of MI antennas 310 can be more difficult to use since there will be significant coupling to more coils 312 and much of the magnetic flux will be coupled in the opposite polarity (e.g., causing destructive interferences and reducing power transmission, if electrically connected in series). In addition, certain such implementations utilize more than two electrically conductive feedthrough conduits (e.g., pins) between the array of MI antennas 310 and the circuitry 330 which can be undesirable.

[0088] To reduce (e.g., avoid) destructive magnetic flux coupling, the circuitry 330 can be configured to controllably select which coils 312 are used to wirelessly communicate with the at least one external coil 422 of the device 400. For example, the circuitry 330 can select only an optimal subset of the coils 312 (e.g., in series; in parallel) and can selectively control the direction of electrical current flow through each coil 312 such that the magnetic flux couplings of the selected coils 312 constructively contribute to one another. In certain other implementations, the circuitry 330 can rectify the output of each coil 312 and sum the contributions of each coil 312, either in series or in parallel. However, forward data and back telemetry transmission can be adversely affected. While the circuitry 330 can be configured to choose the appropriate coils 312 in the array of MI antennas 310 to cover the data transmission functions of the wireless link with the at least one external coil 422, such operation comes at the cost of circuitry and computational complexity.

[0089] In certain implementations, the array of MI antennas 310 is substantially non-planar. For example, a brain stimulator implant can comprise an array of MI antennas 310 configured to be implanted beneath and following the curvature of the scalp or skull. Such an array of MI antennas 310 can be configured to provide a wireless and transcutaneous inductive communication link with an external coil 422 of a device 400 worn on the recipient's head (e.g., in a cap).

[0090] In certain implementations, the at least one external coil 422 can comprise a single coil 422, while in certain other implementations, the at least one external coil 422 comprises multiple external coils 422 which can provide a wider area (e.g., larger misalignments/movements) than can a single coil 422 and which can facilitate the device 400 being used with a magnet-free link.

[0091] FIGs. 12A and 12B schematically illustrate two example devices 400 with multiple external coils 422 in accordance with certain implementations described herein. FIG. 12A shows two external coils 422, each in a corresponding portion 410a,b of the housing 410 (e.g., a circuitry compartment and a battery compartment), the two external coils 422 not overlapping one another. FIG. 12B shows two external coils 422 in a monolithic housing 410 and that do overlap one another (e.g., to have a substantially zero mutual inductive coupling coefficient with one another). In certain implementations, the at least one external coil 422 can comprise more than two external coils 422, while in certain other implementations, the at least one external coil 422 comprises a single external coil 422 having the largest dimensions that fit within the monolithic housing 410.

[0092] The external coils 422 of FIG. 12A can be energized individually (e.g., separately; non-simultaneously; one at a time). For example, the device 400 can include circuitry configured to selectively energize the external coils 422 at a time, based on which external coil 422 has the largest coupling to the array of MI antennas 310 (e.g., determined by periodically activating the external coils 422 one at a time and detecting which external coil 422 provides the best link performance). The external coils 422 of FIG. 12B having a substantially zero mutual inductive coupling coefficient with one another can be configured to be energized simultaneously.

[0093] Although commonly used terms are used to describe the systems and methods of certain implementations for ease of understanding, these terms are used herein to have their broadest reasonable interpretations. Although various aspects of the disclosure are described with regard to illustrative examples and implementations, the disclosed examples and implementations should not be construed as limiting. Conditional language, such as, among others, "can," "could," "might," or "may," unless specifically stated otherwise, or otherwise understood within the context as used, is generally intended to convey that certain implementations include, while other implementations do not include, certain features, elements and/or steps. Thus, such conditional language is not generally intended to imply that features, elements and/or steps are in any way required for one or more implementations or that one or more implementations necessarily include logic for deciding, with or without user input or prompting, whether these features, elements and/or steps are included or are to be performed in any particular implementation. In particular, the terms “comprises” and “comprising” should be interpreted as referring to elements, components, or steps in a non-exclusive manner, indicating that the referenced elements, components, or steps may be present, or utilized, or combined with other elements, components, or steps that are not expressly referenced.

[0094] It is to be appreciated that the implementations disclosed herein are not mutually exclusive and may be combined with one another in various arrangements. In addition, although the disclosed methods and apparatuses have largely been described in the context of various devices, various implementations described herein can be incorporated in a variety of other suitable devices, methods, and contexts. More generally, as can be appreciated, certain implementations described herein can be used in a variety of implantable medical device contexts that can benefit from certain attributes described herein.

[0095] Language of degree, as used herein, such as the terms “approximately,” “about,” “generally,” and “substantially,” represent a value, amount, or characteristic close to the stated value, amount, or characteristic that still performs a desired function or achieves a desired result. For example, the terms “approximately,” “about,” “generally,” and “substantially” may refer to an amount that is within ± 10% of, within ± 5% of, within ± 2% of, within ± 1% of, or within ± 0.1% of the stated amount. As another example, the terms “generally parallel” and “substantially parallel” refer to a value, amount, or characteristic that departs from exactly parallel by ± 10 degrees, by ± 5 degrees, by ± 2 degrees, by ± 1 degree, or by ± 0.1 degree, and the terms “generally perpendicular” and “substantially perpendicular” refer to a value, amount, or characteristic that departs from exactly perpendicular by ± 10 degrees, by ± 5 degrees, by ± 2 degrees, by ± 1 degree, or by ± 0.1 degree. The ranges disclosed herein also encompass any and all overlap, sub-ranges, and combinations thereof. Language such as “up to,” “at least,” “greater than,” less than,” “between,” and the like includes the number recited. As used herein, the meaning of "a," "an," and "said" includes plural reference unless the context clearly dictates otherwise. Also, as used in the description herein, the meaning of "in" includes "into" and "on," unless the context clearly dictates otherwise.

[0096] While the methods and systems are discussed herein in terms of elements labeled by ordinal adjectives (e.g., first, second, etc.), the ordinal adjective are used merely as labels to distinguish one element from another (e.g., one signal from another or one circuit from one another), and the ordinal adjective is not used to denote an order of these elements or of their use.

[0097] The invention described and claimed herein is not to be limited in scope by the specific example implementations herein disclosed, since these implementations are intended as illustrations, and not limitations, of several aspects of the invention. Any equivalent implementations are intended to be within the scope of this invention. Indeed, various modifications of the invention in form and detail, in addition to those shown and described herein, will become apparent to those skilled in the art from the foregoing description. Such modifications are also intended to fall within the scope of the claims. The breadth and scope of the invention should not be limited by any of the example implementations disclosed herein but should be defined only in accordance with the claims and their equivalents.

WHAT IS CLAIMED IS:

1. An apparatus comprising:

an array of magnetic induction (MI) antennas, the array comprising at least:

a first MI antenna comprising an electrically conductive and substantially planar first coil extending around and substantially orthogonal to a first antenna axis; and

a second MI antenna comprising an electrically conductive and substantially planar second coil extending around and substantially orthogonal to a second antenna axis, the second antenna axis substantially parallel to the first antenna axis, the second coil in series electrical connection with the first coil, the first and second MI antennas having a mutual coupling coefficient that is substantially equal to zero.

2. The apparatus of claim 2, wherein the first coil comprises a first wire wound around and substantially orthogonal to the first antenna axis and the second coil comprises a second wire wound around and substantially orthogonal to the second antenna axis.

3. The apparatus of claim 1 or claim 2, wherein the first coil has a first spiral shape and the second coil has a second spiral shape.

4. The apparatus of any preceding claim, wherein the first coil comprises a plurality of first loops having substantially equal widths and the second coil comprises a plurality of second loops having substantially equal widths.

5. The apparatus of any preceding claim, wherein the first coil bounds a first area and the second coil bounds a second area, the first area having a first portion overlapping the second area and a second portion not overlapping the second area, the second area having a first portion overlapping the first area and a second portion not overlapping the first area.

6. The apparatus of any preceding claim, further comprising a pair of electrical conduits in series electrical connection with the first coil and the second coil, the electrical conduits extending substantially parallel to one another, having electrical currents flowing in opposite directions to one another, and having substantially zero magnetic inductive coupling to the first and second coils.

7. The apparatus of any preceding claim, wherein the array of MI antennas further comprises a third MI antenna comprising an electrically conductive and substantially planar

third coil extending around and substantially orthogonal to a third antenna axis, the third antenna axis substantially parallel to the first antenna axis and the second antenna axis, the third coil in series electrical connection with the first coil and the second coil.

8. The apparatus of claim 7, wherein the third MI antenna has a second coupling coefficient with the first MI antenna that is substantially equal to zero and a third coupling coefficient with the second MI antenna that is substantially equal to zero.

9. The apparatus of claim 7 or claim 8, wherein the first coil bounds a first area, the second coil bounds a second area, and the third coil bounds a third area, the first area having a first portion overlapping the second area and the third area, a second portion overlapping the second area and not overlapping the third area, a third area overlapping the third area and not the second area, and a fourth portion not overlapping the second and third areas.

10. The apparatus of claim 9, wherein the second area has a first portion overlapping the first area and the third area, a second portion overlapping the first area and not overlapping the third area, a third portion overlapping the third area and not the first area, and a fourth portion not overlapping the first and third areas.

11. The apparatus of claim 10, wherein the third area has a first portion overlapping the first area and the second area, a second portion overlapping the first area and not overlapping the second area, a third portion overlapping the second area and not the first area, and a fourth portion not overlapping the first and second areas.

12. The apparatus of any of claims 7 to 11, further comprising a first pair of electrical conduits in series electrical connection with the first coil and the second coil and a second pair of electrical conduits in series electrical connection with the second coil and the third coil, the first pair of electrical conduits positioned relative to one another such that the first pair of electrical conduits have substantially zero magnetic inductive coupling to the first and second coil, the second pair of electrical conduits positioned relative to one another such that the second pair of electrical conduits have substantially zero magnetic inductive coupling to the first and second coils.

13. The apparatus of any of claims 7 to 12, wherein the third coil has a third spiral shape or comprises a plurality of third loops having substantially equal widths.

14. The apparatus of any preceding claim, further comprising a casing containing the array of MI antennas, the casing configured to be affixed to a bone surface within a recipient with the first and second antenna axes substantially perpendicular to the bone surface.

15. The apparatus of claim 14, wherein the array of MI antennas are configured to wirelessly transmit signals to and/or receive signals from at least one external MI antenna of a device positioned outside the recipient's skin and over the array of MI antennas.

16. The apparatus of claim 15, wherein the array of MI antennas bounds a substantially planar region through which magnetic flux from the at least one external MI antenna extends in a direction non-parallel to the region.

17. The apparatus of claim 16, wherein the apparatus is an implanted portion of an acoustic prosthesis system, the bone surface comprises a skull surface, and the device is an external portion of the acoustic prosthesis system and is positioned on and/or behind a concha of the recipient.

18. A method comprising:

bending a first portion of a wire to form a substantially planar first coil comprising a first number of coil turns;

bending a second portion of the wire to form a substantially planar second coil comprising a second number of coil turns, the second coil in series electrical connection with the first coil, the first coil between an elongate first section of the wire and an elongate second section of the wire, the second coil between the second section of the wire and an elongate third section of the wire;

positioning an elongate first portion of the first section relative to the second section such that the first portion and the second section have substantially zero magnetic inductive coupling to the first and second coils; and

positioning an elongate second portion of the first section relative to the third section such that the second portion and the third section have substantially zero magnetic inductive coupling to the first and second coils.

19. The method of claim 18, further comprising positioning the second coil relative to the first coil such that electrical current flow through the first coil and electrical current flow

through the second coil are in a common direction as one another and a first region bounded by the first coil partially overlaps a second region bounded by the second coil.

20. The method of claim 18 or claim 19, wherein the first number of coil turns and the second number of coil turns are equal to one another.

21. The method of any of claims 18 to 20, wherein the first coil has a first size and shape and the second coil has a second size and shape substantially equal to the first size and shape.

22. The method of claim 18, further comprising:

bending a third portion of the wire to form a substantially planar third coil comprising a third number of third coil turns, the third coil in series electrical connection with the first coil and the second coil, the third coil between the third section of the wire and an elongate fourth section of the wire; and

positioning an elongate third portion of the first section relative to the fourth section such that the third portion and the fourth section having substantially zero magnetic inductive coupling to the first and second coils.

23. The method of claim 22, wherein the third number of coil turns is equal to the first number of coil turns and/or the second number of coil turns.

24. The method of claim 22 or claim 23, wherein the third coil has a size and shape that are substantially equal to a size and shape of the first coil and/or the second coil.

25. An apparatus comprising:

a plurality of electrically conductive and substantially planar first coil loops that are substantially parallel to one another and in series electrical communication with one another; and

a plurality of electrically conductive and substantially planar second coil loops that are substantially parallel to one another and in series electrical communication with one another, the plurality of second coil loops substantially parallel and in series electrical communication with the plurality of first coil loops, the plurality of second coil loops having substantially zero magnetic inductive coupling with the plurality of first coil loops.

26. The apparatus of claim 25, wherein the first coil loops are substantially coplanar with one another and the second coil loops are substantially coplanar with one another.

27. The apparatus of claim 25 or claim 26, wherein the plurality of first coil loops overlap the plurality of second coil loops.

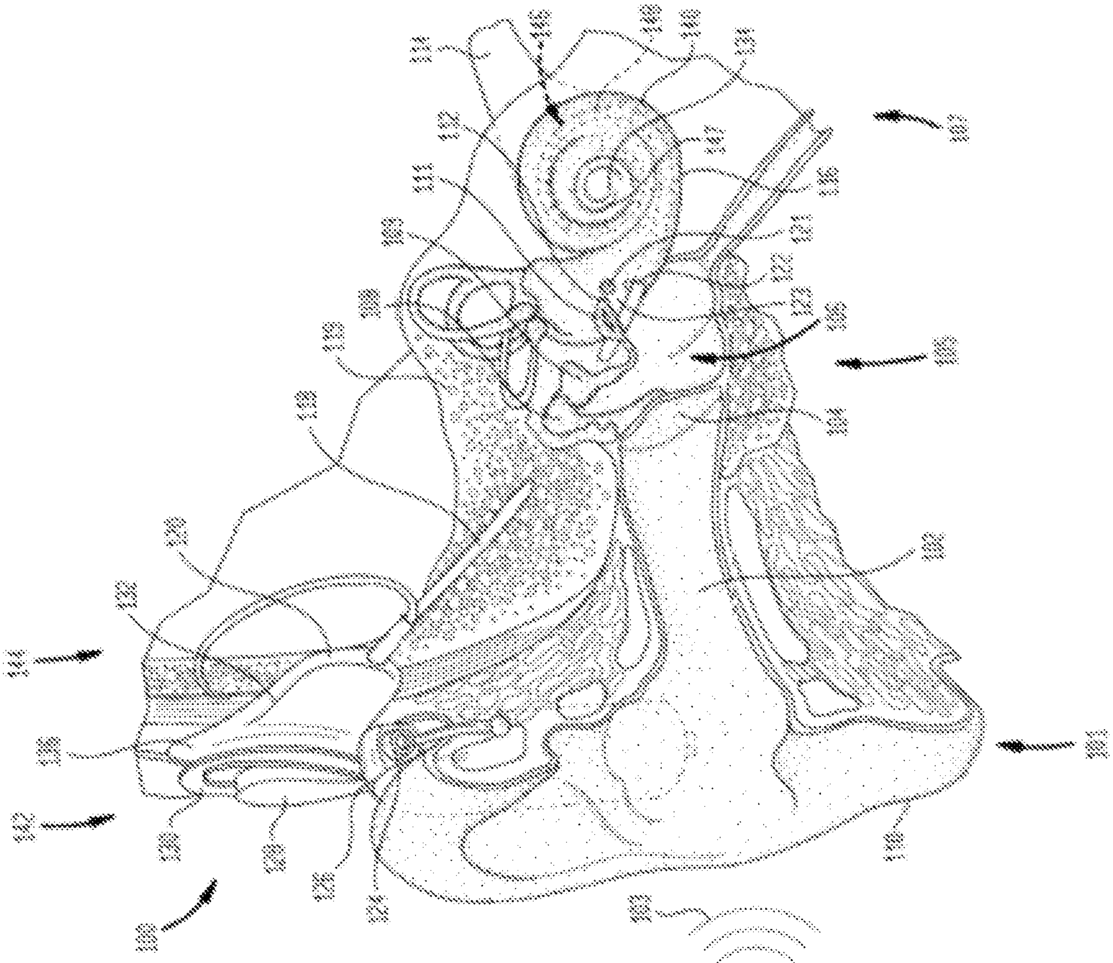


FIG. 1A:

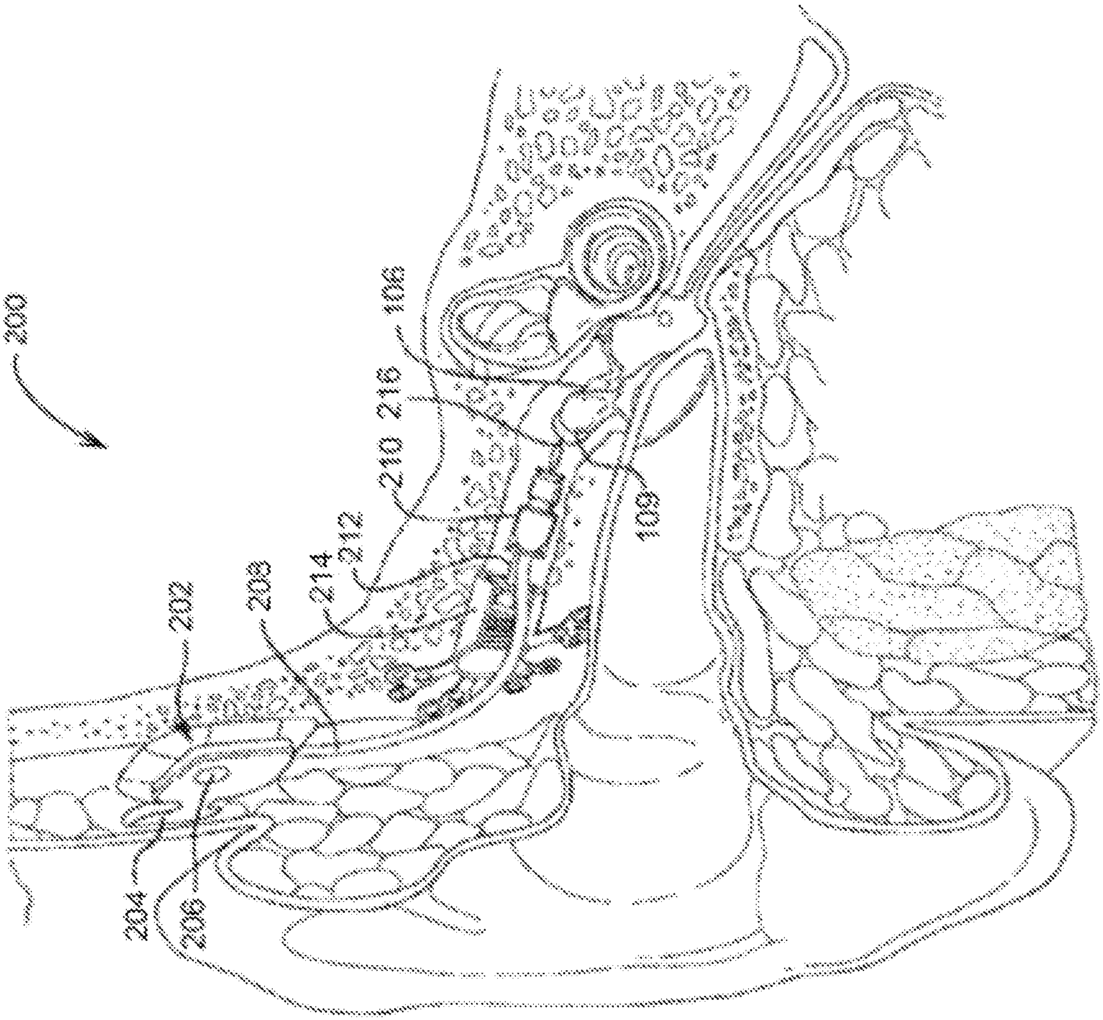


FIG. 1B:

FIG. 2A:

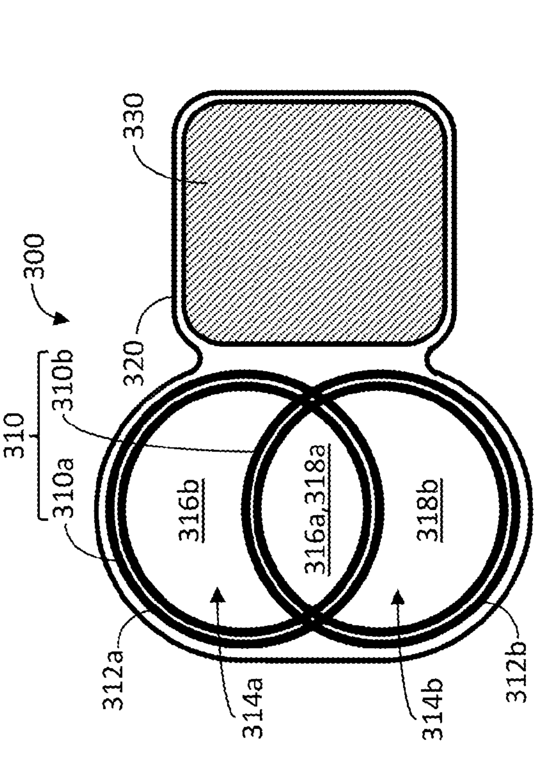


FIG. 2B:

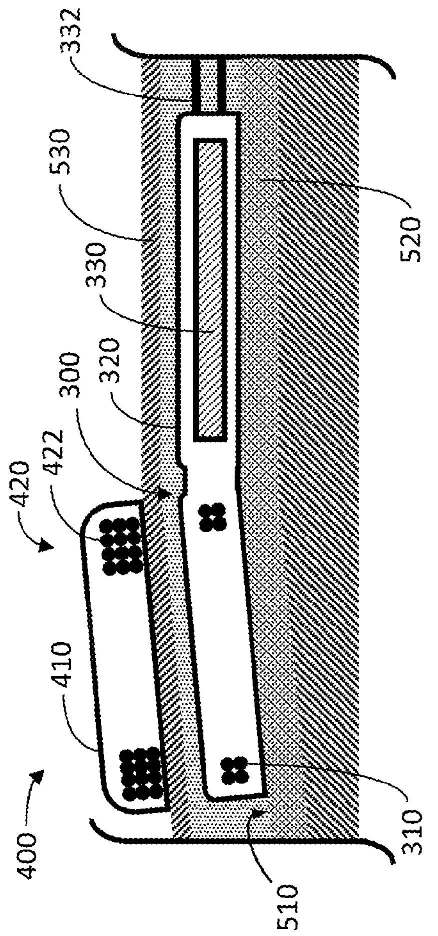


FIG. 2C:

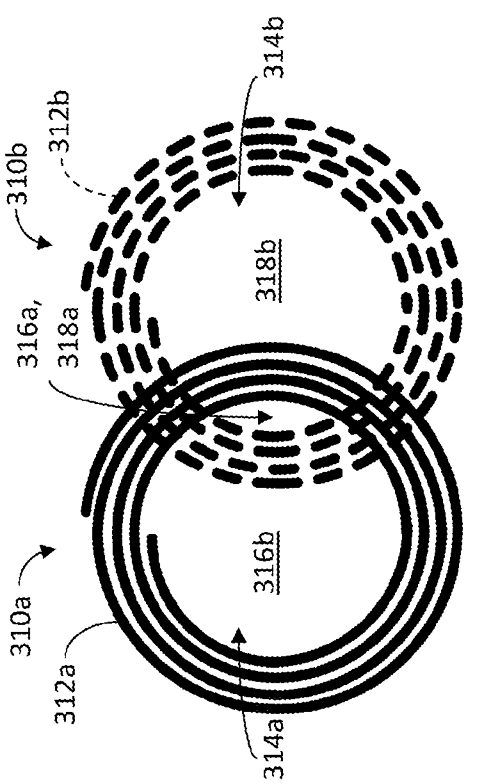


FIG. 2D:

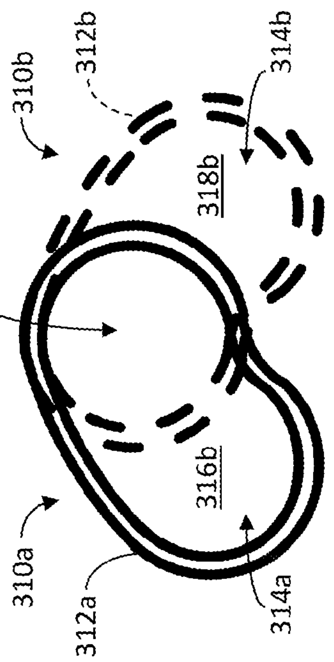


FIG. 3B:

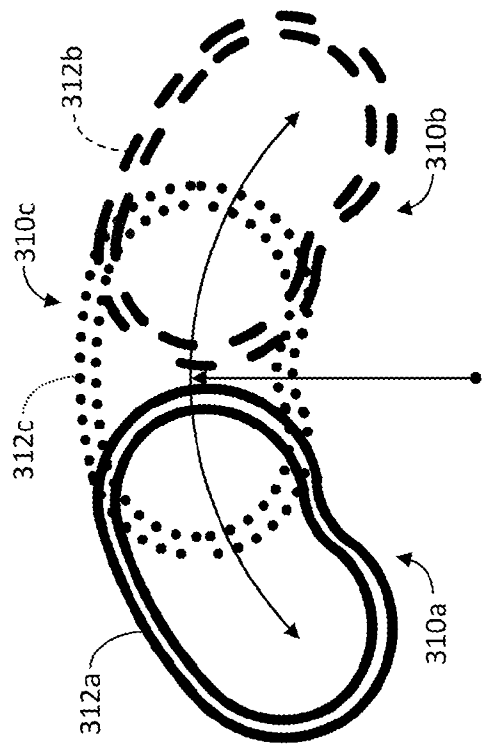


FIG. 3A:

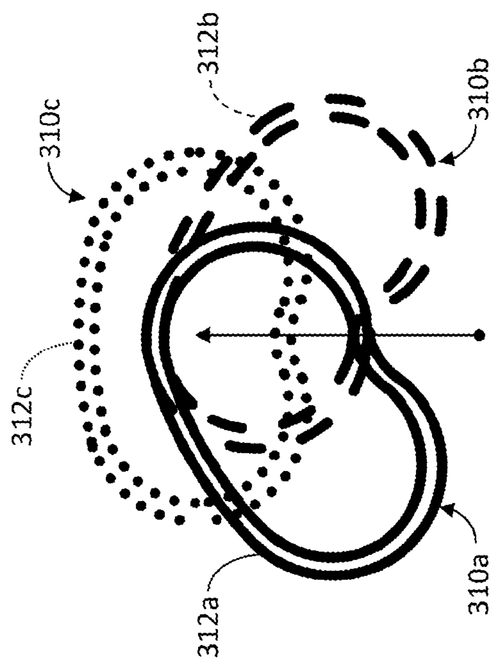


FIG. 3C:

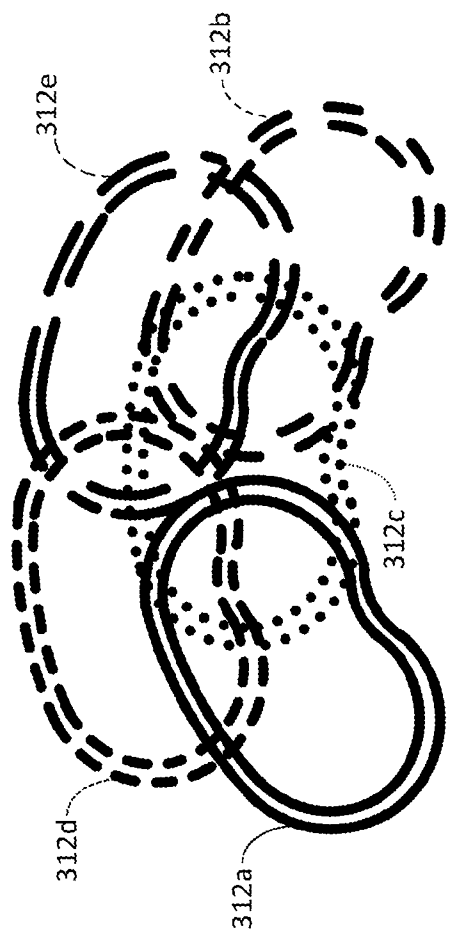


FIG. 4:

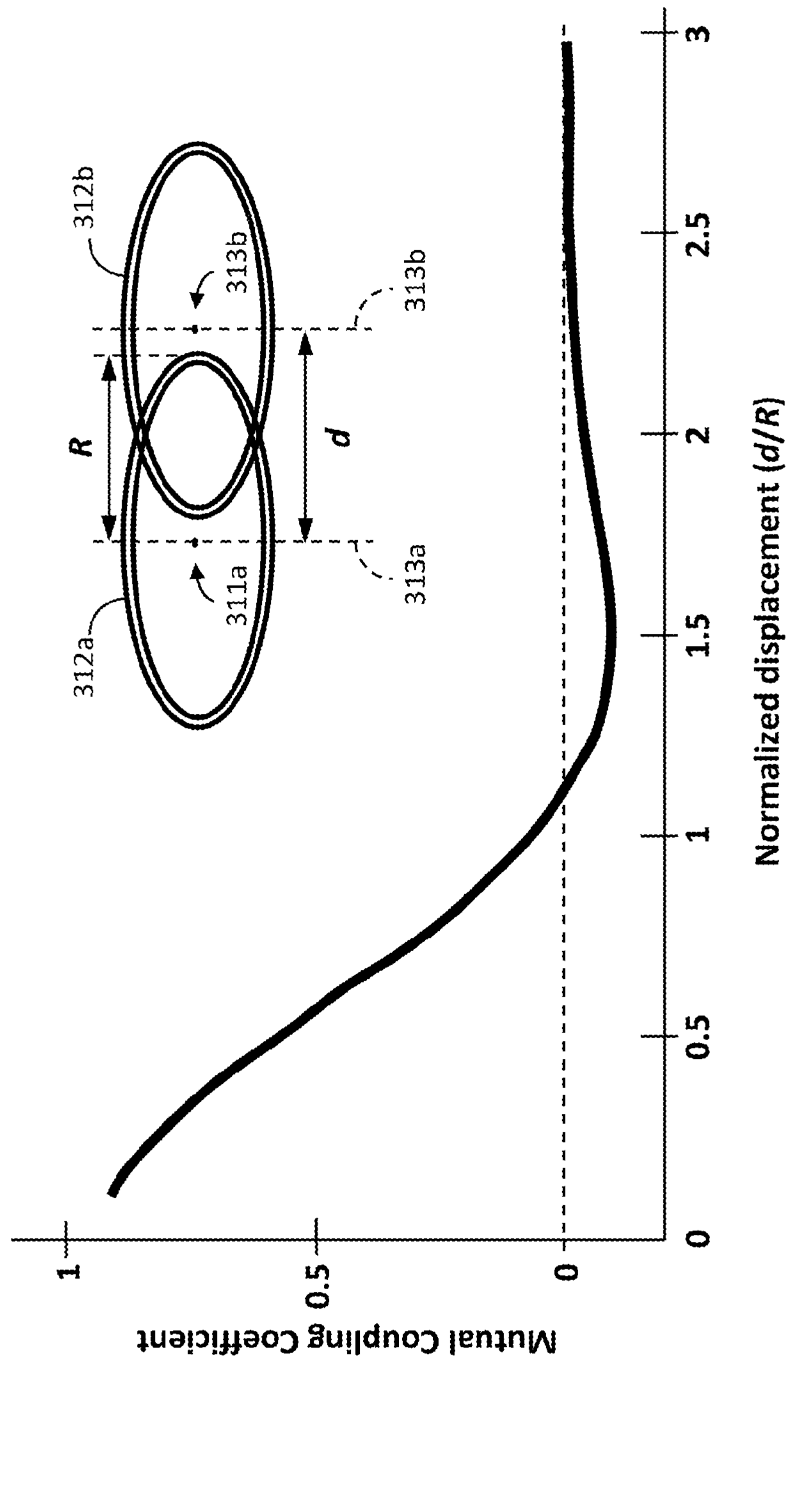

312a
312b
311a
313a
313b
313b
R
d
Mutual Coupling Coefficient
1
0.5
0
Normalized displacement (d/R)
0
0.5
1
1.5
2
2.5
3

FIG. 5A:

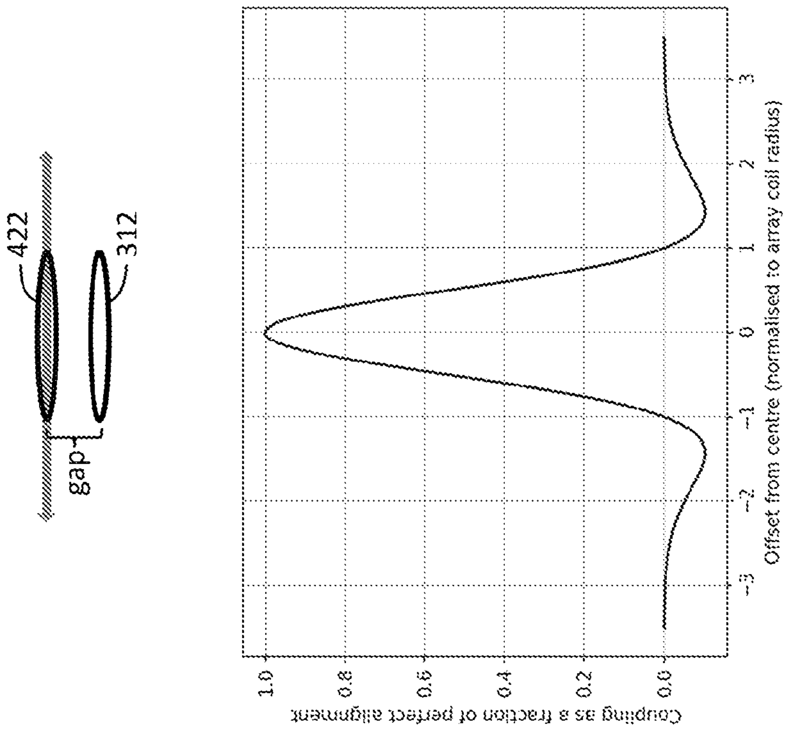
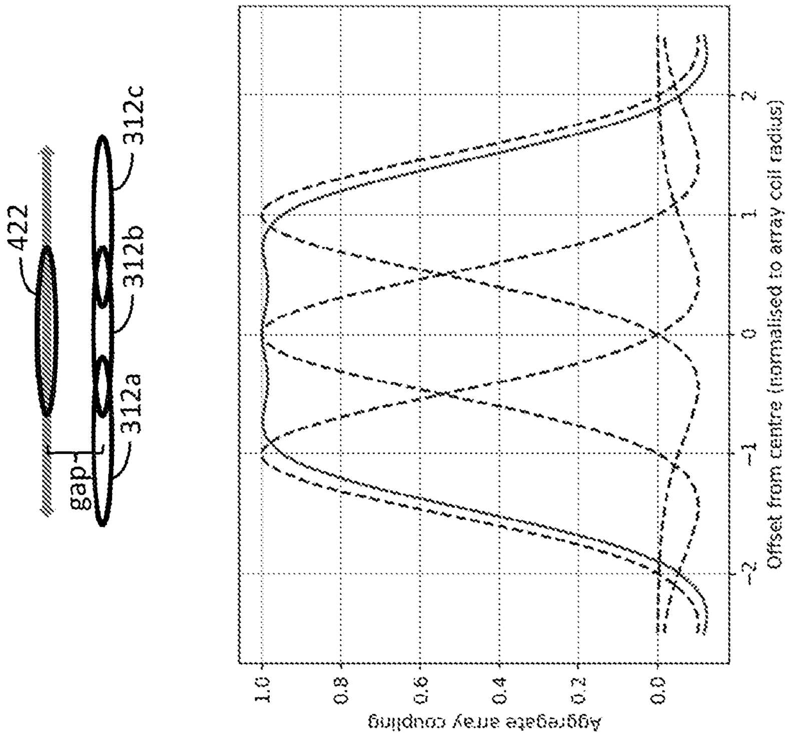

422
312
gap
Coupling as a fraction of perfect alignment
1.0
0.8
0.6
0.4
0.2
0.0
−3
−2
−1
0
1
2
3
Offset from centre (normalised to array coil radius)

FIG. 5B:


422
312a
312b
312c
gap
Aggregate array coupling
1.0
0.8
0.6
0.4
0.2
0.0
−2
−1
0
1
2
Offset from centre (normalised to array coil radius)

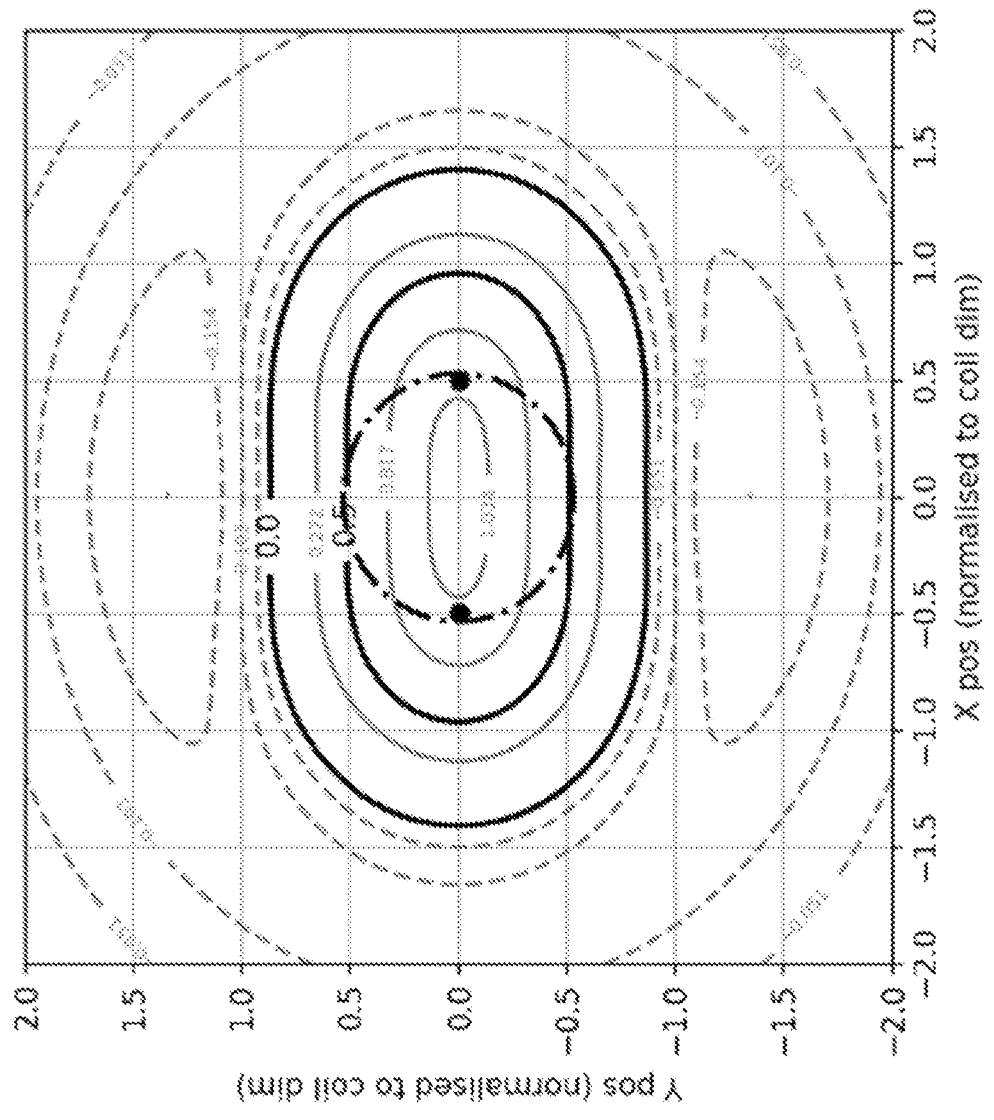
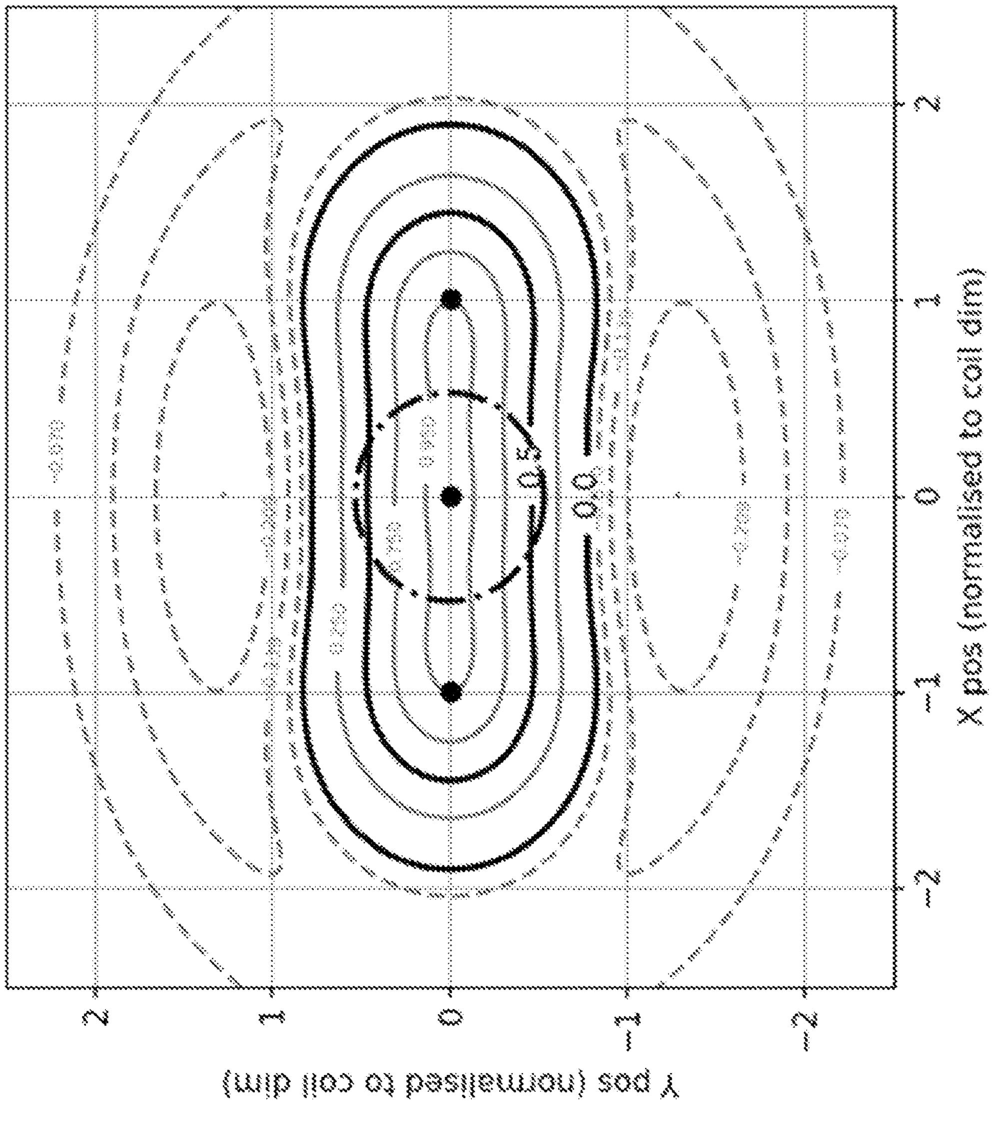

X pos (normalised to coil dim)
Y pos (normalised to coil dim)
−2.0 −1.5 −1.0 −0.5 0.0 0.5 1.0 1.5 2.0
2.0 1.5 1.0 0.5 0.0 −0.5 −1.0 −1.5 −2.0
0.0
0.5

FIG. 6A:

FIG. 6B:


X pos (normalised to coil dim)
Y pos (normalised to coil dim)
−2
−1
0
1
2
0.0
0.5

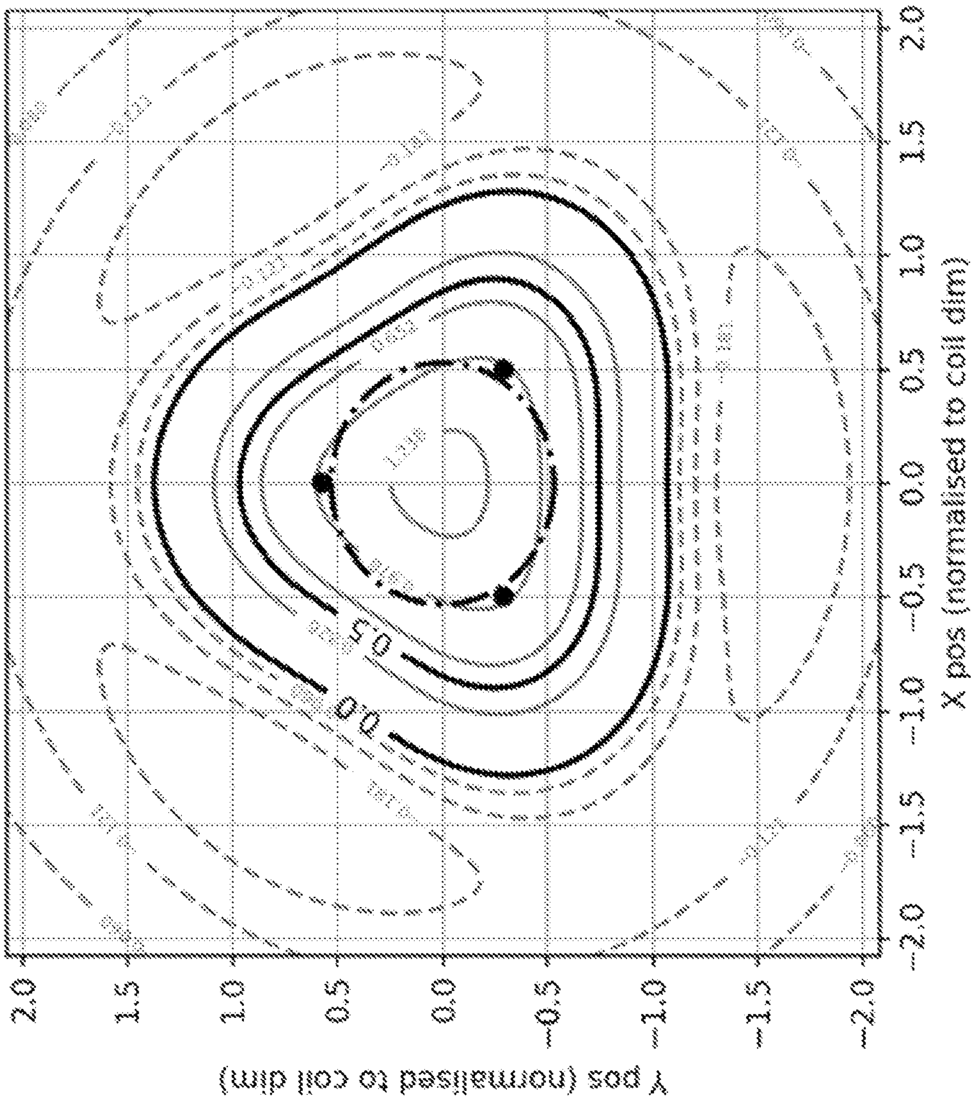

X pos (normalised to coil dim)
Y pos (normalised to coil dim)
0.0
0.5

FIG. 6C:

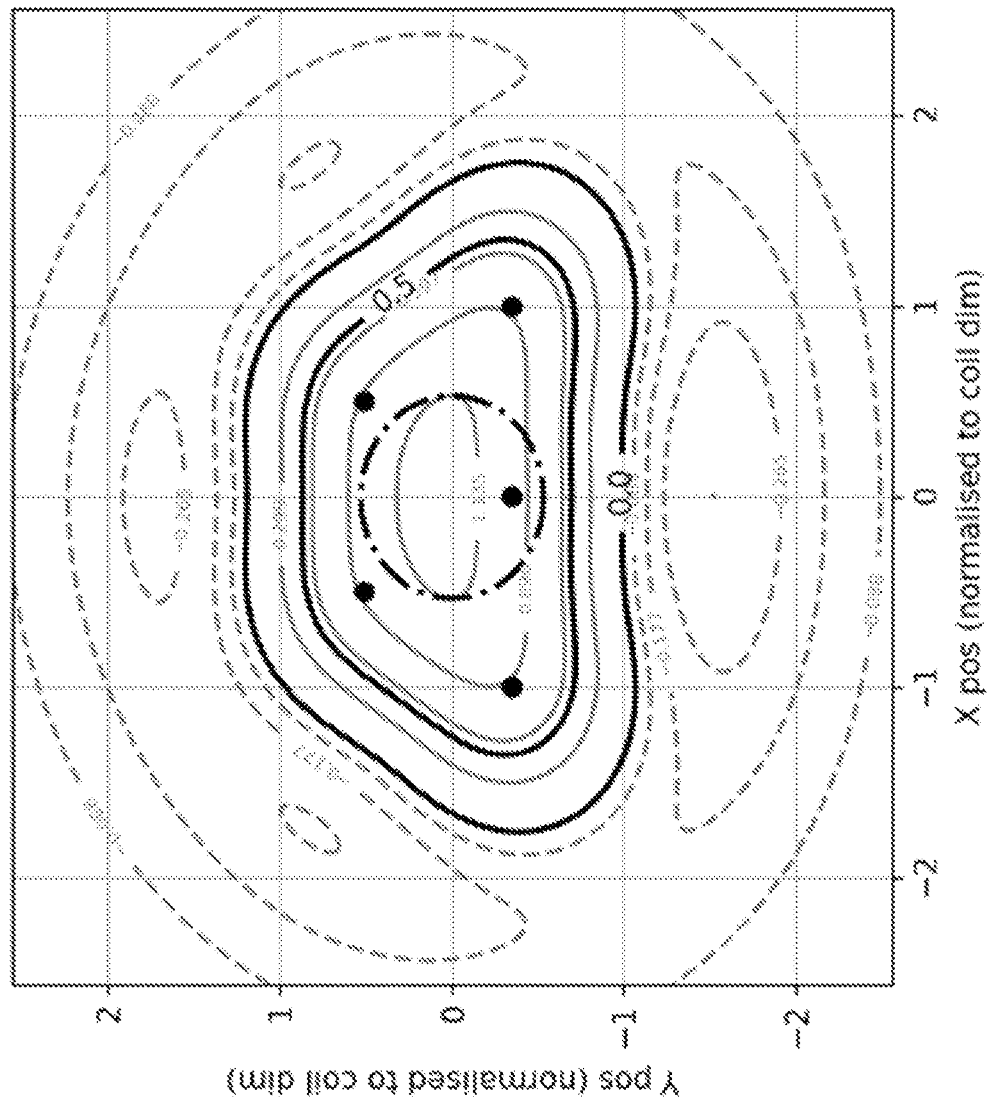

0.5
0.0
X pos (normalised to coil dim)
Y pos (normalised to coil dim)
−2
−1
0
1
2

FIG. 6D:

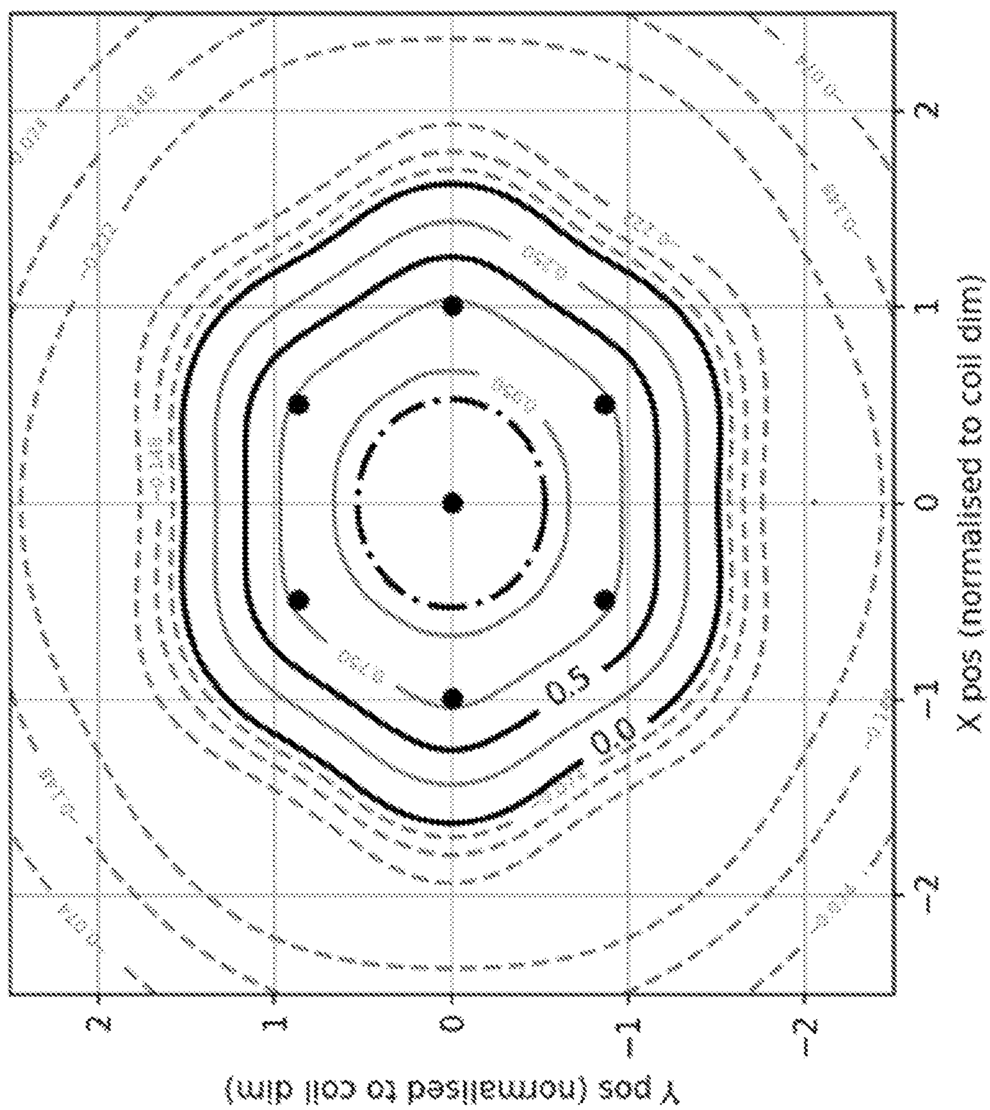

X pos (normalised to coil dim)
Y pos (normalised to coil dim)
−2
−1
0
1
2
0.5
0.0

FIG. 6E:

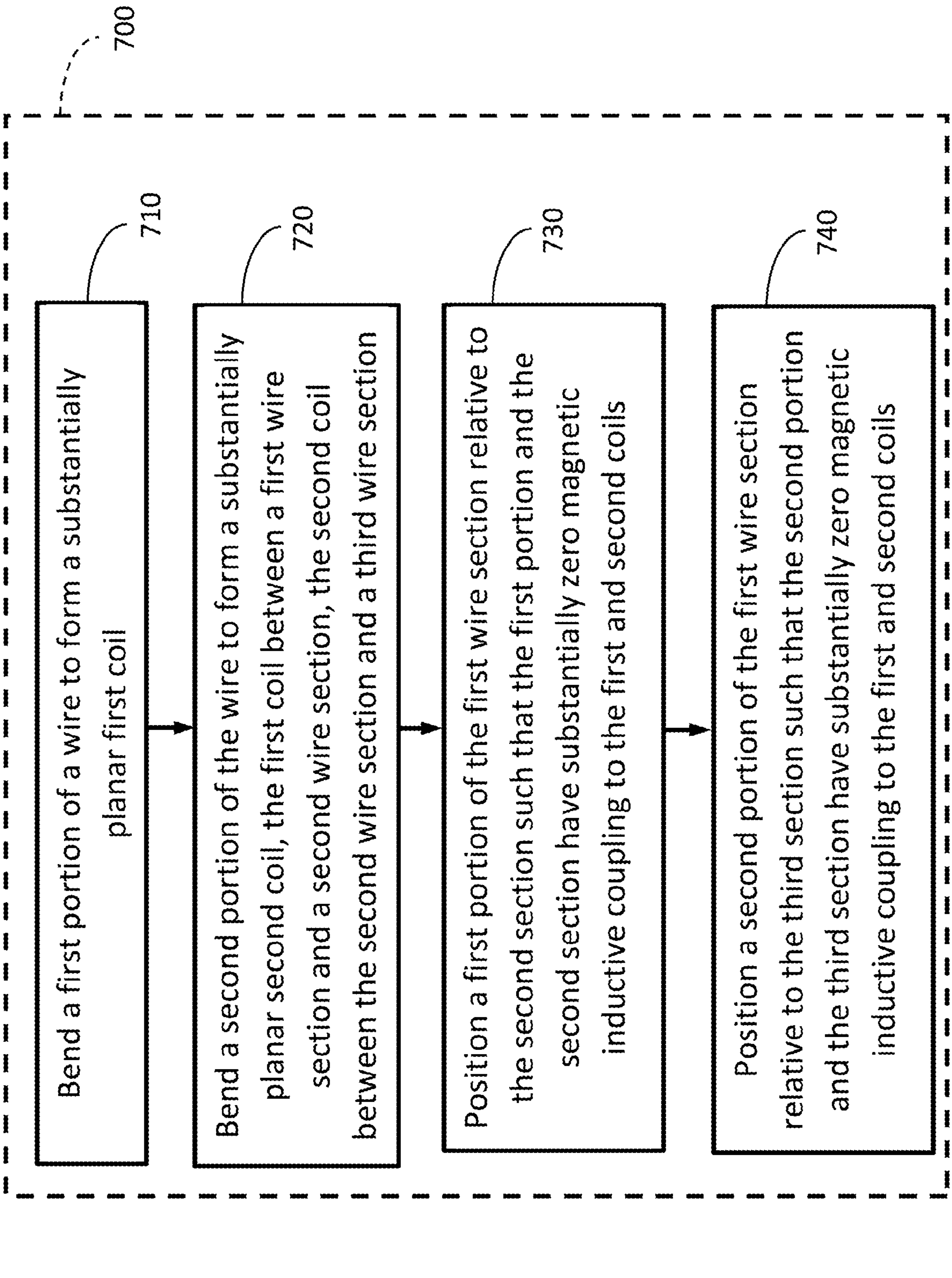

700
710
Bend a first portion of a wire to form a substantially planar first coil
720
Bend a second portion of the wire to form a substantially planar second coil, the first coil between a first wire section and a second wire section, the second coil between the second wire section and a third wire section
730
Position a first portion of the first wire section relative to the second section such that the first portion and the second section have substantially zero magnetic inductive coupling to the first and second coils
740
Position a second portion of the first wire section relative to the third section such that the second portion and the third section have substantially zero magnetic inductive coupling to the first and second coils

FIG. 7:

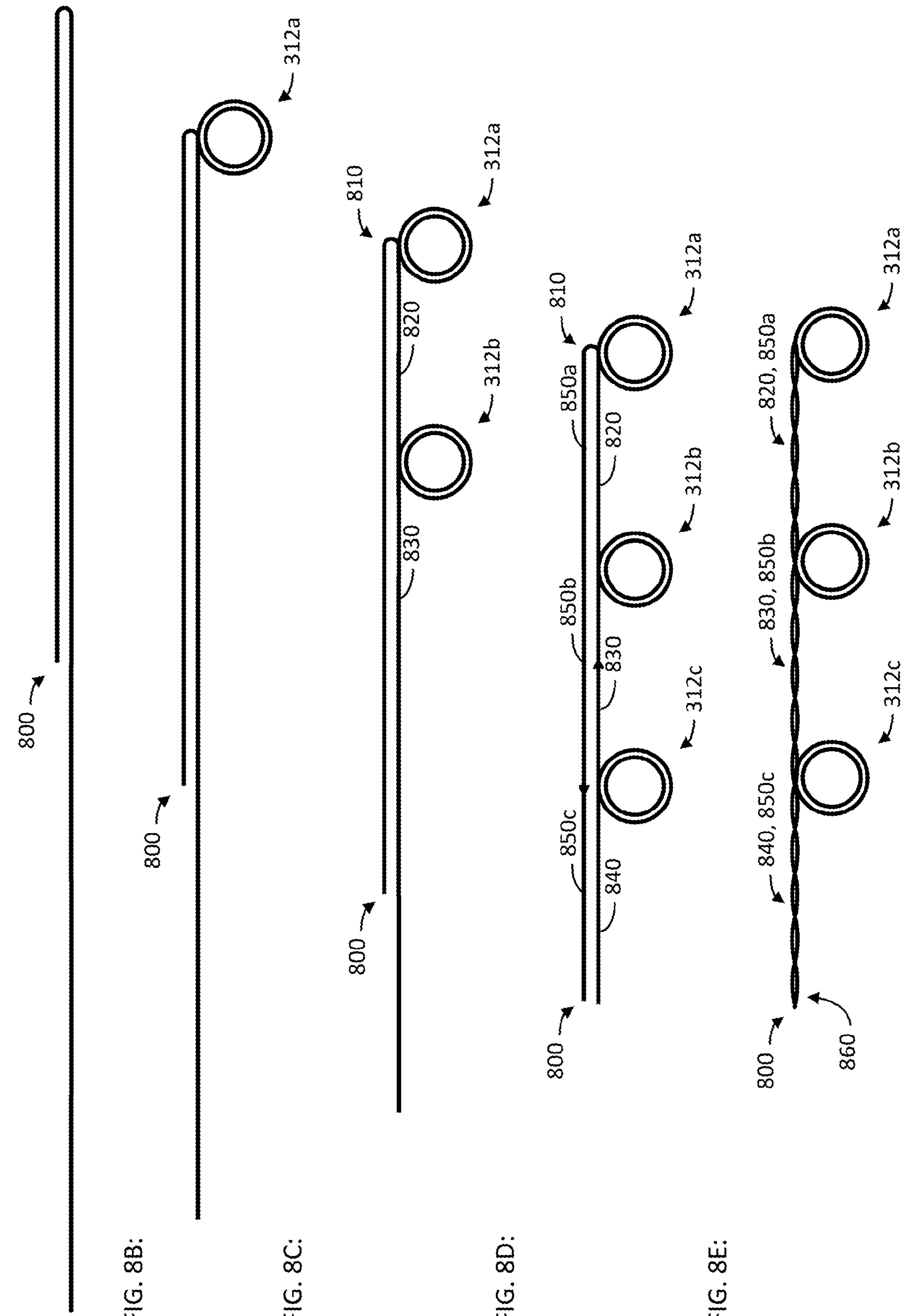


FIG. 8A:

FIG. 8B:

FIG. 8C:

FIG. 8D:

FIG. 8E:

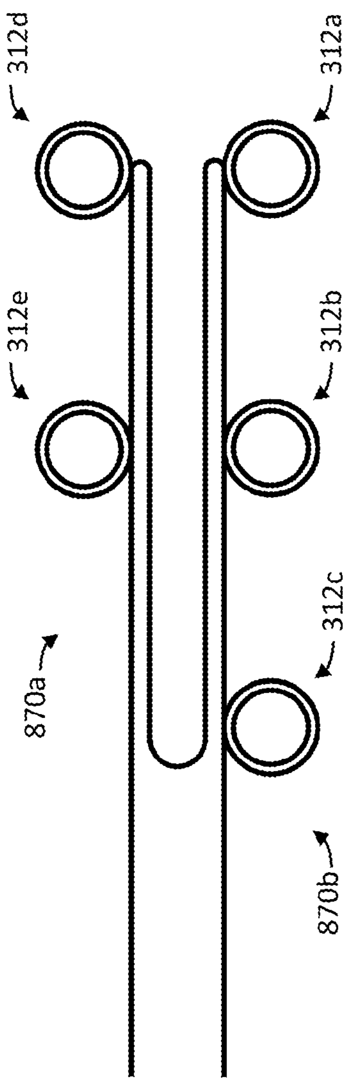


FIG. 9A:

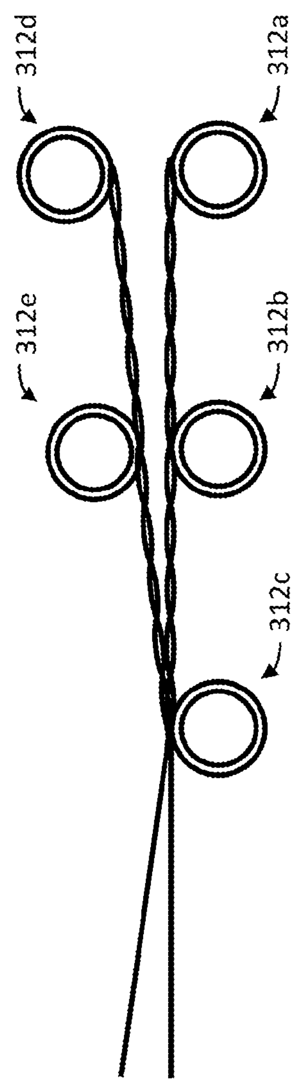


FIG. 9B:

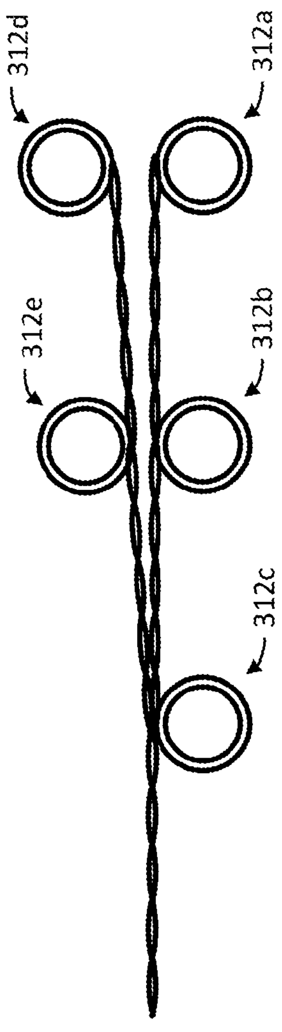


FIG. 9C:

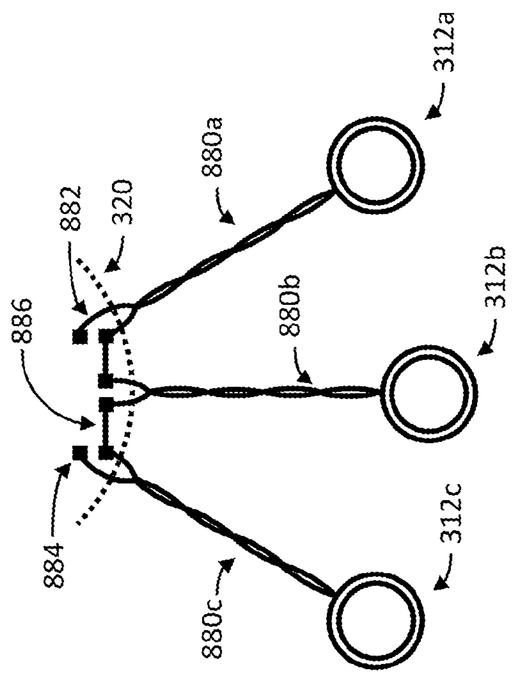


FIG. 10:

FIG. 11A:

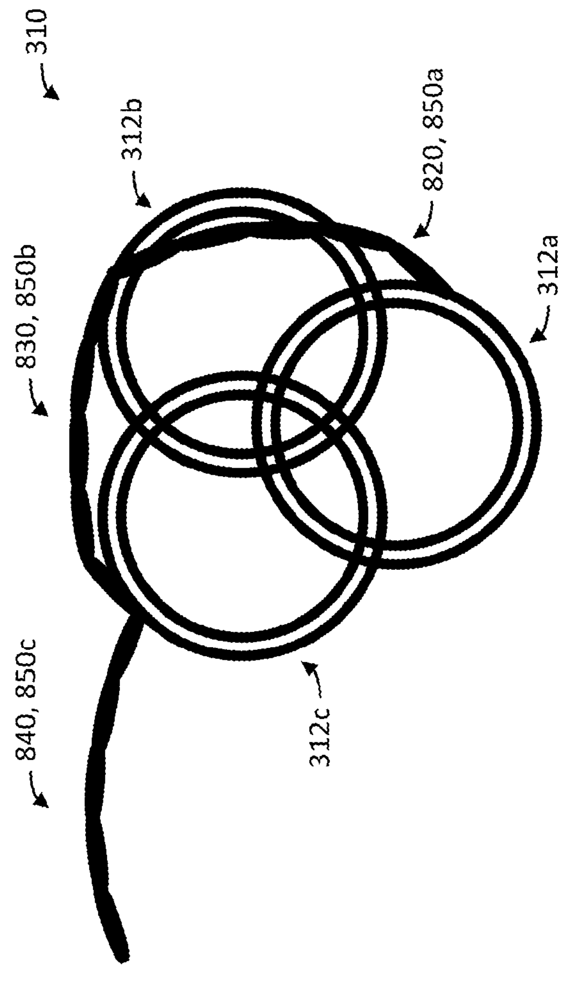


FIG. 11B:

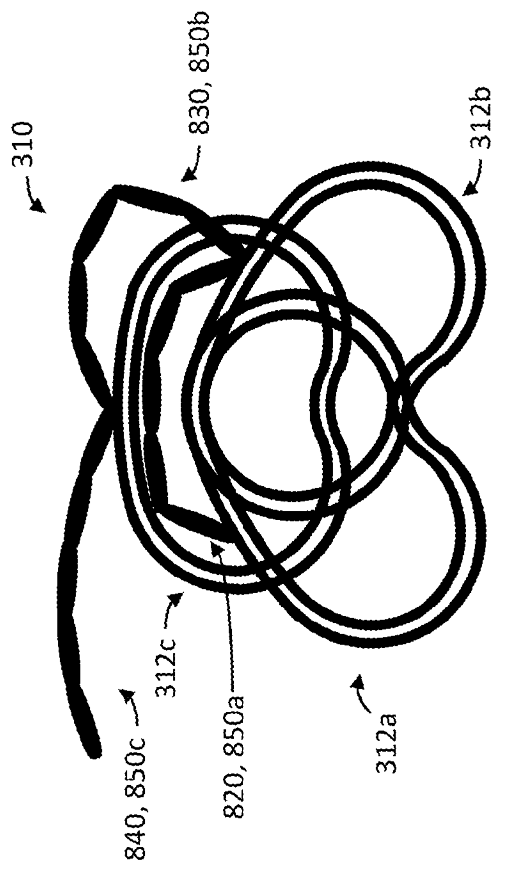


FIG. 12A:

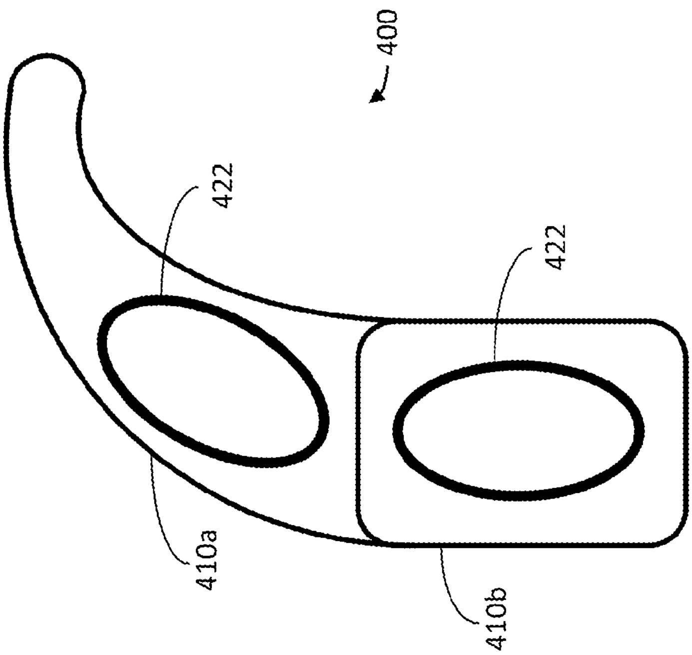
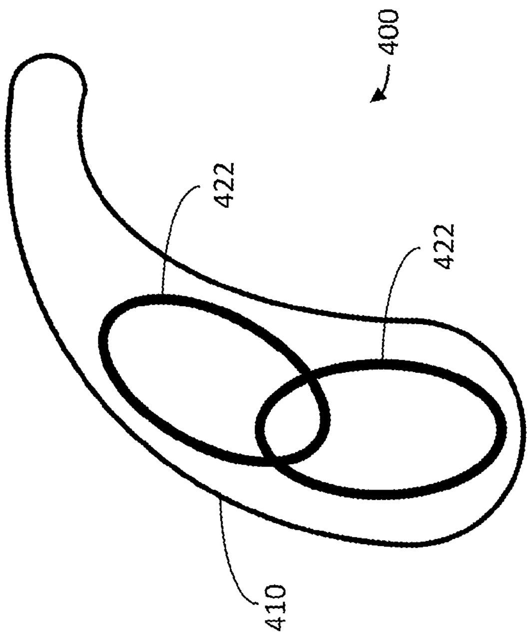


FIG. 12B:



INTERNATIONAL SEARCH REPORT

International application No.
PCT/IB2024/059081

A. CLASSIFICATION OF SUBJECT MATTER

A61N 1/372(2006.01)i; **A61N 1/378**(2006.01)i; **A61N 1/36**(2006.01)i; **H04B 5/79**(2024.01)i; **H04B 5/43**(2024.01)i; **H04B 5/26**(2024.01)i

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)

A61N 1/372(2006.01); A61F 2/48(2006.01); A61M 1/12(2006.01); A61N 1/08(2006.01); A61N 1/36(2006.01); A61N 1/378(2006.01); H04R 25/00(2006.01)

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

Korean utility models and applications for utility models
Japanese utility models and applications for utility models

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

eKOMPASS(KIPO internal) & Keywords: magnetic induction(MI), antenna, coil, planar, coupling coefficient, interference, conductive, parallel

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2023-170500 A1 (COCHLEAR LIMITED) 14 September 2023 (2023-09-14) claims 1-7; paragraphs [0042]-[0051]; figure 2A, 2B, 3H, 3I	1-27
A	WO 2014-145664 A1 (THORATEC CORPORATION) 18 September 2014 (2014-09-18) paragraphs [0087]-[0089], [0104]; figures 2, 10	1-27
A	US 2013-0096651 A1 (OZAWA, R. et al.) 18 April 2013 (2013-04-18) paragraphs [0004]-[0006], ; figures 1A-1C	1-27
A	WO 2009-023905 A1 (VENTRASSIST PTY LTD. et al.) 26 February 2009 (2009-02-26) pages 11-12; figures 1, 8, 9	1-27
A	WO 2009-143560 A1 (COCHLEAR LIMITED et al.) 03 December 2009 (2009-12-03) claim 1; figure 1	1-27

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

* Special categories of cited documents:
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"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
10 January 2025	**13 January 2025**

Name and mailing address of the ISA/KR	Authorized officer
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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/IB2024/059081

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)			Publication date (day/month/year)
WO	2023-170500	A1	14 September 2023	CN	118871168	A	29 October 2024
WO	2014-145664	A1	18 September 2014	US	10476317	B2	12 November 2019
				US	2014-0265621	A1	18 September 2014
				US	2017-0250575	A1	31 August 2017
				US	9680310	B2	13 June 2017
US	2013-0096651	A1	18 April 2013	CA	2848419	A1	18 April 2013
				CA	2848419	C	01 November 2016
				CA	2850226	A1	18 April 2013
				CA	2850226	C	20 December 2016
				EP	2766090	A1	20 August 2014
				EP	2766090	B1	08 February 2017
				EP	2766091	A1	20 August 2014
				EP	2766091	B1	21 December 2016
				JP	2014-528816	A	30 October 2014
				JP	2014-528817	A	30 October 2014
				JP	2016-032766	A	10 March 2016
				JP	6030738	B2	24 November 2016
				US	2013-0096652	A1	18 April 2013
				US	2016-0193472	A1	07 July 2016
				US	9314642	B2	19 April 2016
				US	9446254	B2	20 September 2016
				US	9849298	B2	26 December 2017
				WO	2013-055526	A1	18 April 2013
				WO	2013-055527	A1	18 April 2013
WO	2009-023905	A1	26 February 2009	None			
WO	2009-143560	A1	03 December 2009	US	2011-0137376	A1	09 June 2011
				US	8538545	B2	17 September 2013