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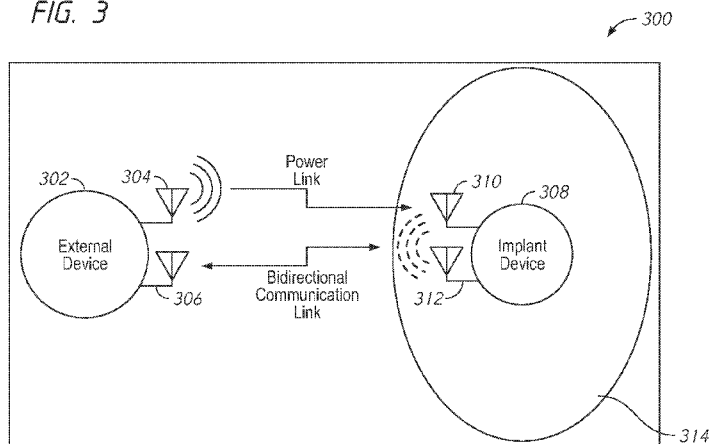
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FIG. 3



(57) Abstract: Examples described herein include dual-band antenna systems for implanted devices (e.g. chronic implanted neural recording and/or stimulation devices). The dual-band antenna systems, for example, may operate in a high frequency (HF) frequency range (e.g. 13.56 MHz) and a very high frequency (VHF) or an ultra high frequency (UHF) range (e.g. 400-460 MHz, 902-928 MHz, 2360-2390 MHz, and 2.4 GHz). Systems described herein generally include implant-side and external antennas. These antennas may be used to supply power to the implant via inductive coupling in the HF band, while data is transferred via VHF or UHF near-field coupling.

**ANTENNA ELEMENTS, IMPLANTED DEVICES, AND SYSTEMS FOR
COMMUNICATION WITH IMPLANTED DEVICES**

CROSS-REFERENCE TO RELATED APPLICATION(S)

- [001] This application claims the benefit under 35 U.S.C. § 119 of the earlier filing date of U.S. Provisional Application Serial No. 62/292,105 filed February 5, 2016, the entire contents of which are hereby incorporated by reference in their entirety for any purpose.

STATEMENT REGARDING RESEARCH & DEVELOPMENT

- [002] This invention was made with government support under EEC1028725 awarded by the National Science Foundation. The government has certain rights in the invention.

TECHNICAL FIELD

- [003] Embodiments of the invention relate generally to implanted biomedical devices, and examples of providing power and communication capability to implanted devices are described.

BACKGROUND

- [004] It is generally desired for implanted biomedical devices, such as those for chronic neural recording and/or stimulation devices, to remain powered over a long duration, and to communicate with an external system with sufficient bandwidth. The small volume, small available power budget, and increasing bandwidth requirements for these devices can make their design challenging.
- [005] Some implanted devices may utilize a same communication band (e.g. frequency range) for wireless power transfer and data communication. This can be problematic in that it may increase the complexity of the implanted device, or require further circuitry to separate the received communication and power signals. In other cases, certain frequency ranges may have favorable characteristics for power delivery efficiency while other frequency ranges may permit wider communication bandwidth, such that choosing a single frequency range for both power and data communication may not yield optimal performance.

SUMMARY

- [006] Examples of apparatuses are described herein. An example apparatus includes a substrate, a first antenna supported on a side of the substrate, the first antenna comprising conductive traces at least partially defining a first antenna area, the first antenna configured for communication in a first frequency range. The example apparatus may further include a second antenna supported on the side of the substrate, the second antenna positioned within the first antenna area and configured for communication in a second frequency range. The example apparatus may further include a conductive material configured to provide a ground, the conductive material provided within the substrate, wherein the first antenna and the second antennas are in electrical communication with the conductive material using conductive interconnects through at least a portion of the substrate. The example apparatus may further include circuitry supported on a second side of the substrate, the circuitry in electrical communication with the conductive material using at least one conductive interconnect through at least another portion of the substrate.
- [007] In some examples, the first frequency range is within a high frequency (HF) frequency range and the second frequency range is within a very high frequency (VHF) or an ultra high frequency (UHF) range.
- [008] In some examples, the first antenna comprises a coil antenna and the second antenna comprises an annular resonator.
- [009] In some examples, the annular resonator is positioned within an area at least partially defined by the coil antenna.
- [010] In some examples, the substrate and the first and second antennas are configured to be implanted into biological tissue.
- [011] In some examples, the substrate comprises a multi-layer printed circuit board having a first layer of insulating material positioned between the side and the conductive material, and a second layer of insulating material positioned between the conductive material and the second side. In some examples, the conductive interconnects are provided through the first layer of insulating material and do not extend into the second layer of insulating material.
- [012] In some examples, the first antenna element includes a first feed contact and wherein the second antenna element includes a second feed contact, and wherein the second feed contact is positioned on a side of the second antenna element opposite a side closest to the first feed contact.

- [013] Examples of systems are described herein. An example system includes an external device comprising a dual-band external antenna comprising a first antenna element configured for operation in a first frequency range and a second antenna element configured for operation in a second frequency range, and an implanted device comprising an implanted antenna comprising a third antenna element configured for operation in the first frequency range and a fourth antenna element configured for operation in the second frequency range. The external device may be configured to power the implanted device using inductive coupling between the first antenna element and the third antenna element in the first frequency range, and the external device and the implanted device are configured to communicate data between the second antenna element and the fourth antenna element using near-field coupling in the second frequency range.
- [014] In some examples, the first frequency range comprises a high frequency (HF) frequency range and the second frequency range comprises a very high frequency or an ultra high frequency (UHF) frequency range.
- [015] In some examples, the first antenna element comprises a first coil antenna and the third antenna element comprises a second coil antenna. In some examples, the first coil antenna at least partially defines an area, and the second antenna element is positioned within the area. In some examples, the second coil antenna at least partially defines a second area, and the fourth antenna element is positioned within the second area.
- [016] In some examples, the second antenna element comprises a segmented loop antenna and the fourth antenna element comprises an annular split ring resonator.
- [017] In some examples, the third and fourth antenna elements are positioned on a same side of an implanted substrate.
- [018] In some examples, the implanted device is implanted in biological tissue and the first antenna element and the second antenna element are positioned a distance away from the biological tissue.
- [019] Examples of methods are described herein. An example method may include positioning an external device a distance from an implanted device, providing power to the implanted device from the external device using inductive coupling to a first antenna element of the implanted device in a first frequency band, and communicating data between the external device and the implanted device using near-field coupling to a second antenna element co-located with the first antenna element in a second frequency band.

[020] In some examples, providing power to the implanted device comprises providing power to the first antenna element on a substrate of the implanted device, and communicating data between the external device and the implanted device comprises using near-field coupling to the second antenna element positioned on the substrate of the implanted device and at least partially within an area defined by the first antenna element.

[021] In some examples, communicating data between the external device and the implanted device comprises bidirectional communication between the external device and the implanted device.

[022] In some examples, providing power to the implanted device comprises providing power to a pacemaker and communicating data between the external device and the implanted device comprises communicating pacemaker parameters.

[023] In some examples, providing power to the implanted device comprises providing power to a cochlear implant and communicating data between the external device and the implanted device comprises communicating signals representative of audio data.

[024] In some examples, providing power to the implanted device comprises providing power to a deep brain stimulator and communicating data between the external device and the implanted device comprises communicating signals representative of control instructions for the deep brain stimulator.

[025] In some examples, providing power to the implanted device comprises providing power to a nerve stimulator such as a vagus nerve stimulator and communicating data between the external device and the implanted device comprises communicating signals representative of control instructions for the nerve stimulator.

[026] In some examples, wherein communicating data between the external device and the implanted device comprises using backscatter communication.

BRIEF DESCRIPTION OF THE DRAWINGS

[027] FIG. 1 is a top-down view of an apparatus including antenna elements for an implanted device in accordance with examples described herein.

[028] FIG. 2 is a cross-section view of a substrate supporting antenna elements for an implanted device arranged in accordance with examples described herein.

[029] FIG. 3 is a schematic illustration of an example system arranged in accordance with examples described herein.

[030] FIG. 4 is a schematic illustration of a dual-band external antenna arranged in accordance with examples described herein.

[031] FIG. 5 is a schematic illustration of antenna placement in a system arranged in accordance with examples described herein.

[032] FIG. 6 is a schematic illustration of a matching network for external and implant antennas in accordance with examples described herein.

[033] FIG. 7 is a schematic illustration of a matching network for external and implant antennas in accordance with examples described herein.

DETAILED DESCRIPTION

[034] Certain details are set forth below to provide a sufficient understanding of embodiments of the invention. However, it will be clear to one skilled in the art that embodiments of the invention may be practiced without various of these particular details. In some instances, well-known circuits, control signals, timing protocols, communication components, and software operations have not been shown in detail in order to avoid unnecessarily obscuring the described embodiments of the invention.

[035] Examples described herein include dual-band antenna systems for implanted devices (e.g. chronic implanted neural recording and/or stimulation devices). The dual-band antenna systems, for example, may operate in a high frequency (HF) frequency range (e.g. 6.78 MHz or 13.56 MHz) and a very high frequency (VHF) or an ultra high frequency (UHF) range (e.g. 400-460 MHz, 902-928 MHz, 2360-2390 MHz, and 2.4 GHz). Systems described herein generally include implant-side and external antennas. These antennas may be used to supply power to the implant via inductive coupling in the HF band, while data is transferred via UHF near-field coupling.

[036] Typical examples of implanted devices may have a volume on the order of a few mm³ to a few cm³, which may be limited by allowable tissue displacement, and a power budget on the order of μ W to mW, which may be limited by tissue heating. The communication bandwidths required, for example in a neural recording or stimulation device, may increase with a number of supported electrodes; data rates into the 10s to hundreds of Mbps may be desired for high density probes with dozens of electrodes.

[037] For neural recording and stimulation in larger rodents or primates, or in humans, with implants in the approximately 1 cm³ volume class, transferring wireless power in the high

frequency (HF) range (e.g. 6.78 MHz or 13.56 MHz) may represent a good compromise between antenna size and efficiency. To support data rates in the 10s to hundreds of Mbps, a communication link in the very high frequency (VHF) and/or ultra high frequency (UHF) range (e.g. 400-460 MHz, 902-928 MHz, 2360-2390 MHz, and 2.4 GHz) may be used, as there may be limited bandwidth available in the HF range.

[038] In part to allow both an implanted and external device to support both frequency ranges (e.g. for power and communication) while being as compact as possible, examples described herein include dual-band integrated planar antenna elements.

[039] Examples of antenna structures for implanted devices described herein include a multi-layer (e.g. three layer) structure with an internal ground plane and "blind" or "buried" (e.g. "partial") vias. The term "blind via" often refers to the case where a via is used to interconnect two or more layers of a multi-layer structure without penetrating at least one of the outer layers of the structure. The term "buried via" often refers to the case where a via is used to interconnect two or more layers of a multi-layer structure without penetrating either of the outer layers of the structure. This stackup may allow implanted electronics to be placed on the back side of the substrate supporting the antenna elements, which may reduce and/or minimize the total volume of the implanted device. In some examples, antenna structures for an external device allow impedance matching components to be integrated on the back of a substrate supporting the external device's antenna elements.

[040] Figure 1 is a top-down view of an apparatus including antenna elements for an implanted device in accordance with examples described herein. Figure 1 illustrates implanted antenna 100 which includes first antenna element 102 at least partially defining antenna area 116, second antenna element 104, substrate 106, ground contact 108, feed contact 110, feed contact 112, and ground contact 114. The components shown in Figure 1 may be re-arranged in other examples, and in some examples, additional, different, and/or fewer components may be used.

[041] Example apparatuses described herein such as the apparatus of Figure 1 may include a substrate, such as the substrate 106. Generally, the substrate may support antenna elements described herein. The antenna elements may be supported by the substrate, for example, by being deposited on and/or manufactured in the substrate 106. In some examples, printed circuit and/or semiconductor manufacturing techniques including, but not limited to, deposition and etch techniques may be used to form antenna elements on a surface of the

substrate 106. Examples of substrates which may be used herein include, but are not limited to, silicon substrates and multi-layer printed circuit boards.

[042] Examples described herein generally include at least two antenna elements supported by the substrate 106. As shown in Figure 1, first antenna element 102 and second antenna element 104 are supported by the substrate 106. The first antenna element 102 is designed for communication in a first frequency range - e.g. the antenna dimensions, layout, and materials, are selected for use in the first frequency range. The second antenna element 104 is designed for communication in a second frequency range - e.g. the antenna dimensions, layout, and materials, are selected for use in the second frequency range. In some examples, the first and second frequency ranges are different. In some examples, there may be overlap between the first and second frequency ranges. In some examples, the first frequency range may be, and/or be within, a high frequency (HF) frequency range and the second frequency range may be, and/or be within, a very high frequency (VHF) and/or ultra high frequency (UHF) frequency range. Other frequency ranges may also be used.

[043] The first antenna element 102 may be implemented using conductive traces (e.g. paths of conductive material). In some examples, the first antenna element 102 may be implemented using a coil antenna, such as a spiral HF coil antenna when the HF frequency range may be used. The conductive traces may at least partially define an antenna area 116. For example, the conductive traces may outline at least portions of the antenna area 116 which may be a generally circular area bounded by conductive traces forming the first antenna element 102.

[044] The second antenna element 104, which may be implemented using an annular resonator, such as an annular split ring resonator, may be positioned within an area at least partially defined by the first antenna element 102, which may be implemented using a coil antenna. The second antenna element 104 may be positioned within the antenna area 116. For example, the second antenna element 104 may be supported by a portion of the substrate located in the antenna area 116. In this manner, a total substrate area required to support the first antenna element 102 and second antenna element 104 may be minimized and/or reduced.

[045] The first antenna element 102 may have feed contact 112 and ground contact 114 where the first antenna element 102 may be coupled to other portions of the device including the implanted antenna 100. The feed contact 112 and ground contact 114 may in some examples refer to a location of conductive traces forming the first antenna element 102 where

such connections are made. In some examples, conductive pads, pins, terminals, and/or other structures may be used to implement feed contact 112 and/or ground contact 114.

[046] The second antenna element 104 may have ground contact 108 and feed contact 110 where the second antenna element 104 may be coupled to other portions of the device including the implanted antenna 100. The feed contact 110 and ground contact 108 may in some examples refer to a location of conductive traces forming the second antenna element 104 where such connections are made. In some examples, conductive pads, pins, terminals, and/or other structures may be used to implement ground contact 108 and/or feed contact 110.

[047] Figure 2 is a cross-section view of a substrate supporting antenna elements for an implanted device arranged in accordance with examples described herein. The device 200 includes substrate 202, antenna element 204, conductive material 206, circuitry 208, insulating material 210, insulating material 212, through-via 214, and partial via (sometimes called "blind" or "buried" via) 216. The components may be rearranged in some examples. Additional, fewer, and/or different components may be used in other examples. In some examples, the device 200 may be a cross-section of the implanted antenna 100 structure shown in Figure 1.

[048] Generally, the cross-section shown in Figure 2 may be representative of the cross-sectional structure of example antennas for implanted devices described herein. Antenna elements (e.g. two antenna elements designed for two different frequency ranges and which may be concentrically disposed, such as first antenna element 102 and second antenna element 104 of Figure 1) may be provided on a first side of a substrate. For example, a cross-sectional portion of the antenna element 204 is shown in Figure 2 on a side of the substrate 202. Circuitry, for example, a cross-sectional portion of circuitry 208 is shown in Figure 2, may be provided on an opposite side of the substrate 202. Conductive material 206 may be provided in the substrate 202. The conductive material 206 may, for example, provide a ground which may aid in shielding operations of the antenna elements from operation of the circuitry, such as the antenna element 204 and circuitry 208. The conductive material 206 may be provided, for example as a layer, which may be a patterned layer allowing some through-vias to pass through the substrate without contact to the conductive material 206.

[049] Connections may be made between antenna elements (e.g. Antenna element 204) and the conductive material 206 using vias which extend between the side of the substrate

containing the antenna element and the conductive material 206. Generally, vias may be formed in the substrate and filled with a conductive material such as a plated metal to form an electrical interconnect.

[050] In an analogous manner, connections may be made between circuitry (e.g. Circuitry 208) and the conductive material 206 using vias which extend between the side of the substrate containing the circuitry and the conductive material 206. Generally, vias may be formed in the substrate and filled with a conductive material such as a plated metal to form an electrical interconnect.

[051] For example, the partial via 216 is shown in Figure 2 filled with a conductive material, forming a conductive interconnect which may extend between circuitry 208 and conductive material 206. The partial via 216 may be referred to as a "partial via" or a "blind via" because it does not extend through an entire cross-section of the substrate 202. Instead, the partial via 216 extends between one side of the substrate and the conductive material 206.

[052] In some examples, the use of partial vias may aid in shielding operation of antenna elements on one side of a substrate from the operation of circuitry on an opposite side of the substrate. In some examples, the use of partial vias may prevent unwanted intrusion of a via into an antenna structure on one or both sides of the substrate.

[053] Some interconnections, however, may be made using through-vias, such as through-via 214, which extend through the substrate 202. The through-via 214 may be filled with a conductive material, such as a plated metal, forming a conductive interconnect connecting the antenna element 204, conductive material 206, and circuitry 208 at a single location.

[054] In some examples, a partial via at one location may be used to connect the circuitry 208 and conductive material 206, such as the partial via 216. Accordingly, a conductive interconnect may be formed between the conductive material 206 and circuitry 208 at one location in the substrate. While not explicitly shown in Figure 2, in some examples, a partial via in another location may be used to connect antenna element 204 and conductive material 206. Accordingly, another conductive interconnect may be formed between antenna element 204 and conductive material 206 at a different location in the substrate from the location of partial via 216. Separation of the connection between the antenna element 204 and conductive material 206 from the connection between the circuitry 208 and conductive material 206 may aid in shielding the operation of antenna element 204 and circuitry 208 from interference with one another.

[055] The substrate 202 may be implemented using any materials and techniques described herein for provision of substrates, including multi-layer printed circuit board materials. In some examples, the substrate 202 includes layers of insulating material, e.g. insulating material 210 and insulating material 212. The insulating material 210 may be provided between a side of the substrate 202 supporting antenna elements and the conductive material 206 providing a ground. The insulating material 212 may be provided between a side of the substrate 202 supporting circuitry and the conductive material 206. While two layers of insulating material are shown in Figure 2, any number may be used in other examples. Partial vias described herein may extend through fewer than all insulating layers provided. For example, the partial via 216 (and therefore a conductive interconnect formed by filling the partial via 216) does not extend into insulating material 210. Partial via 216 extends only through insulating material 212. In some examples, an insulating material may be chosen for favorable dielectric properties, such as a particular dielectric constant, or a low loss tangent. In some examples, a relatively high dielectric constant such as above two may be desirable to reduce the size of an antenna by concentrating an electric field in the insulating material. In some examples, a low loss tangent may be desirable to minimize the power loss or communication signal loss caused by dielectric losses. Some examples of suitable insulating materials include an epoxy fiberglass laminate, a polytetrafluoroethylene (PTFE) laminate, a Teflon laminate, a layer of ceramic material, an aluminum oxide (alumina) material, or composite materials formed of combinations of such materials. In some examples, an insulating material such as FR4, Rogers Corp. RO4003, Rogers Corp. RO4350, or other materials such as low temperature co-fired ceramic (LTCC) materials as are available from DuPont Corp may be used.

[056] The conductive material 206 may be implemented using generally any conductive material and may provide a ground to the antenna elements and/or circuitry provided on the substrate. In some examples, the conductive material 206 is compatible with multi-layer printed circuit board technology. For example, copper, aluminum, carbon, silver, nickel, or gold may be used. In some examples, electroplated gold may be used to passivate another metal such as copper. In some examples, electroless nickel immersion gold (ENIG) plating may be used. In some examples, a glassy carbon may be used as a conductive material. In some examples, the conductive material 206 may be a conductive layer of a multi-layer

printed circuit board. In some examples, the conductive material 206 may be a buried layer in a substrate. In some examples, the conductive material 206 may be patterned.

[057] Through vias and partial vias described herein may be filled with generally any conductive material suitable for making electrical contact, including, but not limited to aluminum, copper, silver, gold, carbon, titanium, or combinations thereof.

[058] Circuitry 208 may include any of a variety of circuit elements, including matching circuitry (which may include inductive and/or capacitive elements), data acquisition circuitry, power harvesting circuitry, communication circuitry, or combinations thereof.

[059] The substrate 202, including any antenna elements and circuitry supported by the substrate 202, may be implanted into biological tissue. Examples of implant locations include, but are not limited to, proximate to the surface of or within brain tissue, the inner surface of the dura, cardiac tissue, the nerves of the spinal cord, the vagus nerve, the peripheral nerves, the optic nerve, the retina, and auditory locations such as within or proximate to the cochlea or auditory nerve.

[060] Figure 3 is a schematic illustration of an example system arranged in accordance with examples described herein. The system 300 includes external device 302, which includes antenna element 304 and antenna element 306, implanted device 308, which includes antenna element 310 and antenna element 312, and biological tissue 314. The implanted device 308 may be implanted in biological tissue 314. The external device 302 may be external to the biological tissue 314. Power may be transferred from external device 302 to implanted device 308 using a power link between antenna element 304 and antenna element 310. Data may be communicated between the external device 302 and implanted device 308 using a bidirectional communication link between antenna element 306 and antenna element 312.

[061] The implanted device 308 may be implemented, or be used to implement, any implanted devices described herein, including those described and/or shown with reference to Figure 1 and Figure 2. For example, the antenna element 310 and antenna element 312 may be implemented using the first antenna element 102 and second antenna element 104 of Figure 1 in some examples. The implanted device 308 may be implemented, for example, using a pacemaker, a cochlear implant, a neural recording device, and/or a neural stimulation device.

[062] The external device 302 may generally have a dual-band external antenna which includes antenna element 304 and antenna element 306. The antenna element 304 may be

designed for operation in one frequency range (e.g. a high frequency (HF) range). The antenna element 306 may be designed for operation in another frequency range (e.g. a very high frequency (VHF) or an ultra high frequency (UHF) range).

[063] Recall the implanted device 308 may also include a dual-band antenna which may include antenna element 310 which may be designed for operation in the same frequency range as antenna element 304 (e.g. a high frequency (HF) range), and antenna element 312 which may be designed for operation in the same frequency range as antenna element 306 (e.g. a very high frequency (VHF) or an ultra high frequency (UHF) range).

[064] In this manner, the external device 302 may power the implanted device 308 using inductive coupling between antenna element 304 and antenna element 310 in the frequency range in which they are designed for operation (e.g. a high frequency (HF) range). The external device 302 and the implanted device 308 may communicate data between antenna element 306 and antenna element 312 using near-field coupling in the frequency range in which they are designed for operation (e.g. a very high frequency (VHF) or an ultra high frequency (UHF) range).

[065] The implanted device 308 may be implanted in biological tissue 314. Generally, the implanted device 308 may be implanted in any variety of biological tissue 314 including, but not limited to, brain, nervous system, vision system, auditory system, or heart tissue.

[066] The antenna structures, such as the antenna element 304 and antenna element 306, of the external device 302 may be positioned a distance away from the biological tissue 314. Generally, the distance may be a distance at which the inductive and/or near-field coupling described herein may occur.

[067] The external device 302 may include any of a variety of other components in communication with the antenna structures, including, but not limited to, memory, processor(s), input devices, output devices, batteries, or combinations thereof. In some examples, the external device 302 may form a unitary device with processing components in a same housing as antenna elements. In other examples, the antenna elements may be in communication, through wired or wireless communication techniques, with other components which may provide power and/or data storage and/or processing.

[068] Figure 4 is a schematic illustration of a dual-band external antenna arranged in accordance with examples described herein. The dual-band external antenna 400 includes antenna element 402, antenna element 404, feed contact 406, ground contact 408, ground

contact 410, and feed contact 412. The dual-band external antenna 400 may be used to implement and/or may be implemented by generally any external antenna described herein. For example, the dual-band external antenna 400 may be used to implement an antenna for the external device 302 of Figure 3.

[069] The antenna element 402 may be designed for operation in a first frequency range (e.g. a high frequency (HF) range). The antenna element 402 may be implemented by a coil antenna. Recall the antenna element 402 may be used to provide power through inductive coupling to an antenna element on an implanted device (e.g. First antenna element 102 of Figure 1), which may also be implemented using a coil antenna. A width of the traces used to implement the coil antenna, a number of turns, an inner-turn spacing, and an overall size of the coil antenna may be selected to improve and/or maximize efficiency between the antenna element 402 and an antenna element of the implanted device (e.g. First antenna element 102 of Figure 1) at an expected distance between the devices with an expected amount of tissue between them.

[070] The antenna element 402 may at least partially define an area (e.g. Antenna area 414). The antenna element 404 may be positioned within the antenna area 414. For example, a coil antenna may be used to implement antenna element 402 and conductive traces forming the coil antenna may at least partially define antenna area 414. The antenna element 404 may be positioned within the antenna area 414, which may generally conserve area for implementation of the dual-band external antenna 400.

[071] The antenna element 404 may be designed for operation in a second frequency range (e.g. a very high frequency (VHF) or an ultra high frequency (UHF) range). In some examples, as shown in Figure 4, the antenna element 404 may be implemented using a segmented loop antenna. The segmented loop antenna may be advantageous for several reasons. First, unlike a continuous loop where the circumference may be comparable to the guided wavelength, segmented loops may yield a relatively uniform H-field within the diameter of the loop. Moreover, because each segment of the loop may be separated by capacitors, the current induced in the UHF loop by the surrounding HF coil may be more easily managed. This may allow the unwanted interaction between the two concentric antenna elements to be reduced when compared to the alternative of a continuous (e.g. non-segmented) inner UHF loop.

- [072] The segmented loop antenna may generally be implemented using conductive traces forming segments of all or a portion of a loop. The segments may be separated by capacitive elements (e.g. capacitors). Recall the antenna element 404 may communicate data to and/or from implanted devices described herein using near-field coupling to an antenna element of the implanted device. For example, the antenna element 404 may communicate data to and/or from an implanted device by communicating with the second antenna element 104 of Figure 1, which may be implemented using an annular split ring resonator.
- [073] The antenna element 402 may have feed contact 412 and ground contact 410 where the antenna element 402 may be coupled to other portions of the device including the dual-band external antenna 400. The feed contact 412 and ground contact 410 may in some examples refer to a location of conductive traces forming the antenna element 402 where such connections are made. In some examples, conductive pads, pins, terminals, and/or other structures may be used to implement feed contact 412 and/or ground contact 410.
- [074] The antenna element 404 may have ground contact 408 and feed contact 406 where the antenna element 404 may be coupled to other portions of the device including the dual-band external antenna 400. The ground contact 408 and feed contact 406 may in some examples refer to a location of conductive traces forming the antenna element 404 where such connections are made. In some examples, conductive pads, pins, terminals, and/or other structures may be used to implement ground contact 108 and/or feed contact 110.
- [075] The antenna elements - e.g. antenna element 402 and antenna element 404 - may be supported by substrate 416. The substrate 416 may be implemented using any of a variety of substrates, including a silicon substrate and/or a printed circuit board substrate. In some examples, a two-layer printed circuit board substrate may be used. Circuitry (e.g. matching elements) may be positioned on an opposite side from a side of the substrate 416 used to support the antenna elements, which may promote a compact design of the overall dual-band external antenna 400.
- [076] During operation of systems described herein, such as the system 300 of Figure 3, an external device (e.g. the external device 302 of Figure 3) may be positioned a distance from an implanted device (e.g. the implanted device 308 of Figure 3). This may involve, for example, bringing an external device including antenna elements described herein into sufficient proximity of an implanted device to allow power and/or data transfer in accordance with examples described herein. Any electronic device may generally be used to implement

an external device and may include antenna elements described herein and provide the functionalities described. Example electronic devices include, but are not limited to, pacemaker controllers, laptops, tablets, and cellular phones.

[077] In some examples, all or portions of the external device (e.g. the antenna elements) may be in a unit which is generally positioned to remain in proximity with the implanted device (e.g. the external device may be a wearable device which may be worn in proximity to the implanted device). Examples include ear-worn or -mounted units containing antenna elements described herein which may be worn in proximity to an implanted device. Other examples of wearable external devices include wristbands, watches, hats, headbands, belts, necklaces, ankle bands, and shoe inserts.

[078] The external device may include a battery or other power source and may provide power to the implanted device using inductive coupling between an antenna element of the external device and an antenna element of the implanted device (e.g. between coil antennas as described herein). Power transfer may occur in a first frequency band (e.g. within a high frequency (HF) range).

[079] Data may be communicated between the external device (e.g. the external device 302) and the implanted device (e.g. the implanted device 308) using near-field coupling between an antenna element of the external device and an antenna element of the implanted device (e.g. between a segmented loop antenna and an annular resonator (such as an annular split ring resonator) as described herein). Data communication may occur in a second frequency band, different from the first frequency band used to provide power. For example, data communication may occur within a very high frequency (VHF) or an ultra high frequency (UHF) range. As described herein, the annular resonator (such as an annular split ring resonator) of the implanted device may be positioned within an area at least partially defined by the coil antenna of the implanted device on a substrate.

[080] In some examples, data communication between the external device 302 and the implanted device 308 may occur using low power communication techniques. For example, the implanted device 308 may include components for backscatter communication and may communicate data to the external device 302 by backscattering one or more carrier signals. The carrier signal may be provided by the external device 302 and/or may be an ambient carrier signal present in the environment. The external device 302 may have a receiver that receives and/or decodes the backscattered signal.

[081] Figure 5 is a schematic illustration of antenna placement in a system arranged in accordance with examples described herein. The system shown in Figure 5 includes a dual-band external antenna 502 positioned external to biological tissue 506. Implanted antenna 504 is implanted in biological tissue 506 and is depicted at or near an interface of bone with the tissue.

[082] Between the dual-band external antenna 502 and the implanted antenna 504 may be an air gap, which may in some examples be less than 10mm, less than 8mm in some examples, less than 6mm in some examples, less than 4mm in some examples. In some examples, the air gap may be 5mm. Other gap distances may be used in other examples. The skin, fat, and bone beneath which the implanted antenna 504 is implanted may also be between the dual-band external antenna 502 and implanted antenna 504. The skin, fat, and bone, may also have varying thicknesses (e.g. 2mm skin in some examples, 2mm fat in some examples, 7mm bone in some examples). It should be appreciated that not all of these layers of biological materials may be present in any given implant location and/or they may be disposed in a different sequence given the anatomy of the implant site.

[083] Figure 6 is a schematic illustration of a matching network for external and implant antennas in accordance with examples described herein. The external antenna 602 may be connected to a matching network connected between a feed contact 604 and ground contact 606. The implanted antenna 608 may be connected to a matching network connected between feed contact 610 and ground contact 612. The example of Figure 6 illustrates examples for antennas in the HF frequency range.

[084] For example, the external antenna 602 may be implemented using the antenna element 402 of Figure 4. The feed contact 604 may be implemented using the feed contact 412 of Figure 4, and the ground contact 606 may be implemented using the ground contact 410 of Figure 4.

[085] For example, the implanted antenna 608 may be implemented using the first antenna element 102 of Figure 1. The feed contact 610 may be implemented using the feed contact 112 of Figure 1. The ground contact 612 may be implemented using the ground contact 114 of Figure 1.

[086] The matching networks may include capacitive and/or inductive elements (e.g. capacitors and/or inductors). Lumped elements may be used in some examples which may in

some examples reduce a required board area compared to printed (e.g. microstrip) matching elements.

[087] Some or all of the elements used in the matching networks may be positioned on an opposite side of the substrate from the antenna elements, and may be connected to appropriate contacts of the antenna elements using through and/or partial vias.

[088] Figure 7 is a schematic illustration of a matching network for external and implant antennas in accordance with examples described herein. The external antenna 702 may be connected to a matching network connected between a feed contact 704 and ground contact 706. The implant antenna 708 may be connected to a matching network connected between feed contact 710 and ground contact 712. The example of Figure 7 illustrates examples for antennas in the VHF and/or UHF frequency range.

[089] For example, the external antenna 702 may be implemented using the antenna element 404 of Figure 4. The feed contact 704 may be implemented using the feed contact 406 of Figure 4, and the ground contact 706 may be implemented using the ground contact 408 of Figure 4.

[090] For example, the implant antenna 708 may be implemented using the second antenna element 104 of Figure 1. The feed contact 710 may be implemented using the feed contact 110 of Figure 1. The ground contact 712 may be implemented using the ground contact 108 of Figure 1.

[091] The matching networks may include capacitive and/or inductive elements (e.g. capacitors and/or inductors). Lumped elements may be used in some examples which may in some examples reduce a required board area compared to printed (e.g. microstrip) matching elements.

[092] Some or all of the elements used in the matching networks may be positioned on an opposite side of the substrate from the antenna elements, and may be connected to appropriate contacts of the antenna elements using through and/or partial vias.

[093] Systems and devices described herein may be used in a variety of applications. In some examples, neural stimulation and/or recording devices may be an implanted device provided with antenna elements described herein. An external device may include antenna elements described herein and may power the neural stimulation and/or recording device. Data may be communicated between the external device and the neural stimulation and/or

recording device (e.g. stimulation commands and/or neural recording data) using the antenna elements described herein.

[094] For example, a pacemaker may be an implanted device provided with antenna elements described herein. An external device (e.g. a pacemaker controller) may include antenna elements described herein and may be brought into proximity of the pacemaker to update and/or program the pacemaker. For example, power may be provided to the pacemaker and various pacemaker parameters may be communicated to the pacemaker from the external device using the antenna elements described herein.

[095] As another example, a cochlear implant may be an implanted device provided with antenna elements described herein. An external device may be worn in or around the ear and may be provided with antenna elements described herein. The external device may power the cochlear implant and may provide signals indicative of audio data to the cochlear implant.

[096] As a further example, a deep brain stimulator may be an implanted device provided with antenna elements described herein. Such a stimulator may be situated on the surface of the brain, on the inner or outer surface of the dura, or on the inner or outer surface of the skull. An external device may be worn on the outside of the scalp to provide power and control signals to the implanted device.

[097] As a still further example, a nerve stimulator may be an implanted device provided with antenna elements described herein. Such a stimulator may have one or more electrodes proximate to a nerve such as the vagus nerve. An external device may be worn or brought close to the outside of the body to provide power and control signals to the implanted device.

[098] In some or all of the aforementioned examples, it should be appreciated that the external device need not always be present. It should further be appreciated that the implanted device may have an energy storage element such as a battery, capacitor, supercapacitor, etc., which permits the implanted device to continue operating even when the external device is not present. In some examples, the energy storage element may be recharged via wireless power transfer from the external device when it is present.

IMPLEMENTED EXAMPLE

[099] A dual-band external antenna was designed for placement external to an outermost tissue layer as shown in Figure 5, with a nominal 5 mm air gap between the inner surface of

the external antenna and the outer surface of the skin. For modeling purposes, the skin and fat were considered to be of 2mm thickness, and the bone of 7mm thickness.

[0100] The dual-band external antenna was implemented as shown in Fig. 4, with a concentric arrangement of HF (outer annulus) and VHF/UHF (inner ring) antenna elements fabricated on a two-layer printed circuit, 85 mm in diameter with 2 mm thick FR-4 substrate and 2 oz copper traces. The antenna was laminated between 0.4 mm thick Teflon sheets, yielding overall dimensions of 85 mm diameter x 3 mm thickness.

[0101] The antenna element 402 of Fig. 4, designed for operation in the HF range, was implemented using a 4-turn continuous spiral loop with outer radius 41.6 mm and inner radius 29.8 mm. The trace width was 1.4 mm and the inter-turn spacing is 1.2 mm. These trace and space parameters were optimized using the frequency domain solver in CST Microwave Studio to maximize the efficiency from the external HF antenna to the implanted HF antenna, given the layered bio model of Figure 5 and the nominal 5 mm air gap.

[0102] The antenna element 404 of Fig. 4, designed for operation in the UHF range, was implemented using a segmented loop diameter of 42 mm, with trace width of 2 mm. Murata 36 pF lumped capacitors (part number GRM1555C1H360GA01D) were used between each of the 11 segments. The capacitor value was chosen by a parameter sweep in CST to yield a uniform current distribution by compensating the phase shift along the loop, which may lead to a more uniform H-field distribution while simultaneously suppressing the radiated E-field component and thus reducing the Specific Absorption Rate (SAR) in the adjacent tissue. Capacitor package parasitics were significant and thus included in the model when performing the parameter sweep. The lumped element matching networks shown in Figs. 6 and 7 were employed.

[0103] An implanted antenna was implemented as shown in Figures 1 and 2. The implanted antenna was laminated with 1 mm thick Teflon on the top and bottom of the stack, yielding a total size of 25 mm diameter and 3 mm thickness. The 25 mm diameter constraint was driven by a smallest dimension of a skull opening intended to be cut during interventional epilepsy surgeries.

[0104] The first antenna element 102 of Figure 1 was implemented using 3 turns with inner radius 9.6 mm, outer radius 12.1 mm, trace width 0.4 mm, and inter-turn spacing 0.3 mm. As with the external coil antenna, these parameters were chosen via optimization using CST's

frequency domain solver to maximize the efficiency given the lossy dielectrics of the layered bio model.

[0105] The second antenna element 104 of Figure 1 was implemented using an annular split ring resonator. The diameter of the ring was 14.6 mm, with an inner circular slot of 1.78 mm diameter. The ring was split along a radius with a split gap of 0.2 mm forming the feed point.

[0106] The time domain solver module in CST was used to calculate the specific absorption rate (SAR) at the implant site when the external antenna was driven with a maximum expected transmitter power of 20 dBm at a frequency of 915 MHz. From a SAR point of view, the regulatory limits may be driven by the UHF case, as tissue absorption at HF frequencies is much lower. The peak UHF SAR value was 0.457 W/kg in 1 g of average mass, which was well below the regulatory limit of 1.6 W/kg.

[0107] From the foregoing it will be appreciated that, although specific embodiments of the invention have been described herein for purposes of illustration, various modifications may be made without deviating from the spirit and scope of the invention.

CLAIMS

What is claimed is:

1. An apparatus comprising:

a substrate;

a first antenna supported on a side of the substrate, the first antenna comprising conductive traces at least partially defining a first antenna area, the first antenna configured for communication in a first frequency range;

a second antenna supported on the side of the substrate, the second antenna positioned within the first antenna area and configured for communication in a second frequency range;

a conductive material configured to provide a ground, the conductive material provided within the substrate, wherein the first antenna and the second antennas are in electrical communication with the conductive material using conductive interconnects through at least a portion of the substrate; and

circuitry supported on a second side of the substrate, the circuitry in electrical communication with the conductive material using at least one conductive interconnect through at least another portion of the substrate.

2. The apparatus of claim 1, wherein the first frequency range is within a high frequency (HF) frequency range and the second frequency range is within a very high frequency (VHF) or an ultra high frequency (UHF) range.

3. The apparatus of claim 1, wherein the first antenna comprises a coil antenna and the second antenna comprises an annular resonator.

4. The apparatus of claim 3, wherein the annular resonator is positioned within an area at least partially defined by the coil antenna.

5. The apparatus of claim 1, wherein the substrate and the first and second antennas are configured to be implanted into biological tissue.

6. The apparatus of claim 1, wherein the substrate comprises a multi-layer printed circuit board having a first layer of insulating material positioned between the side and the conductive material, and a second layer of insulating material positioned between the conductive material and the second side.

7. The apparatus of claim 6, wherein the conductive interconnects are provided through the first layer of insulating material and do not extend into the second layer of insulating material.

8. The apparatus of claim 1, wherein the first antenna element includes a first feed contact and wherein the second antenna element includes a second feed contact, and wherein the second feed contact is positioned on a side of the second antenna element opposite a side closest to the first feed contact.

9. A system comprising:

an external device comprising a dual-band external antenna comprising a first antenna element configured for operation in a first frequency range and a second antenna element configured for operation in a second frequency range; and

an implanted device comprising an implanted antenna comprising a third antenna element configured for operation in the first frequency range and a fourth antenna element configured for operation in the second frequency range;

wherein the external device is configured to power the implanted device using inductive coupling between the first antenna element and the third antenna element in the first frequency range; and

wherein the external device and the implanted device are configured to communicate data between the second antenna element and the fourth antenna element using near-field coupling in the second frequency range.

10. The system of claim 9, wherein the first frequency range comprises a high frequency (HF) frequency range and the second frequency range comprises a very high frequency or an ultra high frequency (UHF) frequency range.

11. The system of claim 9, wherein the first antenna element comprises a first coil antenna and the third antenna element comprises a second coil antenna.

12. The system of claim 11, wherein the first coil antenna at least partially defines an area, and wherein the second antenna element is positioned within the area.

13. The system of claim 12, wherein the second coil antenna at least partially defines a second area, and wherein the fourth antenna element is positioned within the second area.

14. The system of claim 9, wherein the second antenna element comprises a segmented loop antenna and wherein the fourth antenna element comprises an annular split ring resonator.

15. The system of claim 9, wherein the third and fourth antenna elements are positioned on a same side of an implanted substrate.

16. The system of claim 9, wherein the implanted device is implanted in biological tissue and the first antenna element and the second antenna element are positioned a distance away from the biological tissue.

17. A method comprising:
positioning an external device a distance from an implanted device;
providing power to the implanted device from the external device using inductive coupling to a first antenna element of the implanted device in a first frequency band; and
communicating data between the external device and the implanted device using near-field coupling to a second antenna element co-located with the first antenna element in a second frequency band.

18. The method of claim 17, wherein providing power to the implanted device comprises providing power to the first antenna element on a substrate of the implanted device, and wherein communicating data between the external device and the implanted device comprises using near-field coupling to the second antenna element positioned on the substrate of the implanted device and at least partially within an area defined by the first antenna element.

19. The method of claim 17, wherein communicating data between the external device and the implanted device comprises bidirectional communication between the external device and the implanted device.

20. The method of claim 17, wherein providing power to the implanted device comprises providing power to a pacemaker and wherein communicating data between the external device and the implanted device comprises communicating pacemaker parameters.

21. The method of claim 17, wherein providing power to the implanted device comprises providing power to a cochlear implant and wherein communicating data between the external device and the implanted device comprises communicating signals representative of audio data.

22. The method of claim 17, wherein providing power to the implanted device comprises providing power to a deep brain stimulator and wherein communicating data between the external device and the implanted device comprises communicating signals representative of control instructions for the deep brain stimulator.

23. The method of claim 17, wherein providing power to the implanted device comprises providing power to a nerve stimulator such as a vagus nerve stimulator wherein communicating data between the external device and the implanted device comprises communicating signals representative of control instructions for the nerve stimulator.

24. The method of claim 17, wherein communicating data between the external device and the implanted device comprises using backscatter communication.

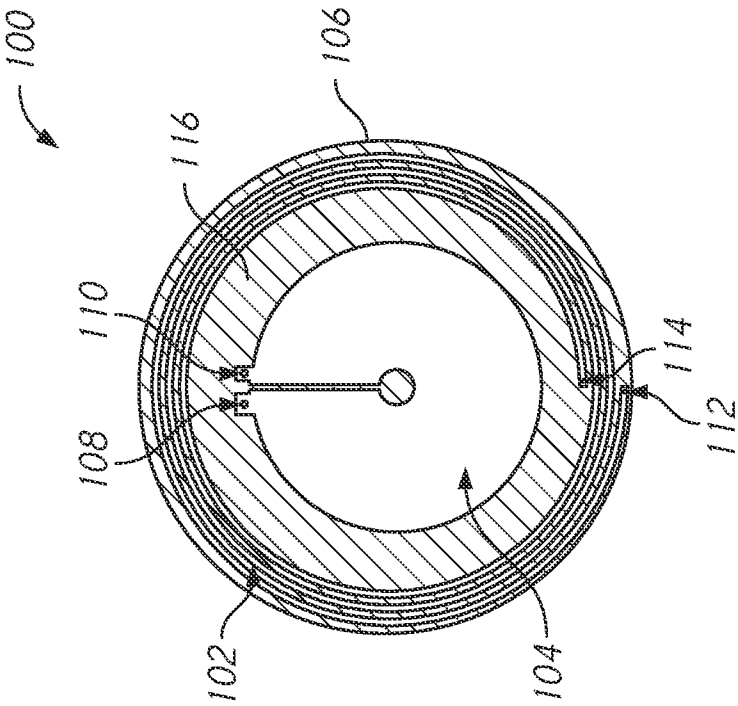


FIG. 1

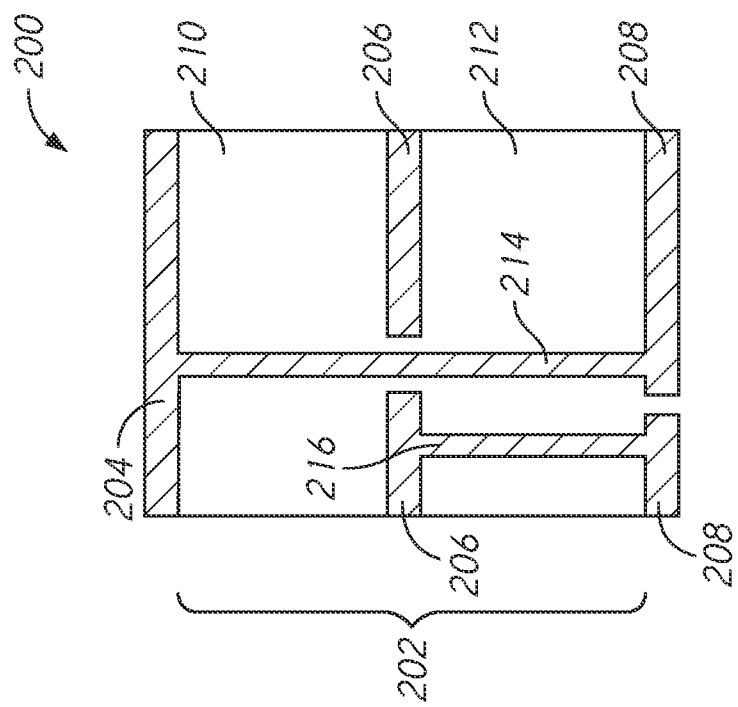


FIG. 2

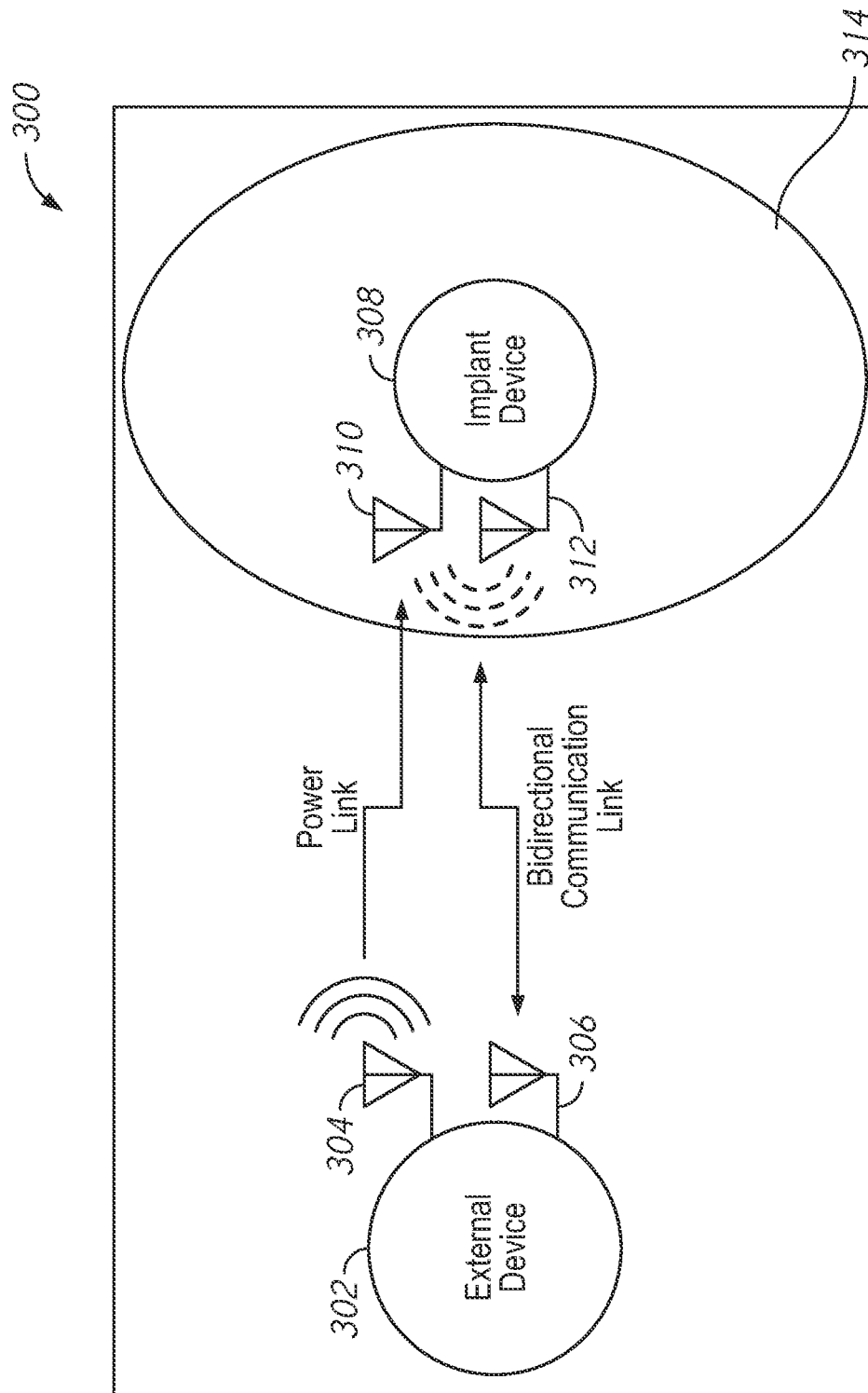


FIG. 3

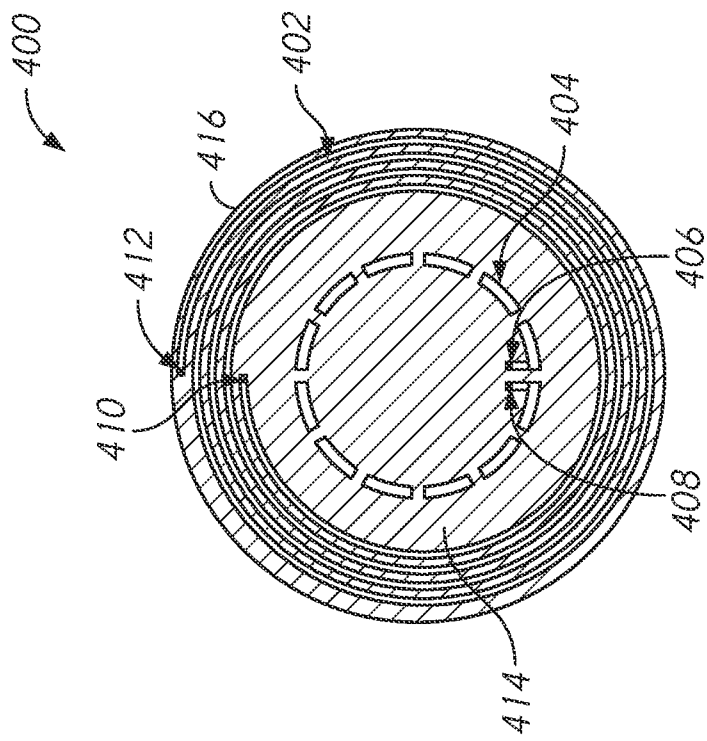


FIG. 4

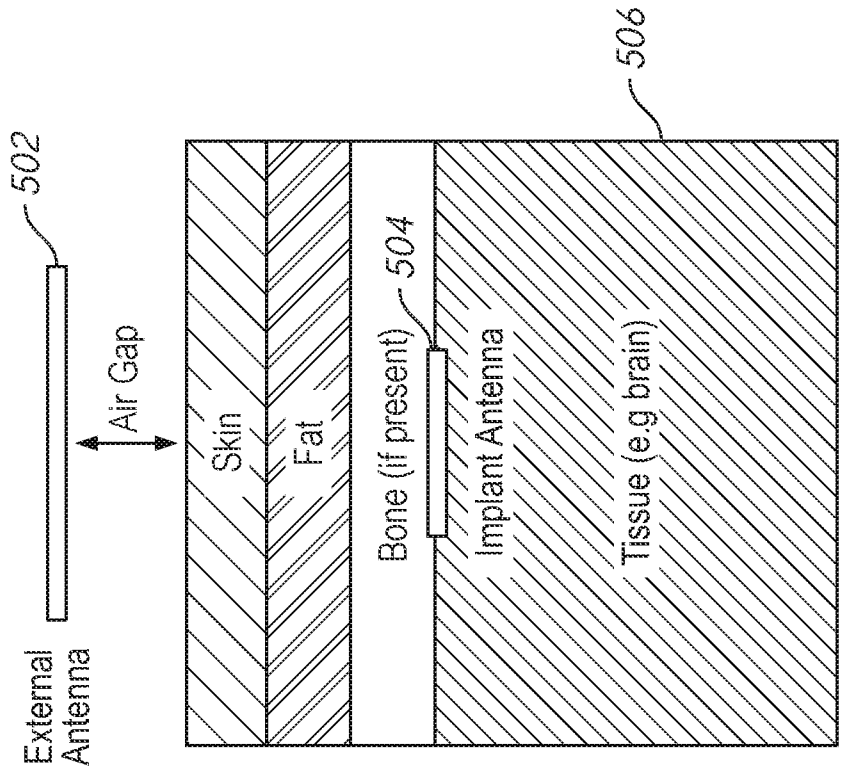


FIG. 5

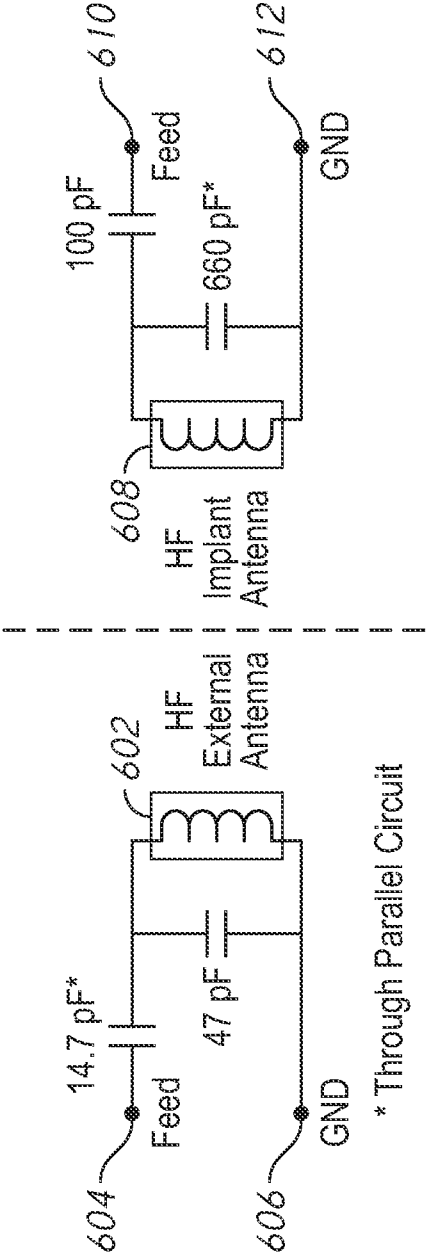


FIG. 6

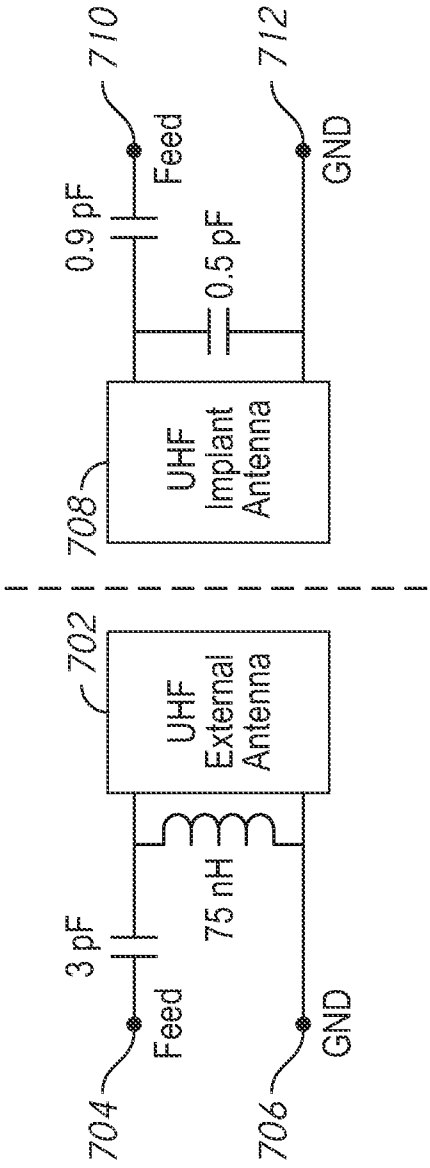


FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US17/16573

A. CLASSIFICATION OF SUBJECT MATTER

IPC - G06K 19/077; H01Q 1/38; A61B 5/0215 (2017.01)

CPC - G06K 19/07767, 19/07786, 19/0779, 19/07756; H01Q 1/38; A61B 5/0215

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)

See Search History document

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

See Search History document

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

See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2012/0287004 A1 (JOSHI, H et al.) 15 November 2012; figures 2, 3, 4B, 4C; paragraphs [0031], [0033], [0042].	1, 5-8
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Y		2-4
Y	US 2005/0267550 A1 (HESS, P et al.) 01 December 2005; paragraph [0044].	2
Y	US 2010/0277376 A1 (CHAKAM, G et al.) 04 November 2010; paragraph [0024].	3-4

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

* Special categories of cited documents:

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

"E" earlier application or patent but published on or after the international filing date

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

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search

16 May 2017 (16.05.2017)

Date of mailing of the international search report

22 MAY 2017

Name and mailing address of the ISA/

Mail Stop PCT, Attn: ISA/US, Commissioner for Patents

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PCT OSP: 571-272-7774

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US17/16573

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fee must be paid.

Group I: Claims 1-8 are directed towards an apparatus comprising a substrate and two antennas.

Group II: Claims 9-16 are directed towards an external device communicating to an implanted device via antenna elements.

Group III: Claims 17-24 are directed towards a method of positioning an external device to communicate with an implanted device.

<***-continued on extra sheet-***>

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-8

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

<***-continued from Box No. III Observations where unity of invention is lacking-***>

The inventions listed as Groups I-III do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons:

The special technical features of Group I include at least a first antenna supported on a side of the substrate, the first antenna comprising conductive traces at least partially defining a first antenna area, a second antenna supported on the side of the substrate, the second antenna positioned within the first antenna area; a conductive material configured to provide a ground, the conductive material provided within the substrate, wherein the first antenna and the second antennas are in electrical communication with the conductive material using conductive interconnects through at least a portion of the substrate; and circuitry supported on a second side of the substrate, the circuitry in electrical communication with the conductive material using at least one conductive interconnect through at least another portion of the substrate., which are not present in Groups II-III.

The special technical features of Group II include at least an implanted device comprising an implanted antenna comprising a third antenna element configured for operation in the first frequency range and a fourth antenna element configured for operation in the second frequency range, and using inductive coupling between the first antenna element and the third antenna element in the first frequency range, which are not present in Groups I and III.

The special technical features of Group III include at least positioning an external device a distance from an implanted device; and providing power from the external device using inductive coupling to a first antenna element of the implanted device in a first frequency band, which are not present in Groups I-II.

The common technical features shared by Groups I-II are a first antenna element configured for operation in a first frequency range and a second antenna element configured for operation in a second frequency range.

However, these common features are previously disclosed by US 2011/0152971 A1 to NGHIEM et al. (hereinafter "Nghiem"). Nghiem discloses a first antenna element configured for operation in a first frequency range and a second antenna element configured for operation in a second frequency range (a first antenna and a second antenna transmit at different frequencies; paragraph [0069]).

Since the common technical features are previously disclosed by the Nghiem reference, these common features are not special and so Groups I-II lack unity.

The common technical features shared by Groups III-III are providing power to the implanted device; and communicating data between the external device and the implanted device using near-field coupling to a second antenna element co-located with the first antenna element in a second frequency band.

However, these common features are previously disclosed by Nghiem. Nghiem discloses providing power to the implanted device (implantable device receives power from the first antenna arrangement; paragraph [0067]); and communicating data between the external device and the implanted device using near-field coupling to a second antenna element co-located with the first antenna element in a second frequency band (receive and transmit communication signals containing information (data) between the external device and the implantable device using near-field communications where the second antenna is capacitively coupled (co-located) to the first antenna in a second frequency; paragraphs [0046], [0066], [0067], [0120]).

Since the common technical features are previously disclosed by the Nghiem reference, these common features are not special and so Groups II-III lack unity.