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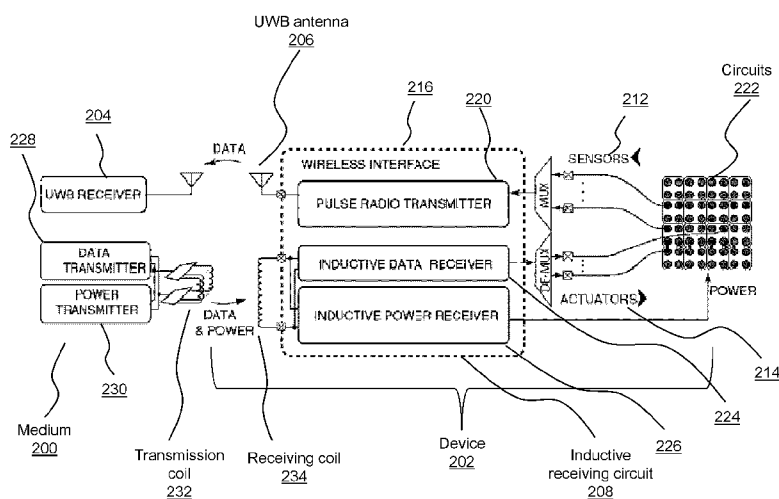


FIG. 2

(57) Abstract: An electronic device for continuous and simultaneous powering and data transfer by using an inductive power receiver operable to generate a power signal from a sensed magnetic field, the power signal; an LC tank and diode pair electrically coupled to the power receiver and operable to obtain the power signal, the LC tank and diode pair cooperating to generate a corresponding clipped signal thereof; and an antenna comprising a high-pass filter, the antenna electrically coupled to the diode pair and operable to emit a pulse-train by high-pass filtering the clipped signal.

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1 WIRELESS POWER AND DATA TRANSMISSION SYSTEM FOR WEARABLE AND
2 IMPLANTABLE DEVICES

3 TECHNICAL FIELD

4 [0001] The following relates generally to wireless power and data systems and more specifically
5 to a wireless power and data transmission system suitable for wearable and implantable
6 devices.

7 BACKGROUND

8 [0002] Wearable electronic devices are becoming ubiquitous. Additionally, the use of
9 “electroceuticals” – that is, implantable electronics, commonly in the medical sensor industry - is
10 also increasing. Such devices are typically worn on or implanted within a human or animal body.

11 [0003] Such devices may be wired or wireless. In wired cases, the devices are only operable
12 when wired to a power source, which presents a clear limitation on mobility of the human or
13 animal wearing or implanted with the device. In wireless cases, the devices may not incorporate
14 battery power. If battery power is the primary source of power, typically wireless data
15 transmission would usually be minimized, to extend the life of the battery and require little or no
16 charging over the useable lifetime of the device, as charging would require a period of wiring or
17 removal of the device from the wearer, which might be difficult or impossible. If battery power is
18 not the primary source of power, then a wireless powering mechanism is always needed to
19 activate the device, in which case the device typically needs to remain in close proximity to a
20 power transmitter.

21 [0004] There is a desire to enable wireless powering (and consequently charging of any reserve
22 battery, if one is provided) for such devices, particularly implantables, which can be difficult to
23 remove for charging, and can be difficult to regulate when wirelessly powered. In cases where
24 such devices are designed to provide wireless data transmission, it can be expected that such
25 transmission requires significant power, in which case most existing forms of wireless powering
26 is not suitable and wired powering/charging is also not realistic.

27 [0005] For the foregoing reasons, it is desirable to provide both wireless power and data
28 transmission between a remote transfer device and the wearable or implantable device.

1 [0006] There are existing solutions for providing wireless power and data transmission. A
2 common example is use of RFID and other wireless sensory domains. A typical RFID
3 implementation comprises a powering device/data receiver which wirelessly transmits power to
4 an RFID tag/sensor, wherein upon the RFID (or other) tag/sensor receiving power, it transmits
5 data to the data receiver contemporaneously. However, in most of these implementations, the
6 read range is to a great extent limited by the phase noise performance of oscillators. Other
7 techniques such as active transmission and time-multiplexing (duty-cycling) are more power-
8 consuming than RFID which effectively reduce the average bandwidth of the wireless link.
9 Further, RFID is generally considered to have a relatively low data bandwidth and, therefore, is
10 not particularly suitable to high data volume applications.

11 [0007] Therefore, most such solutions are not suitable for transmission over greater distances;
12 and high-volume wireless data transmission without running down the battery, or possibly
13 requiring frequent wired charging, which is not realistic in many cases. For example, in chronic
14 disease studies, it is typical to affix a wearable or implantable device to a laboratory animal and
15 continuously monitor the laboratory animals wherein the animal is free to move around during its
16 normal day to day activities without being tied to power and/or data cables.

17 [0008] Further, in wireless power transfer applications, most existing techniques aim to
18 maximize the efficiency of power transfer from a transmitter to a receiver. In other words, good
19 wireless power transfer design is considered to be one that delivers the highest power from a
20 fixed power source. However, in human and animal applications (where the human or animal is
21 present near the device like in biomedical and body area networks), the maximum power is
22 effectively limited by the human and animal safety limits rather than source power availability.
23 Safety is a major concern in the inductive power transfer technology. For biomedical and
24 consumer market applications, observing the specific absorption rate (SAR) limit set by
25 regulations and guidelines is a critical design objective.

26 SUMMARY

27 [0009] In one aspect, an apparatus for wireless power and data communication incorporating
28 an implantable or wearable electronic device is provided, the apparatus comprising: a powering
29 medium comprising a transmission coil electrically coupled to a source providing a power signal
30 and a data signal, the powering medium generating a magnetic field for transmitting the power
31 signal and the data signal wirelessly by the transmission coil; an implantable or wearable

1 inductively powered device comprising a wireless interface communicatively coupled to an
2 application circuit, the wireless interface comprising an inductive receiving circuit including an
3 inductive data receiver and inductive power receiver, and a pulse radio transmitter, the inductive
4 power receiver configured to receive the wirelessly transmitted power signal and data signal and
5 provide the received power signal and data signal to the application circuit, and to transmit data
6 received from the application circuit by an antenna; a receiver in communication with a
7 computer for receiving the data and providing the data to a processor; and a computer
8 comprising the source and the processor.

9 [0010] In another aspect, a method for wirelessly powering and communicating with an
10 implantable or wearable electronic device is provided, the method comprising: wirelessly
11 transmitting a power signal and a data signal via a magnetic field generated by a transmission
12 coil electrically coupled to a source providing the power signal and the data signal; receiving the
13 wirelessly transmitted power signal and data signal at the implantable or wearable inductively
14 powered device using an inductive data receiver and an inductive power receiver;
15 communicating the power signal and the data signal from the an inductive data receiver and
16 inductive power receiver to an application circuit, the application circuit configured to generate
17 data; transmitting the data by an antenna; and receiving the transmitted data at a receiver and
18 providing the data to a computer comprising a processor.

19 [0011] In another aspect, an electronic device for continuous and simultaneous powering and
20 data transfer is provided, the electronic device comprising: an inductive power receiver
21 comprising a resonator having a coil for receiving an externally induced magnetic field and
22 correspondingly generating a resonating current; a rectifier electrically coupled to the inductive
23 power receiver to convert and store a portion of the resonating current to a DC voltage; a limiter
24 electrically coupled to the rectifier for limiting the DC voltage to a threshold voltage to produce a
25 clipped signal thereof; and an antenna electrically coupled to the limiter and configured to emit a
26 pulse-train corresponding to the clipped signal.

27 [0012] In another aspect, a method for optimizing the geometries of magnetic coils is provided,
28 the method comprising maximizing a coil fill factor and a number of turns until a fraction power
29 lost in a biological medium is minimized.

1 [0013] In another aspect, a method for arranging receiving coils is provided, the method
2 comprising stacking a plurality of flexible printed circuit coils to divide energy loss corresponding
3 to a number of stacked coils.

4 [0014] In another aspect, a data transmission circuit is provided, the circuit comprising: an input
5 for receiving a pulse train at a first frequency; an oscillator comprising a switch toggling a
6 digitally-controlled cross-coupled LC tank and a diode pair to produce a clipped pulse train; and
7 a data transmitter configured to receive, from an application circuit, a baseband data stream for
8 transmission, a delay lock loop and to align the baseband data stream to the pulse train, and a
9 stream generator to generate a transmission stream by operating on the data stream with the
10 pulse train.

11 [0015] In another aspect, an electronic device for continuous and simultaneous powering and
12 data transfer is provided, the electronic device comprising: an inductive power receiver operable
13 to generate a power signal from a sensed magnetic field, the power signal; an LC tank and
14 diode pair electrically coupled to the power receiver and operable to obtain the power signal, the
15 LC tank and diode pair cooperating to generate a corresponding clipped signal thereof; and an
16 antenna comprising a high-pass filter, the antenna electrically coupled to the diode pair and
17 operable to emit a pulse-train by high-pass filtering the clipped signal.

18 [0016] In another aspect, an electronic device for continuous and simultaneous powering and
19 high-resolution data transfer from wireless sensor nodes including wireless medical implantable
20 devices is provided.

21 [0017] In another aspect, a radio transmitter which products electrical impulses with minimum
22 power dissipation in the form of heat is provided. The reduction in energy dissipation allows the
23 radio to transmit significantly more data in a unit of time as compared to currently available
24 UWB radio design.

25 [0018] In another aspect, a method of high datarate transmission is provided, the method based
26 on limiting the output swing of a high-Q resonating LC tank and feeding the resulting high-
27 bandwidth signal into a UWB antenna.

28 [0019] In another aspect, a low radiation high-power wireless energy transfer system is
29 provided, the system operable through biological media by minimizing the fraction of energy lost
30 in the medium to received power.

1 [0020] In another aspect, a method for optimizing the geometries of magnetic coils is provided,
2 the method comprising maximizing a coil fill factor and a number of turns until the fraction power
3 lost in a biological medium is minimized.

4 [0021] In another aspect, a method for arranging receiving coils is provided, the method
5 comprising stacking multiple flexible printed circuit coils to divide energy loss corresponding to
6 the number of stacked coils.

7 [0022] In another aspect, a method for manufacturing an integrated magnetic coil on a CMOS
8 substrate for remotely energizing an implantable microchip with alternating magnetic field is
9 provided.

10 [0023] These and other aspects are contemplated and described herein. It will be appreciated
11 that the foregoing summary sets out representative aspects of systems, methods and apparatus
12 for wireless power and data transmission system suitable for wearable and implantable devices
13 to assist skilled readers in understanding the following detailed description

14 DESCRIPTION OF THE DRAWINGS

15 [0024] A greater understanding of the embodiments will be had with reference to the Figures, in
16 which:

17 [0025] Fig. 1 illustrates an exemplary embodiment of a wireless power and data transmission
18 system for wearable and implantable devices, as applied to a free moving laboratory animal;

19 [0026] Fig. 2 illustrates an exemplary block diagram of an inductively powered wireless
20 sensor/actuator interface device;

21 [0027] Fig. 3 illustrates an exemplary schematic diagram of an inductive power receiving circuit;

22 [0028] Fig. 4 illustrates two exemplary pulse generation circuits, one using a high-frequency
23 transient and the other a low-frequency steady-state LC tank;

24 [0029] Fig. 5 illustrates an exemplary schematic diagram of a UWB pulse radio transmitter
25 circuit;

26 [0030] Fig. 6 illustrates an exemplary schematic diagram of a DLL circuit used for OOK
27 modulation;

- 1 [0031] Fig. 7 illustrates an exemplary transistor-level schematic of a UWB pulse generator;
- 2 [0032] Fig. 8 illustrates an exemplary modulated time-domain output of a transmitter and power
3 spectrum;
- 4 [0033] Fig. 9 illustrates an exemplary receiving antenna return loss and measured output;
- 5 [0034] Fig. 10 illustrates an exemplary schematic diagram of a near-field data receiver;
- 6 [0035] Fig. 11 illustrates orthogonal-phase dissipative currents induced in biological tissue by
7 coupled resonant coils;
- 8 [0036] Fig. 12 illustrates exemplary circuit models of an inductive powering system;
- 9 [0037] Fig. 13 illustrates an exemplary layout of a square spiral inductor developed on a 2-layer
10 printed circuit board;
- 11 [0038] Fig. 14 illustrates exemplary inductance and quality factors of transmit and receiver coils;
- 12 [0039] Fig. 15 illustrates SAR-optimal outer and inner radii for coils;
- 13 [0040] Fig 16 illustrates exemplary coil dimensions;
- 14 [0041] Fig. 17 illustrates a coil stacking arrangement; and
- 15 [0042] Fig. 18 illustrates an exemplary design of integrated inductors on a CMOS substrate.

16 DETAILED DESCRIPTION

17 [0001] Embodiments will now be described with reference to the figures. For simplicity and
18 clarity of illustration, where considered appropriate, reference numerals may be repeated
19 among the Figures to indicate corresponding or analogous elements. In addition, numerous
20 specific details are set forth in order to provide a thorough understanding of the embodiments
21 described herein. However, it will be understood by those of ordinary skill in the art that the
22 embodiments described herein may be practised without these specific details. In other
23 instances, well-known methods, procedures and components have not been described in detail
24 so as not to obscure the embodiments described herein. Also, the description is not to be
25 considered as limiting the scope of the embodiments described herein.

1 [0043] Various terms used throughout the present description may be read and understood as
2 follows, unless the context indicates otherwise: “or” as used throughout is inclusive, as though
3 written “and/or”; singular articles and pronouns as used throughout include their plural forms,
4 and vice versa; similarly, gendered pronouns include their counterpart pronouns so that
5 pronouns should not be understood as limiting anything described herein to use,
6 implementation, performance, etc. by a single gender; “exemplary” should be understood as
7 “illustrative” or “exemplifying” and not necessarily as “preferred” over other embodiments.
8 Further definitions for terms may be set out herein; these may apply to prior and subsequent
9 instances of those terms, as will be understood from a reading of the present description.

10 [0044] The following provides a wireless power and data transmission system for wearable and
11 implantable devices. The system may comprise transmitter and receiver circuits, and is
12 operable to provide wireless power and data transmission at a greater level within a certain
13 power budget than the aforementioned techniques. Without limitation, the system is particularly
14 suitable for implantable or wearable devices in that one aspect of the design of the system is a
15 counterintuitive consideration for safety limits applicable to wearable and implantable devices
16 placed on or within humans or animals, even in view of a compromise to power efficiency.

17 [0045] In one aspect, the system comprises a power receiving device providing ultra-wide
18 bandwidth (UWB) data transmission even in view of potential lowering of power efficiency from
19 the power transmitter, but deriving the UWB signal from a lower frequency steady state power
20 signal. This is achieved by use of a diode pair, which further provides isolation between the
21 power circuit and the application (data generating) circuit in a wearable or implantable device.

22 [0046] The system is generally operable with wireless interface sensor and/or actuator systems.
23 There are many applications in laboratory and industrial settings where the mechanical
24 decoupling that an all-wireless interface offers dramatically reduces the impact of the observing
25 instruments on the events being observed. One example of such application is responsive
26 sensory arrays implanted in or worn by a patient, or an animal or human subject participating in
27 a medical experiment.

28 [0047] While the following is described with particular reference to wearable and implantable
29 devices, the system serves as a wireless power and data interface for sensing, imaging, and
30 recording electronics or any other application where analog data is collected from a source
31 external to the circuits (the environment, animal or human body, etc.) and transmitted to an end

1 storage and processing device such as a computer or a network of computers, or to another
2 sensor node to relay the data to an end device.

3 [0048] Referring first to Fig. 1, an example system implementation is shown. The system (100)
4 comprises a powering medium (102) configured as an inductive floor, which provides a
5 magnetic field for a power signal (104) to an implanted inductively powered device (106) on an
6 animal (108). The inductive floor comprises an $m \times n$ array of planar inductive coils which
7 transfer power to the device via resonant magnetic induction. In some embodiments, the floor
8 may be configured to actively search through all the coils in the array to find the one closest to
9 the device (106), and powers the device (106) by turning on that coil only. Such a configuration
10 enables long term operability without battery replacement or removal from the power signal,
11 while permitting the animal to be free to move anywhere on the floor without being tied to power
12 and/or data cables.

13 [0049] The device (106) incorporates a wireless interface (shown in Fig. 2) and an application
14 circuit (not shown). The wireless interface is configured to receive the power signal (104),
15 convert the power signal to a DC power supply for the application circuit, provide the power to
16 the application circuit, receive commands (110) from the powering medium and transmit data
17 (112) to a receiver (114). The receiver is in communication with a computer (116) for processing
18 the received data. The computer (116) is further in communication with the powering medium to
19 provide power (118) and commands (120).

20 [0050] The application circuit performs its functions and provides data to the wireless interface
21 for transmission to the receiver (114). An example of an application circuit is a seizure detection,
22 monitoring and avoidance circuit. An exemplary device receives streams of data generated from
23 a plurality neural recording sensors, and transmits it to the laboratory computers. An algorithm
24 analyzes the real-time data from all the neural sensors to determine if a seizure onset is about
25 to happen. In a closed-loop implementation, the computer then alerts the device of the likelihood
26 of a seizure happening soon via the wireless data interface, at which point actuators linked to
27 the wireless device may attempt to stop the seizure using neuro-stimulation.

28 [0051] Referring now to Fig. 2, a block diagram of a powering medium (200) and an exemplary
29 inductively powered device (202) is shown. Energy is inductively transferred from the medium
30 (200) to the device (202) by an alternating magnetic field while data is transmitted from the
31 device (202) to the medium (200) or other UWB receiver (204) (which may be located away

1 from the medium) in the form of a pulse train radiated from a UWB antenna (206). A suitable
2 period for the pulse train is in the range of pico or nanosecond.

3 [0052] The medium (200) comprises a data transmitter (228) and power transmitter (230) linked
4 to a transmission coil (232).

5 [0053] As previously noted, the inductively powered device (202) comprises a wireless interface
6 device (216) communicatively coupled to an application circuit (222). The wireless interface
7 device (216) comprises an inductive receiving circuit (208) including an inductive data receiver
8 (224) and inductive power receiver (226), and a pulse radio transmitter (220).

9 [0054] The device (202) is powered by the inductive power receiver (226) which is linked to a
10 receiving coil (234) that harvests energy from an alternating magnetic field created by a power
11 transmitter (230) and radiated by the transmission coil (232). This power is used to operate the
12 sensors (212) and/or actuators (214) interfaced with the wireless interface device (216) as well
13 as all the other circuits (222) within the device (202) itself. The serial data coming from the
14 sensors (212) are sent out to by the pulse radio transmitter (220) to a nearby UWB receiver
15 (204) via UWB antenna (206), which in turn feeds the data to a computer (116) for real-time or
16 offline analysis, and storage.

17 [0055] Fig. 3 shows a schematic diagram of an inductive power receiver which converts the
18 energy of the received magnetic field to a usable DC supply. The inductive power receiver
19 shown comprises a resonator (302), de-tuning element (304), rectifier (306) and limiter (308). In
20 the resonator (302), a hollow-core high-inductance magnetic coil (300) is induced with an
21 alternating magnetic field (310), which causes the coil (300) and a parallel-connected capacitor
22 (312) to resonate together at the frequency of the magnetic field (i.e., the coil and the capacitor
23 have the same resonant frequency as the magnetic field). While the coil is resonating, the
24 double-half-wave rectifier (306) converts a portion of the resonating current to a DC voltage and
25 stores it across another capacitor "Cs" (314). The detuning element (304) is optional. The limiter
26 (308) may be provided for overvoltage protection. The limiter discharges the excess charge on
27 the capacitor Cs to prevent the Cs voltage from rising beyond a threshold set by the forward
28 voltages of the 2 series diodes. Without the limiter, the Cs voltage may become too high, which
29 may break down the components in the implant circuits.

30 [0056] The received power signal is used to form a pulse train for transmitting data back from
31 the device. The wireless interface applies UWB backscattering to enable the transmission of a

1 significant amount of data even when the power signal is of a relatively low frequency.
2 Backscattering utilizes the same channel for data transmission as power reception, while
3 applying a different data rate. The present system implements a novel switching circuit to switch
4 the signal window between data transmission and power reception.

5 [0057] Referring now to Fig. 4, two switching circuits are shown for providing UWB data
6 transmission in a backscattering application. Fig. 4(a) shows a first circuit used in UWB
7 transmitter, and Fig. 4(b) shows a second circuit for a UWB transmitter. With the circuit of Fig.
8 4(b), in an example where the power signal is provided at around 1.5MHz, a UWB data
9 transmission rate is possible with the up to two data pulses sent back for each power signal
10 period. Additionally, if the wireless interface incorporates a frequency upconverter, it is possible
11 to achieve data rates at least as high as 250 Mbps.

12 [0058] Ultra-wideband impulse radio (UWB-IR) is in many cases a suitable architecture for
13 short-range (e.g., less than 10m) medium data rate (e.g., greater than 10Mb/s) transmission. A
14 UWB-IR transmitter (TX) directly radiates a train of short (e.g., less than 1ns) pulses each
15 typically representing one symbol. The direct transmission of impulses results in high data rates
16 as the symbol period can be nearly as small as the duration of the individual impulses.
17 Compared with some existing low-power narrow-band transmitters, UWB-IR transmitters may
18 offer 10 times or higher bandwidth and lower per-bit energy dissipation.

19 [0059] The high bandwidth of a UWB-IR TX, however, comes at the cost of reduced TX power
20 efficiency. Compared with some existing narrow-band TXs, UWB-IR TXs may be at least 4
21 times less power efficient. The reduced power efficiency of the UWB-IR TX may be attributed to
22 poor efficiency of the output stage which drives the antenna. Unlike narrow-band transmitters,
23 which typically utilize a high-efficiency switching power amplifier (PA), a UWB-IR TX that derives
24 the data signal from the power signal cannot typically use a switching PA since the main
25 component of the typical switching PA, a passive narrow band filter, would block the UWB
26 impulses entirely.

27 [0060] In some low-power UWB-IR architectures, a set of inverters generates the UWB
28 waveform and drives the antenna. In these architectures, the TX only radiates power during the
29 logic-state transitions. The TX efficiency is therefore limited by that of a CMOS inverter during
30 rise and fall times which is limited to 50% in the ideal case. In practice, due to the added

1 consumption in the digital delay-lines and other pulse-shaping circuits, the architecture tends to
2 yield a small overall power efficiency of approximately 0.5%.

3 [0061] The circuit of Fig. 4(a) generates UWB pulses by activating a switch (400) to turn on and
4 off a digitally-controlled cross-coupled LC tank (402) which operates as an oscillator. In this
5 circuit, the TX efficiency performance therefore depends on the efficiency of the LC tank (402)
6 during the startup period. Power efficiency slowly increases to its maximum value in the steady
7 state. Generally, the pulse period is over prior to the steady state and the LC tank (402) is
8 switched off.

9 [0062] In the circuit of Fig. 4(b), a low power UWB data transmission is provided by obtaining
10 pulses from the power coil, shaping them with a diode-pair, then feeding them into a UWB
11 antenna. The inclusion of the diode-pair effectively keeps the high-speed RF path outside of the
12 sensors/tag chip semiconductor region of the device where the electronics are typically much
13 slower than the passive substrates of the coil, antenna and the feedlines outside the chip. Using
14 this technique, an RFID tag, wireless sensor or a wireless medical implant can send out many
15 times more data using a small power budget at the minimal cost of adding the diode-pair
16 between the power harvesting coil and the data transmitting antenna. Moreover, using this
17 architecture, a wireless sensor or biomedical implantable or wearable device will have more
18 power available to provide to its functional circuitry to increase sensing resolution, speed or
19 accuracy, or to and/or to decrease frequency of maintenance for battery replacement, etc. In the
20 case of wearable and implantable biomedical devices, the devices can sense and transmit
21 many times more data at much faster pace than the aforementioned available wireless interface
22 systems.

23 [0063] In this circuit, the UWB pulses are generated from an LC tank (404) oscillating in the
24 steady state, such that the high efficiency of the resonant LC tank (404) can be maintained. The
25 LC tank (404) is permitted to remain in the steady state and two UWB pulses (406) are
26 generated in every oscillation period. The high-bandwidth pulses (406) are generated by
27 clipping the output of the LC tank (404), V2 (408), with two diodes (410) between two DC levels
28 (0V 412 and VMAX 414). The clipped signal, V2 (408), contains higher-order harmonics due to
29 the abrupt limiting action of the diodes (410). The spectral power of the higher order harmonics
30 depends on the threshold voltages VMAX (414) and VMID (shown in Fig. 7) which are digitally
31 controlled with DAC1 and DAC2 (shown in Fig. 7). A raw UWB pulsetrain, V3 (406), is created
32 at the antenna (416) by high-passing the clipped signal V2 (408). In an example

1 implementation, it has been found that a circuit conforming to this UWB-IR TX provides an
2 overall power efficiency of about 21.3% at a data rate of about 230Mb/s.

3 [0064] Therefore, it will be appreciated that the present system is operable to provide a very
4 high datarate even in view of potential reduction of power efficiency. Thus, the system provides
5 a suitable approach to enabling high data rate wireless power and data communication with
6 wearable and implantable devices, while permitting designers of such devices to mitigate power
7 efficiency to meet safety needs. The following provides further aspects of the system.

8 [0065] Referring now to Fig. 5, two examples of a pulse radio data transmitter are shown.
9 Fig.5(a) is a schematic diagram of a pulse radio data transmitter including a resonator (500)
10 implemented as a resonating LC tank, voltage limiting diodes (502), high-pass filter (504)
11 modulating tri-state-buffers (506), and ultra-wideband antenna (508). The radio data transmitter
12 is powered by the inductive power receiving circuit and uses another resonant coil, L3 (512),
13 which is closely coupled to the power receiving coil L2 (shown in Fig. 3). The resonating coil L3
14 (512) creates a high voltage sinusoidal swing which when limited by the diode-cap bridge,
15 results in sudden short pulses being ejected in to the feedline of the UWB antenna.

16 [0066] Fig. 5(b) is a schematic diagram of a variation of the circuit of Fig. 5(a), embodied as a
17 standalone radio transmitter (i.e., without the inductive powering). In absence of the inductive
18 receiving coil L2, the resonating coil L3 (514) is driven by a separate power amplifier (516)
19 which boosts the output of a frequency synthesizer circuit (518) which generates, for example, a
20 pure 915MHz frequency tone from a 14.3MHz crystal oscillator (520) as a reference. The clock
21 (522) to run the sensors is also sourced from the crystal oscillator (520) so that the baseband
22 data stream (DATA) (524) is in synchrony with the UWB pulse train.

23 [0067] A delay-locked-loop (DLL), an example of which is shown in Fig. 6, may be used to align
24 the baseband data stream bits with the UWB pulse train. The DLL comprises a phase detector
25 (PD) (600), low-pass filter (LPF) (602), and variable delay line (604). The DLL regulates the
26 variable delay of the inverter-chain delay line until the outputs (610, 612, respectively) of the
27 delay line (the on-off key, OOK) (606) and the PA (608) are misaligned by exactly $T/4$, where T
28 is the LC tank oscillation period, and with the latter rising edge preceding.

29 [0068] The DLL quantifies the misalignment between the two rising edges by comparing the
30 duration of every OOK "1" bit with the duration of the concurring "1" bit of the output of the PA
31 being positive. For this, the PA output (612) is digitized to a squarewave using an inverter with

1 an AC-coupled input, as shown in Fig.6. The digitized PA output is NORed with the output of the
2 delay line (606). Two pulse-averaging RC filters (614) quantify the pulsewidths of the data "1"
3 bits as seen at the output of the delay line (610) and the output bits NORed with the PA output
4 (612). The RC filter which averages the delay line output (OOK) (616), as shown in Fig. 6, has a
5 DC gain of 1/2, such that the two filters output may be at equal levels when the PA and the data
6 bits are exactly a quarter of a period apart in phase. The difference between the outputs of the
7 two RC filters is quantified by a differential amplifier (618) which may be implemented as a self-
8 biased differential pair. The compensation capacitor Cc (620) may be added to the differential
9 amplifier output to stabilize the feedback loop. As shown in the timing diagram of Fig. 6, an
10 auxiliary quarter-period "1" bit may follow every data bit to ensure that the loop settles only
11 when the bits precede the PA zero crossings by a T/4. Without the auxiliary "1" bit, the DLL may
12 just as likely settle when the bits follow the PA output by a T/4.

13 [0069] Fig. 7 shows a schematic diagram of a pulse generation circuit comprising a pre-
14 amplifier (700), power amplifier (702), LC tank (704), clipping diodes (706) and OOK switch
15 (708). The pre-amplifier shown is a self-biased differential pair with current mirror biasing for the
16 tail current device M1. The power amplifier shown is a common-source stage with an inductive
17 load biased as a class-C amplifier. Low-frequency components of the TX output waveform are
18 further suppressed by the high-pass characteristics of the antenna feedline.

19 [0070] The clipping diodes shown are each implemented by two series diode-connected triple-
20 well NFET devices (M4, M5). In an example embodiment, all the diode-connected devices have
21 a width of 50 μ m and the minimum length possible. The OOK switch may be implemented by the
22 NMOS device M3 which may be characterized by the minimum length and a width of 200 μ m. To
23 set the DC threshold voltages VMAX (710) and VMID (712), C1 (714) and C2 (716) may be
24 used as decoupling capacitors at the outputs of DAC1 (718) and DAC2 (720). C1 and C2 may,
25 for example, be implemented with banks of poly capacitors each, for example, with the total
26 capacitance of 200pF.

27 [0071] Fig. 8 illustrates a signal output representing an example modulated transient output of
28 the transmitter at the maximum output power. Fig. 8(a) shows the transient output of the
29 transmitter modulated by a pseudorandom binary sequence (PRBS). Fig. 8(b) is the spectrum of
30 the OOK modulated pulse train spread over the 3-5GHz frequency range. At higher UWB
31 frequencies, antennas typically either have a small aperture or are extremely sensitive to
32 misalignment. Therefore extending radiated spectral power beyond this frequency range may be

1 of less interest, especially for biomedical wearable and implantable sensor applications where
2 misalignment of antennas often cannot be avoided.

3 [0072] Fig. 9 illustrates a signal output representing transmitted pulses. A receiver recovers the
4 pulses by interpreting the results according to the correlated double sampling scheme described
5 in Fig. 9(a) and described below. The receiver may be set to be triggered by any notch in the
6 received signal that is smaller than a predetermined width, such as 500ps wide, for example.
7 The receiver may be configured such that once a notch is detected, a segment, such as 10ns in
8 this example, of the recorded RX signal containing the notch is stored in a memory. All the
9 stored RX segments may be later processed by a computer to determine the bit error rate
10 (BER), which is determinable following determination of bit value. The computer may perform a
11 correlated double sampling scheme as shown in Fig. 9(a). By taking three consecutive samples
12 from the RX signal in predetermined intervals, such as 100ps in this example, the computer may
13 detect whether a transmitted UWB pulse exists within each stored segment of the scope. The
14 "EDGE1" and "EDGE2" signals are the outputs of two slope detection blocks within the scheme
15 which evaluate the rise in amplitude from t_0 to t_1 , and from t_1 to t_2 , respectively. A UWB pulse
16 may be flagged to be present within the segment when the output of both slope detectors
17 "EDGE1" and "EDGE2" are high. A bit "1" may be assigned to each recorded RX segment when
18 the algorithm detects a UWB pulse during that segment. Each segment may also have a time
19 stamp recorded therein using a separate channel. By comparing the bit "1" segments with the
20 original transmitted PRBS sequence, the BER may be estimated. A bit "0" may be assumed
21 where no pulse is detected by the algorithm. Fig. 9(b) shows the combined output of the two
22 detectors based on the detection scheme in Fig. 9(a). Fig. 9(a) also illustrates a receiving UWB
23 antenna, and its return loss plot over the 0-10GHz frequency range, which shows that it may be
24 most sensitive to signals within the 3GHz-8GHz frequency range.

25 [0073] Referring now to Fig. 10, the system may further comprise a near-field data receiver for
26 command transfer. The near-field data receiver may comprise a digital envelope detector
27 (1000), a data slicer (1002), and a clock recovery circuit (1004). The data recovered by the
28 receiver may be used to configure the sensors or activate all or a subset of the actuators. A
29 PWM envelope containing both clock and data information may be sourced from the power
30 receiving coil L2 (as seen in Fig. 3). To communicate with the receiver, short intervals (1006) of
31 attenuation in the envelope, $V(L1+)$, may denote "0" bits while a long gap (1008) may denote
32 "1's". Regardless of whether a 0 or 1 is being received, the voltage V_x may rise which may

1 cause the clock output (CLK) to toggle at fixed intervals. The data bits may then be recovered at
2 each edge of the clock based on the length of the last pulse in Vx.

3 [0074] In another aspect, and referring to Fig. 12, a set of resonant inductive coils (1200, 1202)
4 being optimized for maximum SAR-constrained power transfer (PLmax) is provided. A method
5 comprises optimizing the geometries of magnetic coils comprising maximizing a coil fill factor
6 and a number of turns until the fraction power lost in a biological medium is minimized.

7 [0075] Fig. 12(a) shows the lumped model (1204) of the resonating 2-coil system in Fig. 11. Fig.
8 12(b) shows an equivalent simplified circuit (1206) to Fig. 12(a). Fig. 12(c) shows an equivalent
9 simplified circuit (1208) to Fig. 12(b).

10 [0076] At frequencies well below the self-resonant frequency (SFR) of the coil (1200, 1202), the
11 parasitic capacitances between the coil turns may be neglected. Neglecting the parasitic
12 capacitances, the lumped model (1204) may be simplified as shown in the 2-port model (1206)
13 in Fig. 12(b). All reactive parts in this circuit (1204) are eliminated due to resonance. Based on
14 the resonant model (1206) in Fig. 12(b), the SAR-constrained model (1208) of the inductive
15 power transfer system in Fig. 12(c) can be derived. The magnetic flux density is strongest at the
16 receiver (1210); therefore, the receiver current has known value in this model. Thus, the
17 receiver (1212) may be modelled as powered by an independent source (1214) in the lumped
18 model (1210) of Fig. 12(c).

19 [0077] As shown in Fig. 11, magnetic fields of the 2 coils, B1 (1100) and B2 (1102) resonate in
20 orthogonal phase, and the total magnetic flux density is $B_{2,Tot} = B_{21} + B_2$, assuming quality
21 factors of both coils are high enough such that Q_1^2 (square of quality factor of first coil) $\gg 1$
22 and Q_2^2 (square of quality factor of second coil) $\gg 1$. B21 is the small component of the
23 magnetic field at the second coil which is sourced from B1. In other words, B21 is the field of the
24 first coil at the location of the second coil. As B2 is created by induction of B1 into L2, and
25 assuming that size of first coil is bigger than the gap between the coils, total local flux density at
26 the receiver may be approximated by:

27
$$B_{loc}^2 \approx B_1^2 (1 + Q_2^2) \quad (1)$$

28 [0078] Therefore, the loaded quality factor of the second coil, Q_2 , can sharply increase local
29 SAR and reduce the maximum deliverable power. Fig. 12(c) shows the flux-constrained model
30 of the inductive power transfer system in Fig. 12(a) and Fig. 12(b) assuming the diameter of the

1 first coil is larger than the gap so that B1 at the second coil is not attenuated significantly. The
 2 total delivered power is then given by:

$$3 \quad P_L = \left(\frac{\omega N_2 A_2}{\sqrt{R_L} + \frac{R_{s2}}{\sqrt{R_L}}} \right)^2 B_1^2, \quad (2)$$

4 where A_2 is the effective area of the second coil, R_L and R_{s2} are load and conductor resistances
 5 and N_2 is number of turns, all referring to the second coil. As evident from the above equation
 6 and the half-circuit model for the second coil in Fig. 12(c), the delivered power to the load (R_L) is
 7 maximized at the upper limit of the of flux density, $B_{Tot} = B_{max}$ and the load resistance of $R_L =$
 8 R_{s2} ; in other words the load must be matched to the winding resistance of the second coil. Using
 9 the exposure limit of $16.3/f_M A_m^{-1}$ and $407.5/f_M A_m^{-1}$ for the whole body and local SAR for the
 10 frequencies between 0.1MHz-100MHz (where f_M is the operating frequency in MHz), the
 11 absolute maximum transferable power to the load may be determined by $f_M A_m^{-1}$ for the whole
 12 body and local SAR for the frequencies between 0.1MHz-100MHz (where f_M is the operating
 13 frequency in MHz), absolute maximum transferable power to the load may be determined by

$$P_{Lmax} = P_L \Big|_{B_{max}, R_{s2}} = \frac{(\omega A_2)^2}{4R_{\square 2}} \times B_{max}^2. \quad (3a)$$

$$= 1.63^2 (2\pi)^4 \frac{A_2^2}{R_{\square 2}} \min \left\{ 1, \frac{25^2}{1 + Q_2^2} \right\} \quad (3b)$$

14

15 where A_2 is effective area, $R_{\square 2}$ is the resistance of a wide 1-turn RX inductor as shown in Fig.
 16 13, L is the inductance per turn such that $R_s \approx N_2 R_{\square}$ and $L \approx N_2 L_{\square}$, (R_{\square} is independent of size
 17 while L_{\square} is proportionate to OD) and f_M is the operating frequency in Megahertz.

18 [0079] In the maximum power transfer equation 3b, the whole body SAR limit dominates at
 19 lower frequencies while the local SAR term dominates at high frequencies where $Q_{22} \gg 1$. The
 20 critical frequency above which local SAR limits power transfer is

$$21 \quad f_{opt} \approx 2 \times \frac{R_{\square 2}}{L_{\square 2}}, \quad (4)$$

22 which is effectively the highest frequency that will result in maximum power delivery.

1 [0080] According to equation 3b, when $f_M \leq f_c$, the maximum transferable power is determined
 2 by OD (size) and copper thickness (tCu), and the value drops by frequency when $f_M > f_c$. Any
 3 frequency below f_c therefore provides the maximum deliverable power. However, from the
 4 power efficiency point of view, it is not desirable to decrease the operating frequency as it leads
 5 to unnecessary loss of power in the transmitter. Therefore, we conclude that f_c is the optimal
 6 operating frequency for inductive power transfer systems having live human or animal tissue as
 7 medium.

8 [0081] Planar coil design parameters, as shown in Fig. 13(a), are outer diameter (OD) (1300),
 9 inner diameter (ID) (1302) and number of turns (N) (1304). The dimensions of the receiving coil
 10 are typically dictated by the size of the device. On the other hand, ID (1302) may have an
 11 optimum value. Qualitatively, reducing the ID (1302) by adding more inner turns to the inductor
 12 (1306) in Fig. 13(b) will increase the induced voltage but increases the winding resistance of the
 13 coil. However, the turns in the center generally do not contribute significantly to the induced
 14 voltage despite still significantly increasing the parasitic resistance. Therefore, an optimal ID
 15 (1302) may exist which maximizes PLmax.

16 [0082] Since OD_2 is a known value, to find the optimal inner diameter for RX, the optimum value
 17 of $r = ID_2/OD_2$ must be determined. The optimal r maximizes PLmax for a given induced flux
 18 density B_{21} . Fig. 14 shows the geometrical representation of $\sqrt{PL_{max}}$ described by equation 3a
 19 in terms of A_2 and R_{s2} , where the volume of the 3D trapezoid (1400) in Fig. 14(a) is proportional
 20 to the total induced flux, and the volume under the dome (1402) in Fig. 14(b) which results from
 21 revolving the arcs and the trapezoid represents square root of total delivered power ($\sqrt{PL_{max}}$).
 22 Based on Fig. 14(b), there is an optimum fill factor, ϕ_{opt2} , which maximizes the volume of the 3-
 23 dimensional trapezoid under the dome (1402) in Fig. 14(b). This volume represents the
 24 maximum transferable power to a coil with outer diameter of 1, and its value is given by:

$$P_{Lmax} = \frac{\sigma t}{2} \left(\frac{1-r}{1+r} \right) (1+r+r^2)^2 B_{21}^2 \quad (5)$$

26 [0083] Differentiating with respect to r and equating to zero yields the optimal value of $r = 0.37$.

27 [0084] The size of the transmitting coil may not be limited such as in the case of the receiver.
 28 Therefore, the outer radius r_1 may be where r_i is the distance of the i^{th} turn from the center of
 29 the coil. In the scenario where each added turn has a fixed width of w , $(r_i - r_{(i-1)}) = w$, and

1 assuming that w is small, the sum in equation 6 can be approximated by the definite integral
 2 $\int_{r_1}^{r_2} r^2 dr = (1 + r_2^2) \sqrt{1 + 2r^2}$, where r_1 and r_2 are the inner and outer radii of the coil. Similarly,
 3 the total resistance of the coil, R_s , can be approximated by the definite integral $RN \int_{r_1}^{r_2} r dr$,
 4 where RN is the resistance of the turn at $r = 1$. To optimize the transmitting coil is to find r_1 and
 5 r_2 which maximize the ratio $B21 = R_s1$. This is equivalent to finding the roots of:

$$6 \quad \frac{d}{dr_{1,2}} \left[\frac{1}{\sqrt{r_2^2 - r_1^2}} \int_{r_1}^{r_2} \frac{r^2 dr}{(1 + r^2)\sqrt{1 + 2r^2}} \right] = 0. \quad (6)$$

7 which as shown in Fig. 15 has unique real roots at about $r_1 = 0.13$ and $r_2 = 2.62$, which are the
 8 optimum values of inner and outer diameters of the transmitting coil normalized to the coil
 9 separation d .

10 [0085] Graphically, optimizing r_1 and r_2 is to maximizing the product of $\cos 2\theta$ and $\sin \alpha$ in Fig.
 11 14(c) and Fig. 14(d) which may be roughly represented by the shaded rectangular area (1404)
 12 when θ is small. It can be verified that disproportionately large TX coils are inefficient as $\cos \theta$
 13 and the shaded area (1404) in Fig. 14(d) tend to zero when $r \gg 1$. In practice, however, it may
 14 be beneficial to select a somewhat greater outer diameter as the coil separation d could slightly
 15 vary depending on the application. While not being the optimum size, increasing r_2 slightly
 16 beyond the $2.62d$ value may not significantly reduce the power delivery. This can be verified
 17 visually as θ and α in Fig. 14(d) change slowly when $r_2 > 2.6$.

18 [0086] It must be noted that this result may be valid provided the integral approximation of the
 19 sum in equation 6 holds. For instance, the approximation may not be accurate if there are only
 20 few turns in the transmitting coil which would result in the sum of equation 6 only having few
 21 terms, rendering the approximation by an integral inappropriate. On the other hand, $N1$ is
 22 designed to be as high as possible, making this analysis fairly accurate in such cases.

23 [0087] Equation 3b establishes that in the SAR-constrained model, the delivered power is a
 24 function of the size and sheet resistance of the receiving coil. Therefore, neither $N1$ or $N2$ may
 25 impact the PL_{max} as they do not impact the size or sheet resistance. In other words, as long as
 26 the load (R_L in Fig. 12(b)) is matched to the R_{s2} , the receiver is at maximum power. However,
 27 the task of matching R_L to R_{s2} using a matching network becomes increasingly challenging
 28 when R_{s2} is small. Since $R_{s2} = N2R_{s2}$, a practical receiving coil has as many turns as
 29 necessary to best match the RX resistance (R_{s2}) to the load, therefore:

$$N2 = \left[\sqrt{\frac{R_L}{R_{\square 2}}} \right].$$

1

2 [0088] On the transmitting side shown in Fig. 12(b), both R_{S1} and R_{12} are proportional to $N21$,
 3 which again makes the coil-to-coil power delivery insensitive to $N1$. Here again, if $N1$ is small,
 4 power loss in the source resistance R_S in Fig. 12(b) becomes very large, leading to poor source-
 5 to-load efficiency. Therefore, much like $N2$, $N1$ is determined by impedance matching condition.
 6 However, to minimize power loss in the TX coil, the real parts of coil impedance (in the left side
 7 network in Fig. 12(c)) must not be matched to the source resistance R_S , but rather much larger
 8 than R_S to minimize the ohmic loss in the TX coil. On the other hand, at some point continuing
 9 to increase $N1$ may begin reducing the quality factor (an effect less likely to occur in the RX coil
 10 due to smaller self-resonant frequency). Based on this trade-off, the optimal number of turn for
 11 TX coil may be found as:

$$N1 = \left[\sqrt{\frac{R_S}{R_{\square 1}}} \right],$$

12

13 where R_S is the source resistance.

14 [0089] Optimization formulas for all coils parameters (fill factors, size and number of turns) are
 15 listed in Table I below, based on a given receiver size and maximum separation of the coils d .
 16 The formulas in Table I are based on low-frequency approximations. However, given that the
 17 optimum frequency in the analysis is also far below the self-resonant frequency, the listed
 18 expressions may be valid for SAR-constrained optimizations.

TABLE I
COIL DESIGN FORMULAE*

Parameter	Best PTE design	Best SAR design	Reported values
Frequency (f_{opt})	$\frac{1/2\pi}{\sqrt{C_{p1}L_{\square 1}}}$	$2^\ddagger \times \frac{R_{\square 2}}{L_{\square 2}}$	$\frac{\sqrt{e/k'_T}}{2\pi}$ [38]
Transmitting coil			
Size (OD_1)	$3d$	$5.24d$	$3.2d$ [44]
Fill factor (ϕ_1)	34%	92%	49% [18]
Turns (N_1)	2	$\sqrt{R_S/R_{\square 1}}$	-
Receiving coil			
Fill factor (ϕ_2)	46%	46%	49% [18]
Turns (N_2)	$\frac{1}{\omega\sqrt{C_{p2}L_{\square 2}}}$	$\sqrt{R_L/R_{\square 2}}$	-

* For given RX size (OD_2) and coil separation (d).
 † Based on the limit of local exposure being 1/25 that of the whole body as in [11].
 ‡ A constant in Debye relaxation model.

1

TABLE II
COMMON SHEET EXPRESSIONS*

$R_{\square 1,2}$	$L_{\square 1,2}$	$L_{1,2}$	$Q_{c1,c2}$
$\frac{2k_S}{\phi_{1,2}\sigma t_{1,2}}$	$\frac{1.27\mu_0 OD_{1,2}g(\phi_{1,2})}{1+\phi_{1,2}}$	$N_{1,2}^2 L_{\square 1,2}$	$2\pi f_{opt} \frac{L_{\square 1,2}}{R_{\square 1,2}}$

* where $t_{1,2}$, and σ are thickness and conductivity of metal traces.
 $k_S = t/(\delta(1 - \exp -t/\delta))$ [27], and $g(\phi) = [\ln 2.07/\phi + 0.18\phi + 0.13\phi^2]$ [9].

2

3 [0090] Table I lists the design formulae for planar square coils having the best SAR and PTE
 4 performance under 2 conditions: (a) the receiver size OD_2 and distance d are constants whose
 5 value is determined by the application, and (b) the RX coil is implanted in biological tissue or
 6 worn directly on the surface of the skin, and (c) the profile of the maximum allowable SAR
 7 decreases proportionately with frequency. The design values resulting from PLmax optimization
 8 is a unique value set of values. These value are distinct from the PTE maximization results with
 9 the exception of RX fill factor ϕ_2 .

10 [0091] Fig. 16 shows illustrative coil geometries resulting from PTE and SAR (PLmax)
 11 optimizations. The PLmax optimization results are listed in Fig. 16. It is evident that TX coils
 12 have clearly distinct shapes when designed for PLmax (1600) as compared to when designed
 13 for maximum efficiency regardless of tissue absorption (1602). The TX shape in the latter case
 14 (1602) is a full planar coil with varying number while the former (1600) is always a sparse 2-turn
 15 coil. The RX coils, on the hand, are similar in both methods, where the primary difference is
 16 their number of turns which is based on the distinct output impedance of the transmitting coils.

17 [0092] In the case of the 3mm integrated inductor (third design case, 1604) in Fig. 16, both
 18 optimization analyses assume that there is no impact from the substrate under the inductor.

1 Therefore, the analyses discount the impact of the conduction within the silicon substrate as
 2 well as its impact in reducing the self-resonant frequency of the coil. These additional effects are
 3 likely to reduce the optimum operating frequency well below values listed in Fig. 16.

4 [0093] The most significant distinction between the two methods, however, is the operating
 5 frequencies. The PTE favors operating at higher MHz frequencies where quality factors are
 6 maximal. This is while the optimal SAR-based design operates at the frequency where the local
 7 magnetic flux density at the RX has not increases more than 25 times that of the TX. As shown
 8 previously in sections III-B and III-C, this limits the quality factor of the RX coil which in turn
 9 limits the operating frequency to a small fraction of the self-resonant frequency. Operating at
 10 frequencies well below the SRF has other advantages such as a predictable resonance
 11 frequency value, which simplifies the design of the matching and rectification circuits.

12 [0094] Table IV, below, lists the operating frequencies, coil geometries and best performance
 13 metric for the inductive links reported in the three designs discussed above. The geometric and
 14 performance parameters for the designs after applying the optimization formulae in Table I is
 15 listed in bold for each design. It can be seen that despite the moderate power transfer efficiency
 16 values of 12%-28%, the designs offer an improvement of 8x to 560x in the maximum
 17 transferable power. When PLmax is well above the minimum required level to run the device
 18 attached to the RX coil, the remaining PLmax margin translates into reduced SAR level
 19 proportionate to the PLmax margin.

TABLE IV
 PERFORMANCE COMPARISON

Param.	f_o (MHz)	d (cm)	OD_1 (cm)	OD_2 (cm)	φ_1	φ_2	N_1	N_2	η_m (%)	P_{Lm} (mW)
[4] SAR- Optimized	13.6 1.71	1 1	4.3 5.2	1 1	0.77 0.92	0.4 0.46	15 21	6 25	100 28	0.5 4
[2] SAR- Optimized	0.137 13.6	7 7	17 36.4	2.5 2.5	0.006 0.92	0.016 0.46	1 36	2 58	68 23	1 410
[5] SAR- Optimized	13 0.1	4 4	13.5 20.8	4.4 4.4	0.48 0.92	0.023 0.46	3 21	3 112	77 12	10 5600

20

21 [0095] Fig. 17 illustrates a method of fabricating high-inductance high-quality-factor planar
 22 inductors without increasing the available number of metal layers (e.g. copper layers) or
 23 thickness of the available metal layers in the fabrication process. Inductance and quality factor
 24 may be simultaneously multiplied by stacking multiple planar spiral inductors such that the last

1 turn of an inductor on a layer is connected to the first turn of the inductor on the next layer while
2 maintaining the same direction of rotation of the turns going from one turn to the next.

3 [0096] Fig. 18 illustrates the same stacked RX coil design technique as in Fig. 17, where the
4 coil may be fabricated on an integrated circuit (IC) substrate instead of a PCB substrate. Energy
5 may be harvested inductively to power the sensors and/or data processing circuits of the chip.
6 To obtain the maximum level of power from the coil, the turns may be traced in series with
7 minimum allowable width and spacing on all of the thick metal layers of the semiconductor
8 technology while the thinner lower metal layer may be used to fabricate peripheral power and
9 data processing circuits directly underneath the RX coil, including rectifiers, storage n-well
10 capacitors, voltage limiter, regulators, array readout circuits including multiplexers and decodes,
11 and clock and data recovery circuits.

12 [0097] An area in the center of the semiconductor chip may be left untraced, which is the size of
13 the minimum area required to fabricate the sensor array or any other on-chip circuits that uses
14 at least one of the thick metal layers in its layout (including MIM capacitors, and spiral inductors
15 other than the RX coil).

16 [0098] Although the invention has been described with reference to certain specific
17 embodiments, various modifications thereof will be apparent to those skilled in the art. The
18 scope of the claims should not be limited by the preferred embodiments, but should be given the
19 broadest interpretation consistent with the description as a whole.

CLAIMS

1. An apparatus for wireless power and data communication incorporating an implantable or wearable electronic device, the apparatus comprising:
 - a powering medium comprising a transmission coil electrically coupled to a source providing a power signal and a data signal, the powering medium generating a magnetic field for transmitting the power signal and the data signal wirelessly by the transmission coil;
 - an implantable or wearable inductively powered device comprising a wireless interface communicatively coupled to an application circuit, the wireless interface comprising an inductive receiving circuit including an inductive data receiver and inductive power receiver, and a pulse radio transmitter, the inductive power receiver configured to receive the wirelessly transmitted power signal and data signal and provide the received power signal and data signal to the application circuit, and to transmit data received from the application circuit by an antenna;
 - a receiver in communication with a computer for receiving the data and providing the data to a processor; and
 - a computer comprising the source and the processor.
2. The apparatus of claim 1, wherein the powering medium is an inductive floor.
3. The apparatus of claim 2, wherein the inductive floor comprises an $m \times n$ array of planar inductive coils which transfer the power signal to the inductively powered device via resonant magnetic induction.
4. The apparatus of claim 3, wherein the inductive floor is configured to actively search through all coils in the array to find one of the coils closest to the device.
5. The apparatus of claim 1, wherein the application circuit comprises a seizure detection and monitoring circuit.
6. The apparatus of claim 5, wherein the application circuit further comprises a seizure avoidance circuit.
7. The apparatus of claim 6, wherein the application circuit receives streams of data generated from a plurality of neural recording sensors for transmission to the computer.

8. The apparatus of claim 7, wherein the computer is configured to provide a command to the application circuit via the powering medium to apply neurostimulation to avoid a detected seizure onset.
9. The apparatus of claim 1, wherein data is transmitted in a pulse train having a period in the range of picoseconds.
10. The apparatus of claim 1, wherein data is transmitted in a pulse train having a period in the range of nanoseconds.
11. The apparatus of claim 1, wherein the inductively powered device transmits the data to the processor using an ultrawide bandwidth signal.
12. A method for wirelessly powering and communicating with an implantable or wearable electronic device, the method comprising:
 - wirelessly transmitting a power signal and a data signal via a magnetic field generated by a transmission coil electrically coupled to a source providing the power signal and the data signal;
 - receiving the wirelessly transmitted power signal and data signal at the implantable or wearable inductively powered device using an inductive data receiver and an inductive power receiver;
 - communicating the power signal and the data signal from the an inductive data receiver and inductive power receiver to an application circuit, the application circuit configured to generate data;
 - transmitting the data by an antenna; and
 - receiving the transmitted data at a receiver and providing the data to a computer comprising a processor.
13. The method of claim 12, wherein the application circuit comprises a seizure detection and monitoring circuit.
14. The method of claim 13, wherein the application circuit further comprises a seizure avoidance circuit.
15. The method of claim 14, wherein the application circuit receives streams of data generated from a plurality of neural recording sensors for transmission to the processor.

16. The method of claim 15, wherein the computer is configured to provide a command to the application circuit via the wirelessly transmitted signals to apply neurostimulation to avoid a detected seizure onset.
17. The method of claim 12, wherein data is transmitted in a pulse train having a period in the range of picoseconds.
18. The method of claim 12, wherein data is transmitted in a pulse train having a period in the range of nanoseconds.
19. The method of claim 12, wherein the inductively powered device transmits the data to the processor using an ultrawide bandwidth signal.
20. An electronic device for continuous and simultaneous powering and data transfer, the electronic device comprising:
 - a. an inductive power receiver comprising a resonator having a coil for receiving an externally induced magnetic field and correspondingly generating a resonating current;
 - b. a rectifier electrically coupled to the inductive power receiver to convert and store a portion of the resonating current to a DC voltage;
 - c. a limiter electrically coupled to the rectifier for limiting the DC voltage to a threshold voltage to produce a clipped signal thereof; and
 - d. an antenna electrically coupled to the limiter and configured to emit a pulse-train corresponding to the clipped signal.
21. The electronic device of claim 20, wherein the resonating current resonates at the frequency of the externally induced magnetic field.
22. The electronic device of claim 20, wherein the rectifier comprises an LC tank and the limiter comprises a diode pair, the LC tank and diode pair cooperating to generate the clipped signal.
23. The electronic device of claim 20, wherein the antenna comprises a high-pass filter to filter the clipped signal.
24. The electronic device of claim 20, wherein the pulse train is usable for data transmission.

25. A method for optimizing the geometries of magnetic coils comprising maximizing a coil fill factor and a number of turns until a fraction power lost in a biological medium is minimized.
26. A method for arranging receiving coils comprising stacking a plurality of flexible printed circuit coils to divide energy loss corresponding to a number of stacked coils.
27. A data transmission circuit comprising
 - an input for receiving a pulse train at a first frequency;
 - an oscillator comprising a switch toggling a digitally-controlled cross-coupled LC tank and a diode pair to produce a clipped pulse train; and
 - a data transmitter configured to receive, from an application circuit, a baseband data stream for transmission, a delay lock loop and to align the baseband data stream to the pulse train, and a stream generator to generate a transmission stream by operating on the data stream with the pulse train.

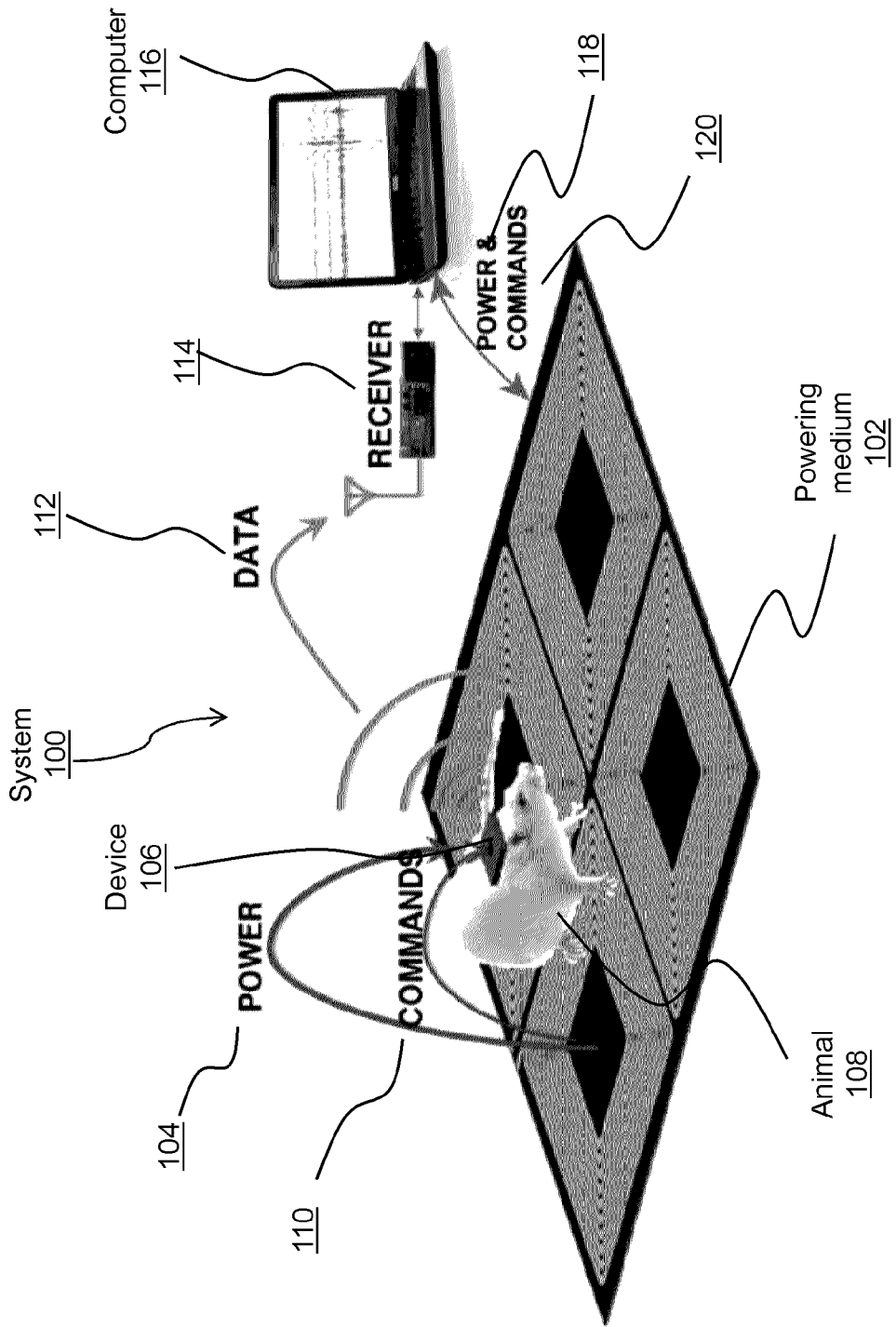


FIG. 1

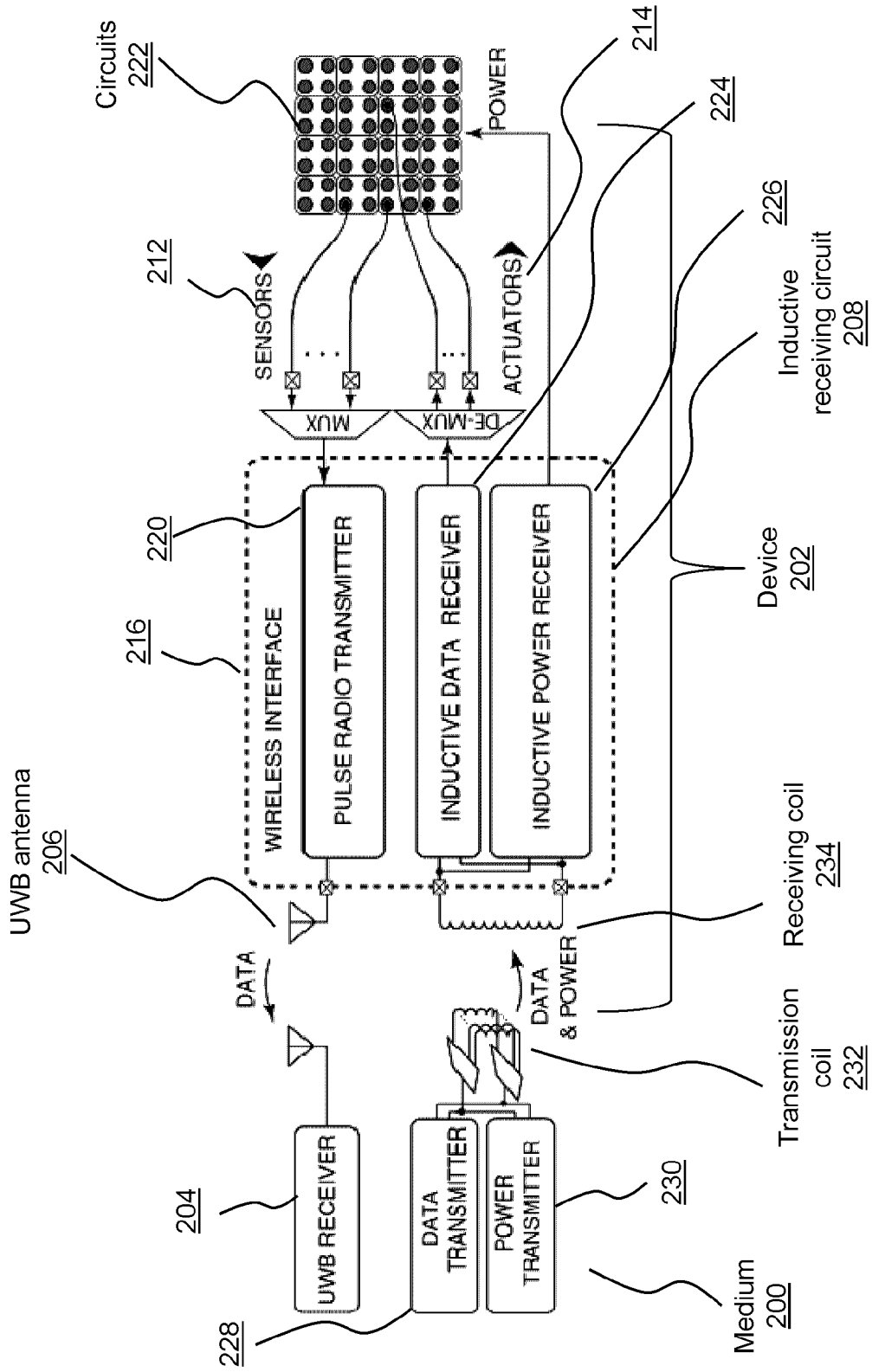


FIG. 2

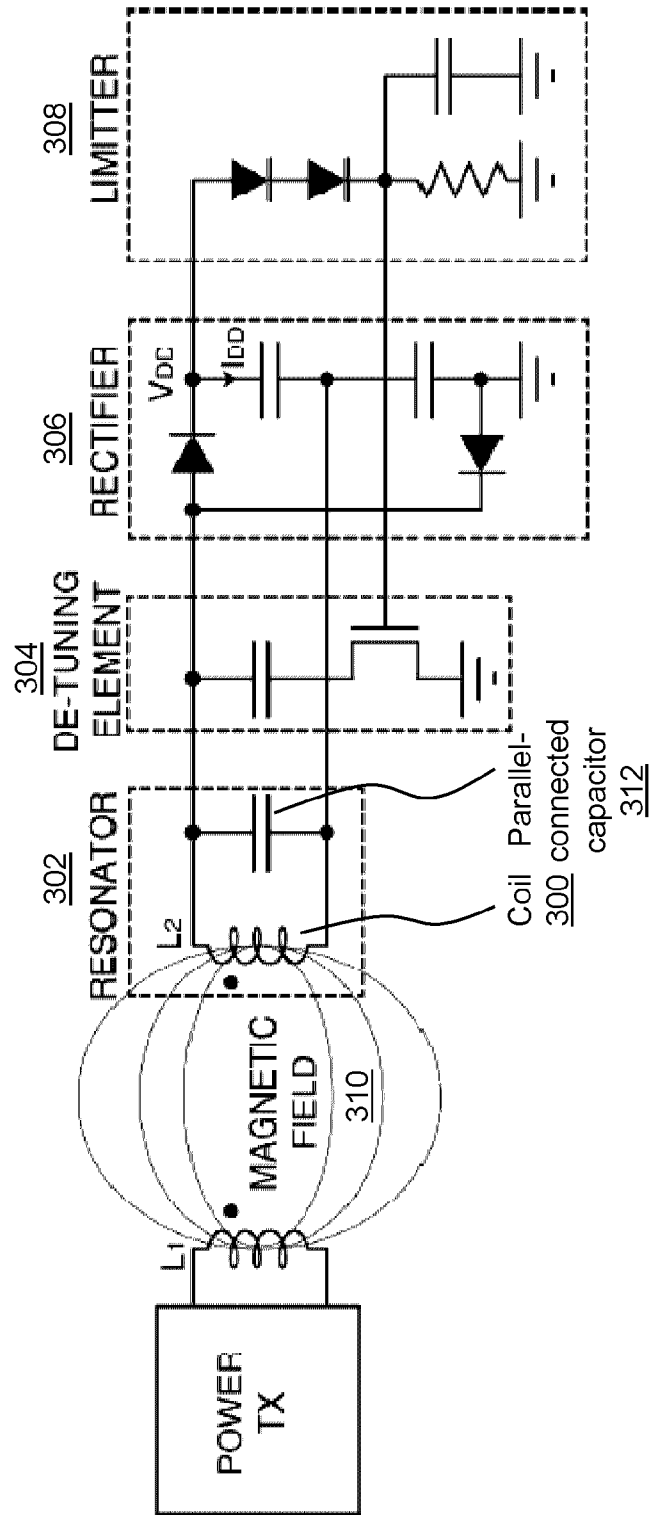


FIG. 3

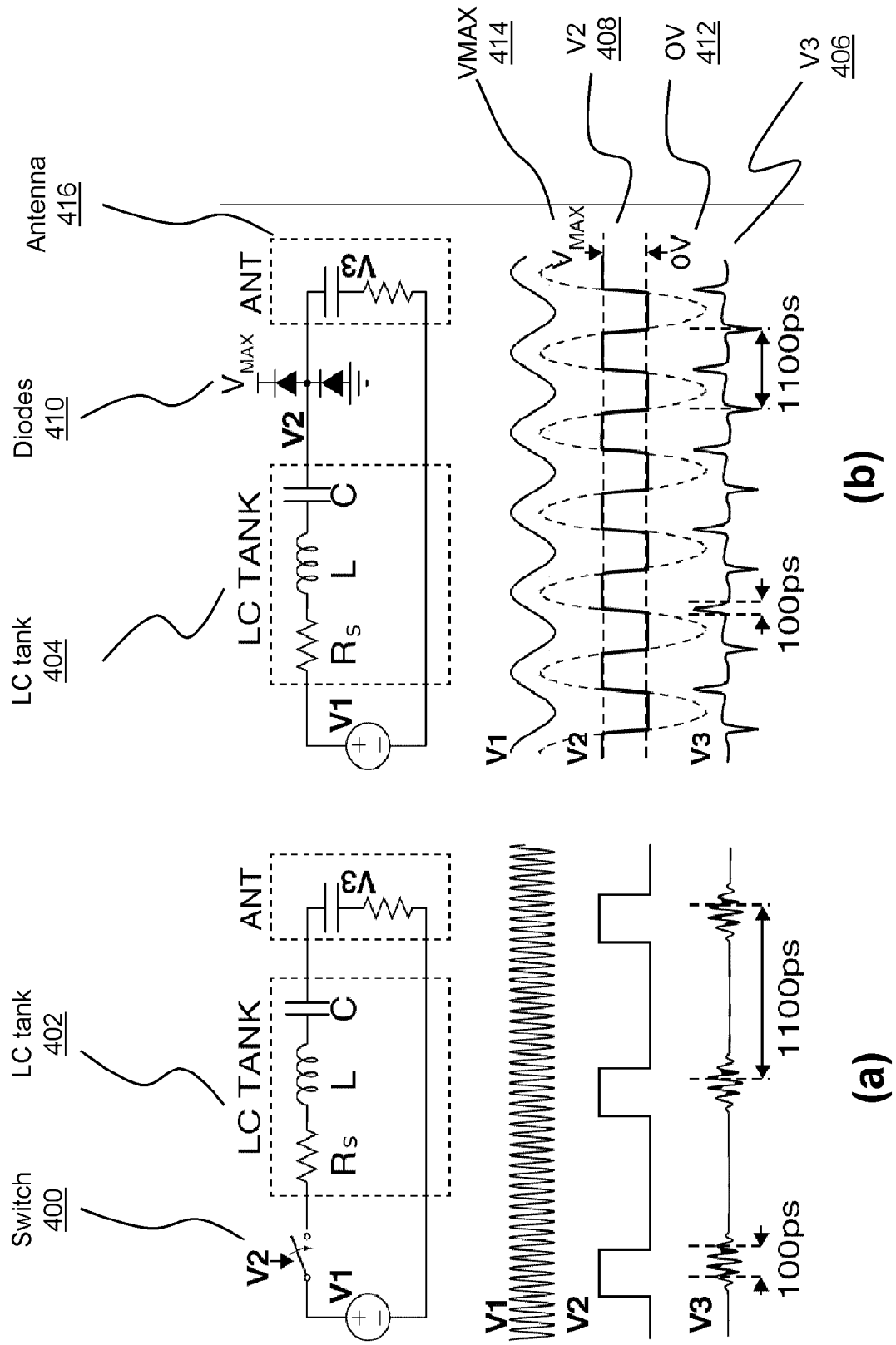


FIG. 4

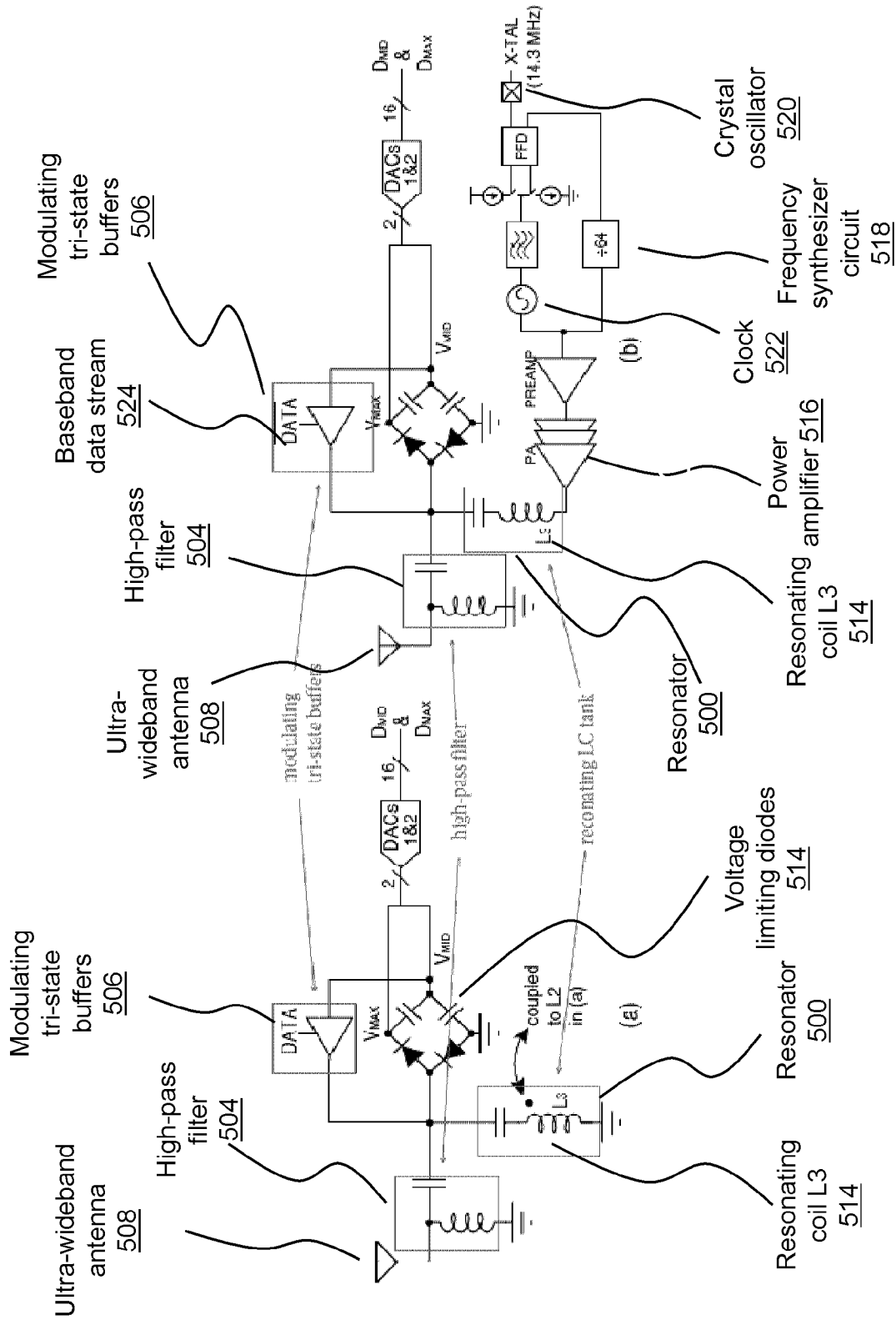


FIG. 5

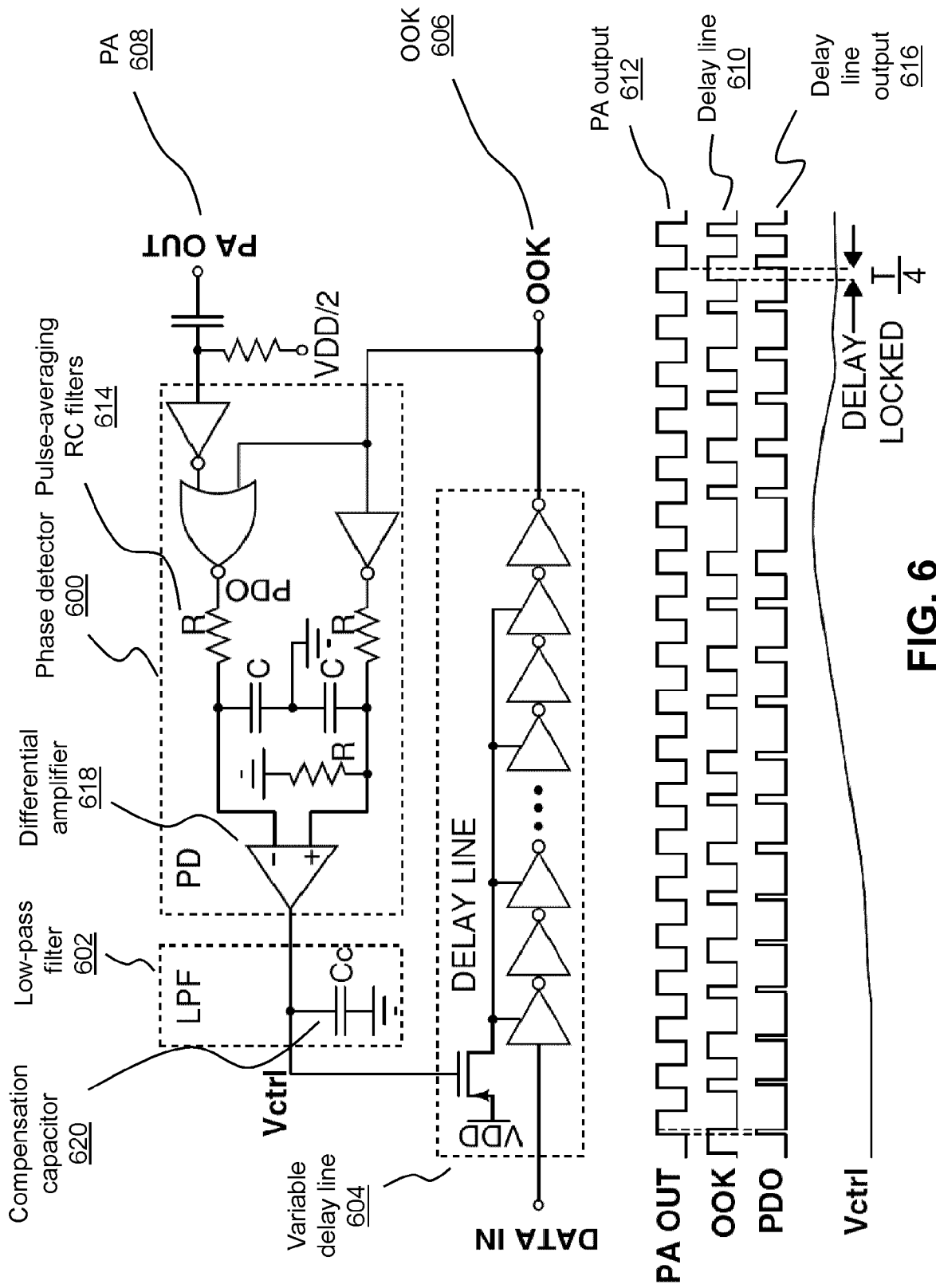


FIG. 6

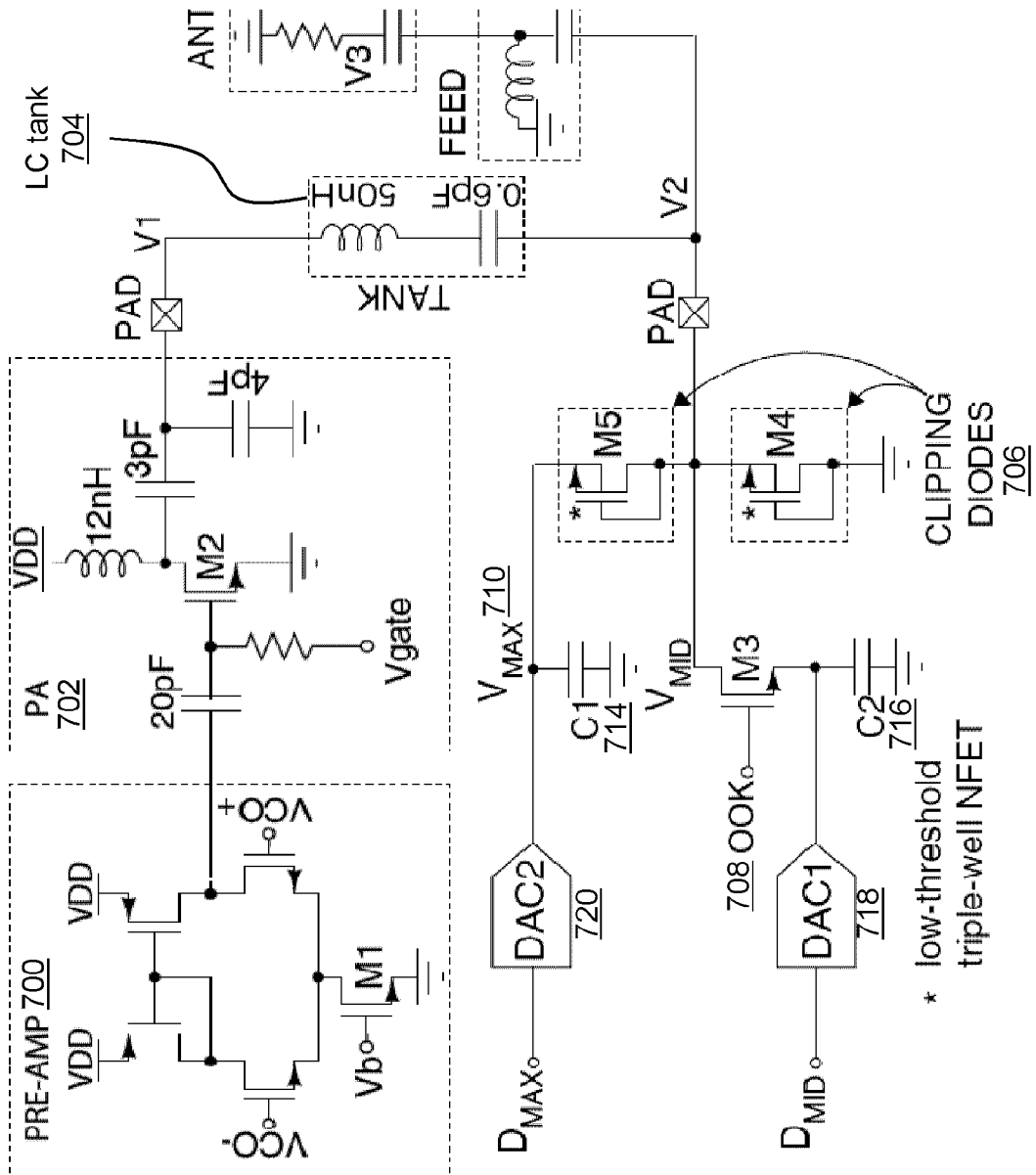
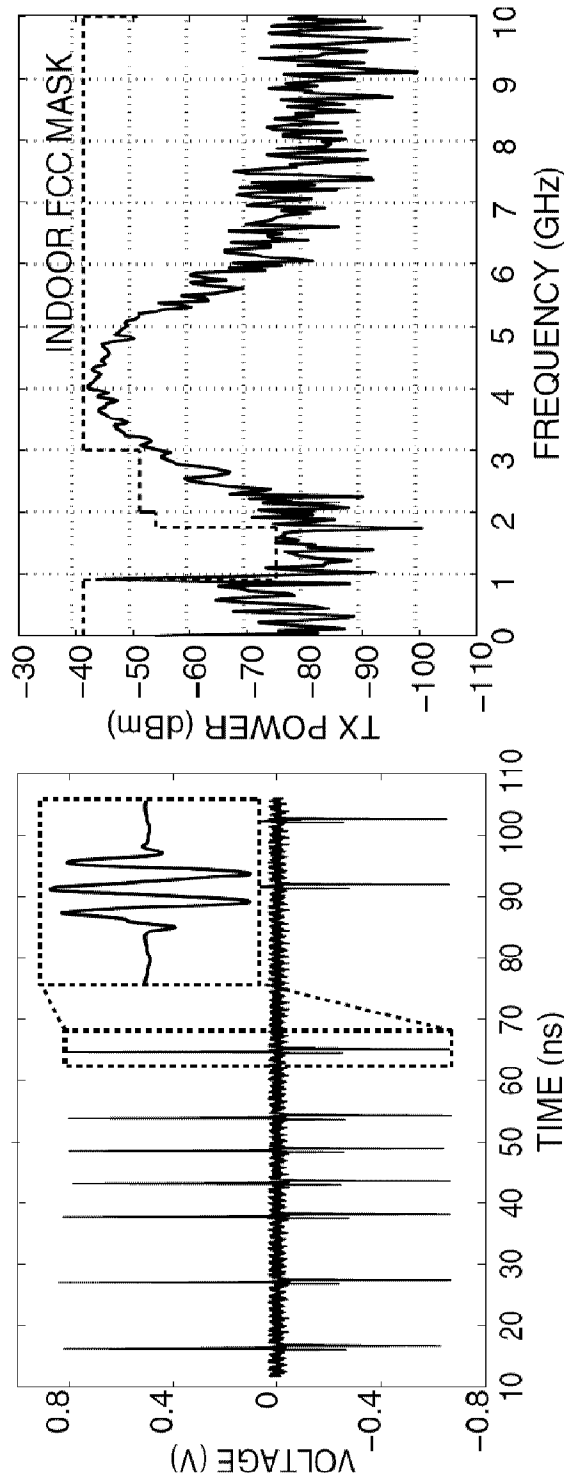


FIG. 7



(a)

(b)

FIG. 8

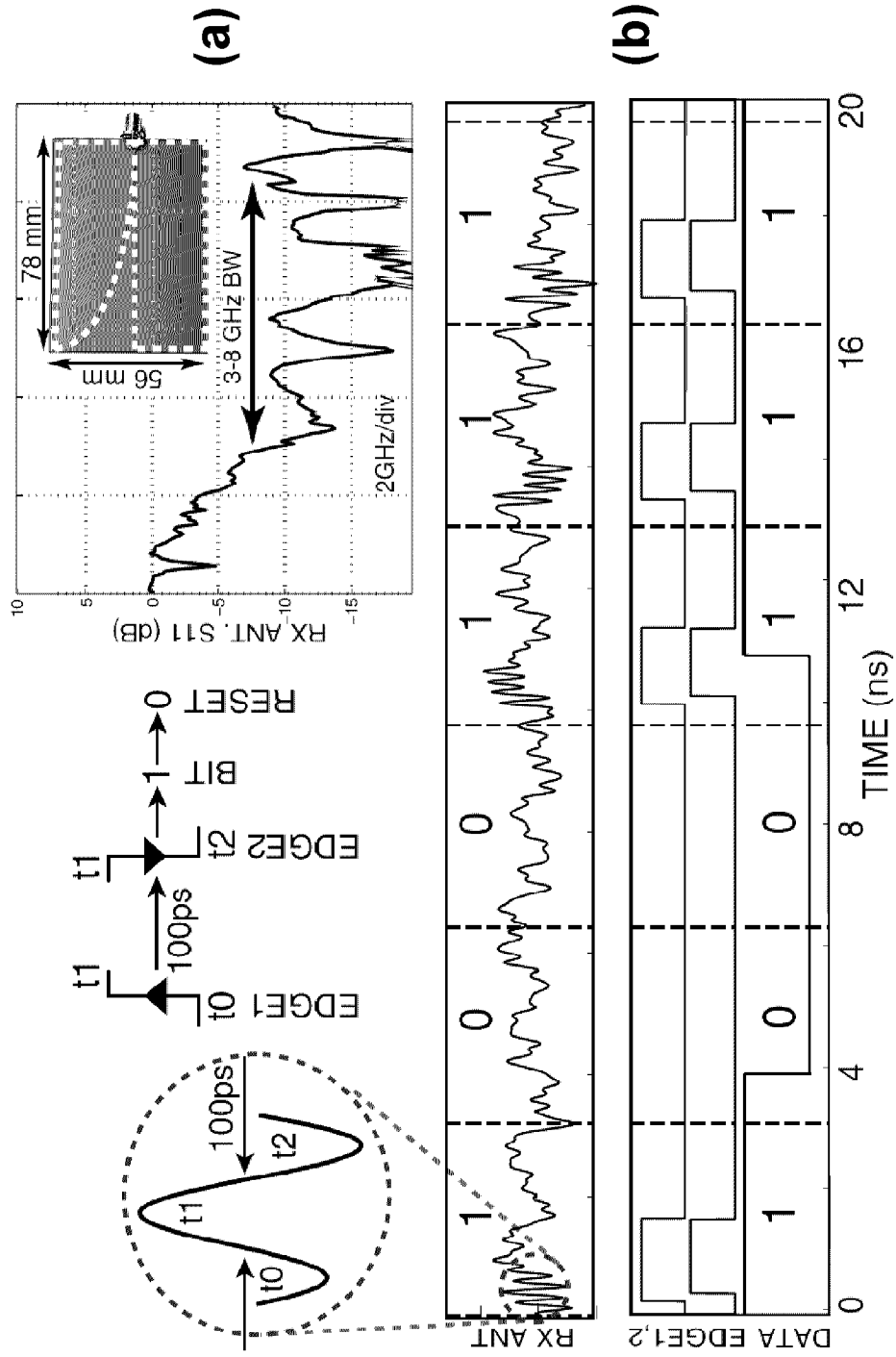


FIG. 9

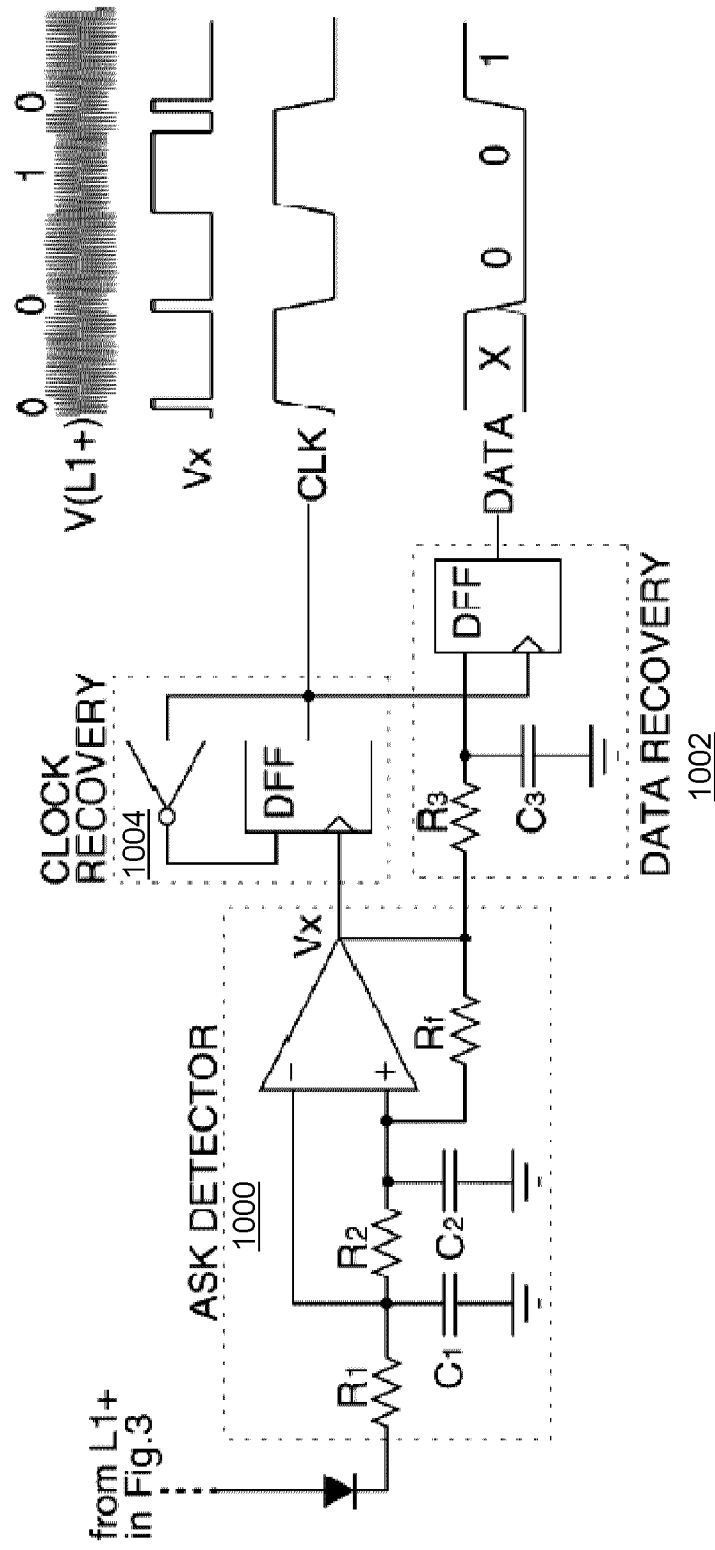


FIG. 10

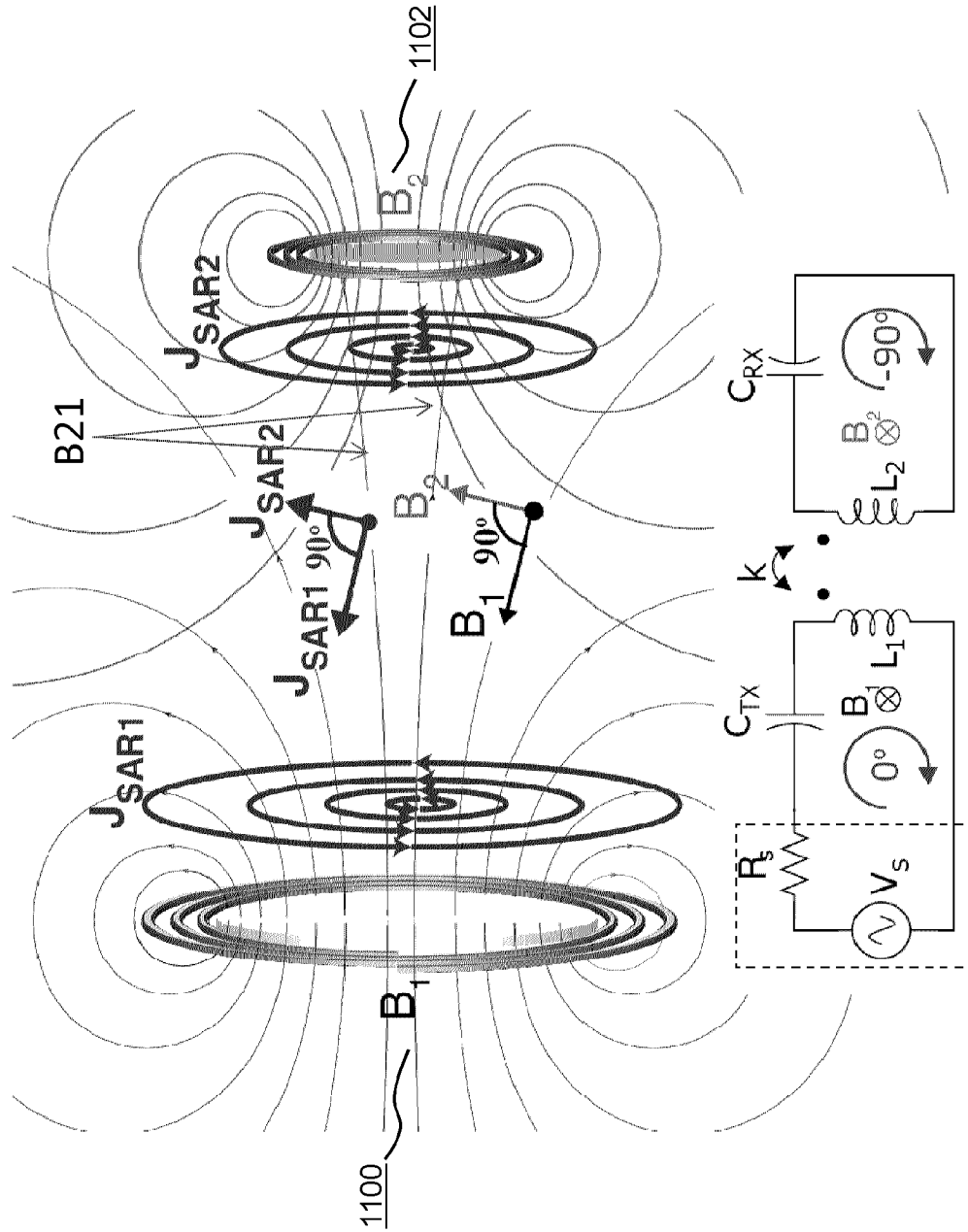


FIG. 11

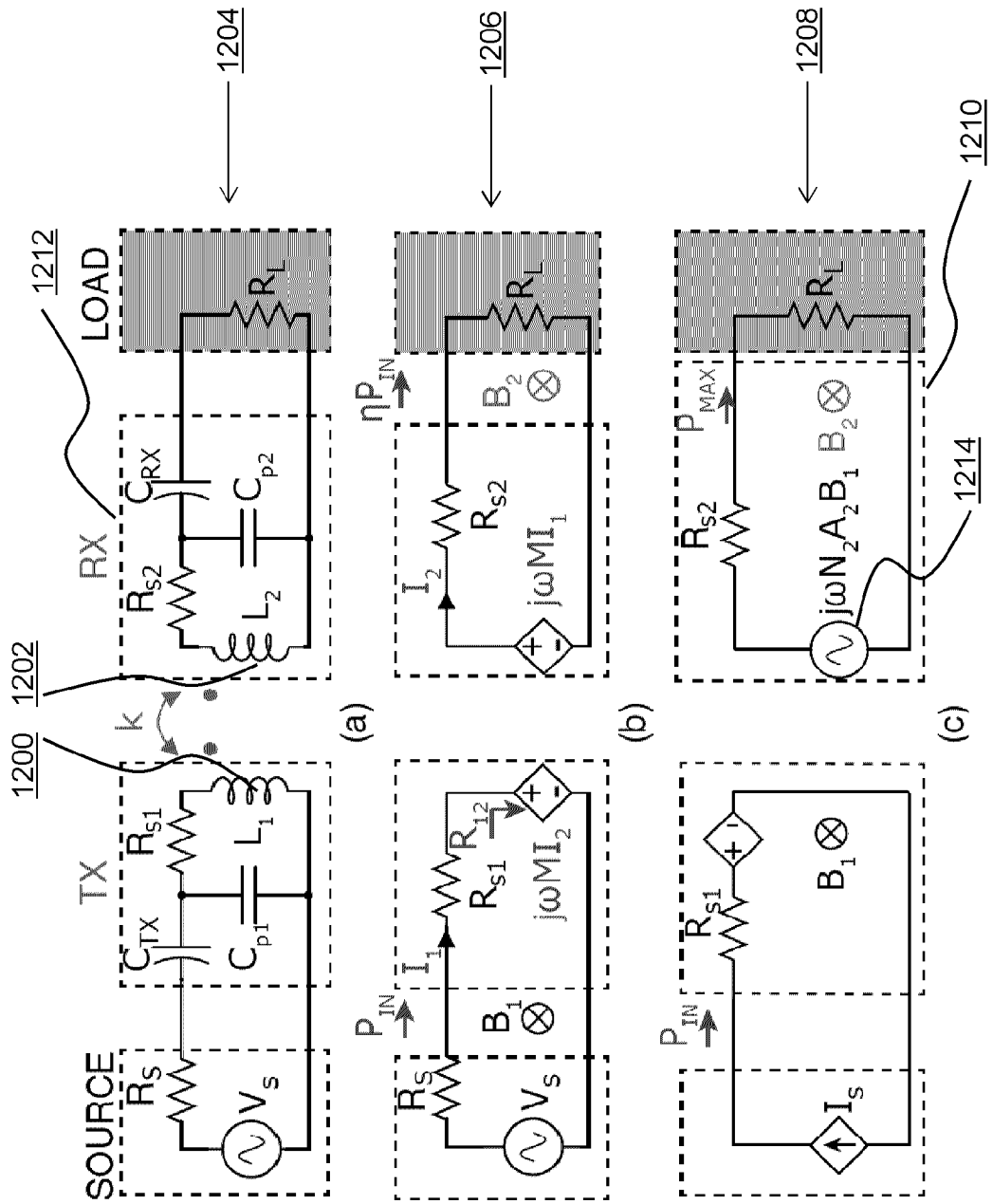


FIG. 12

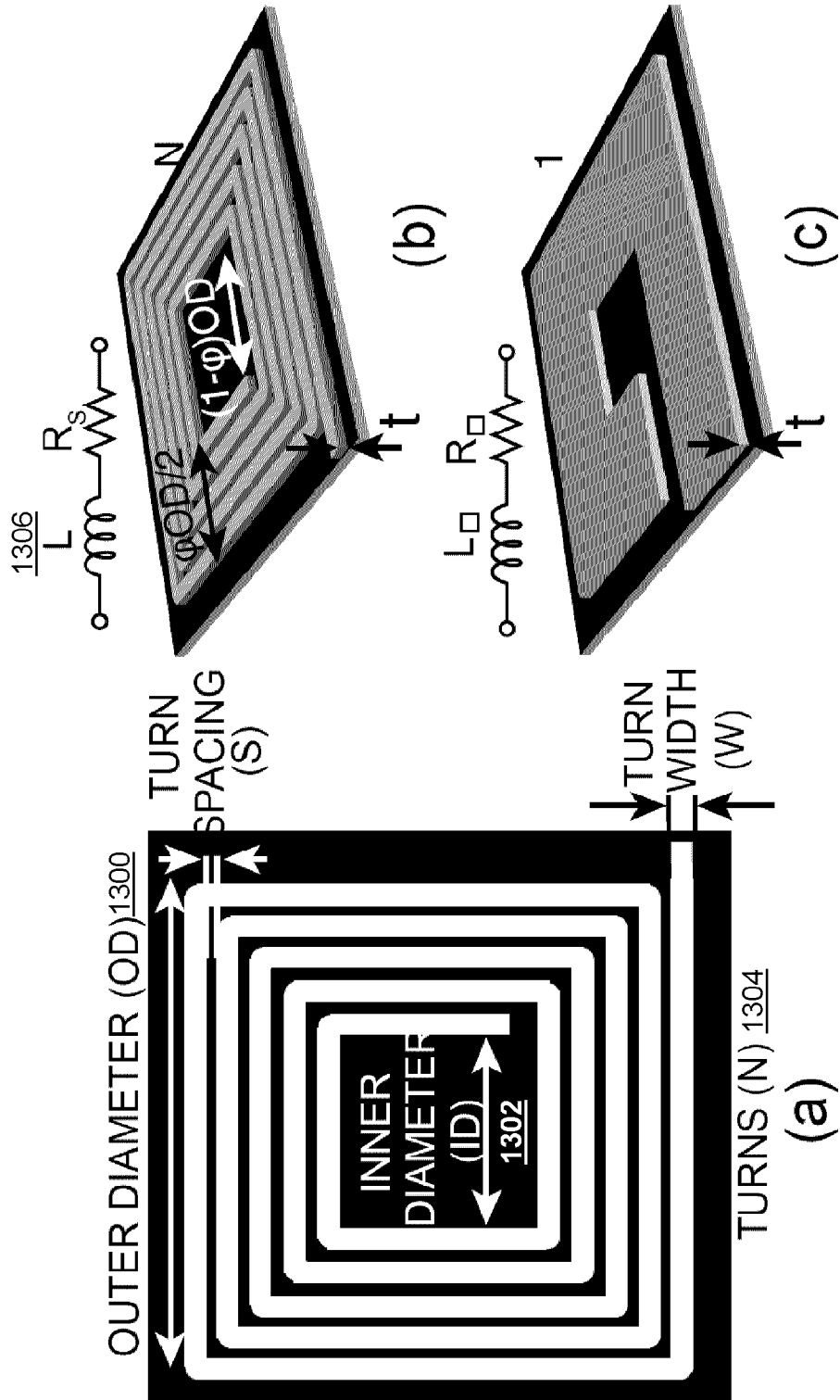


FIG. 13

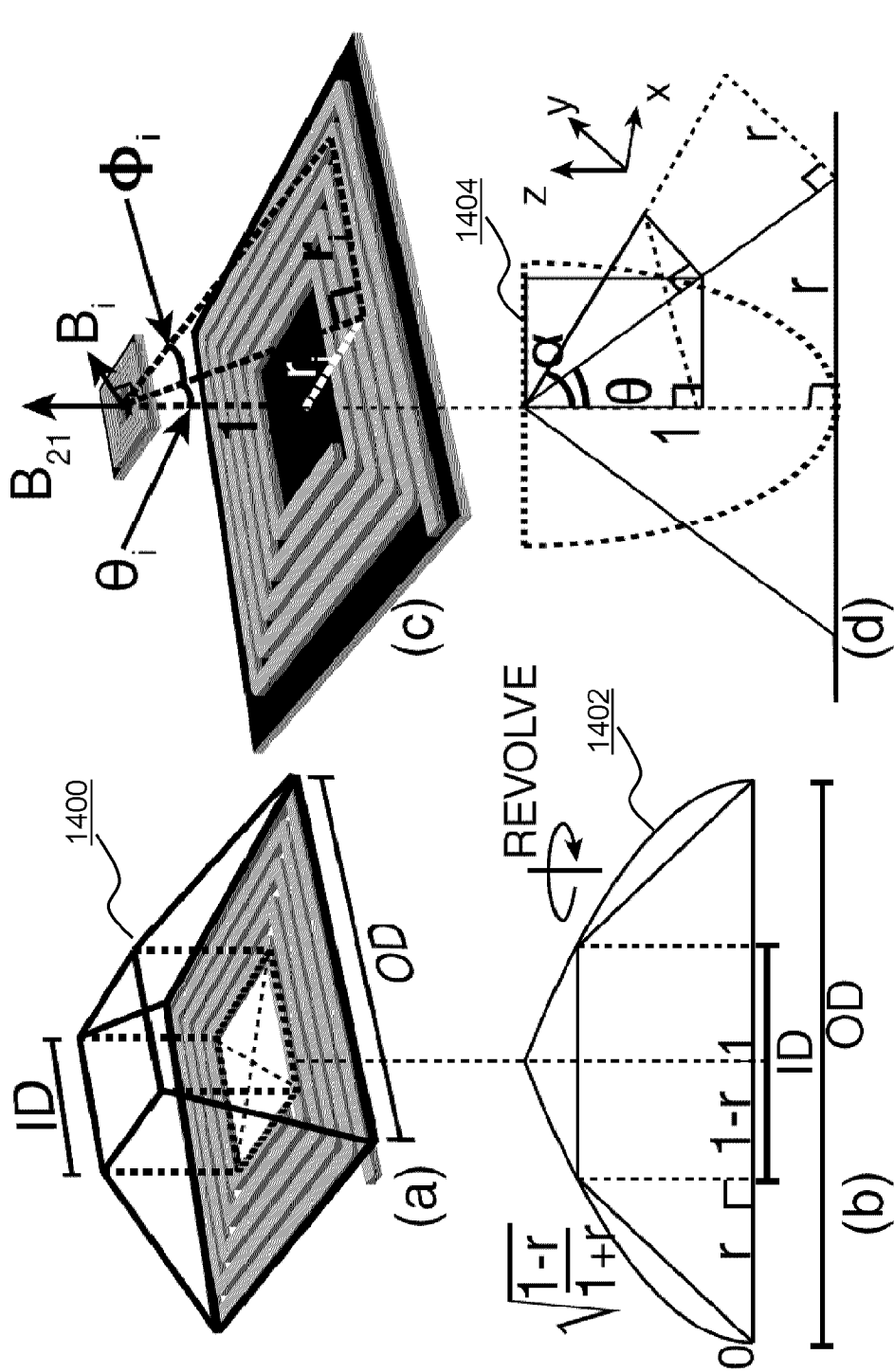


FIG. 14

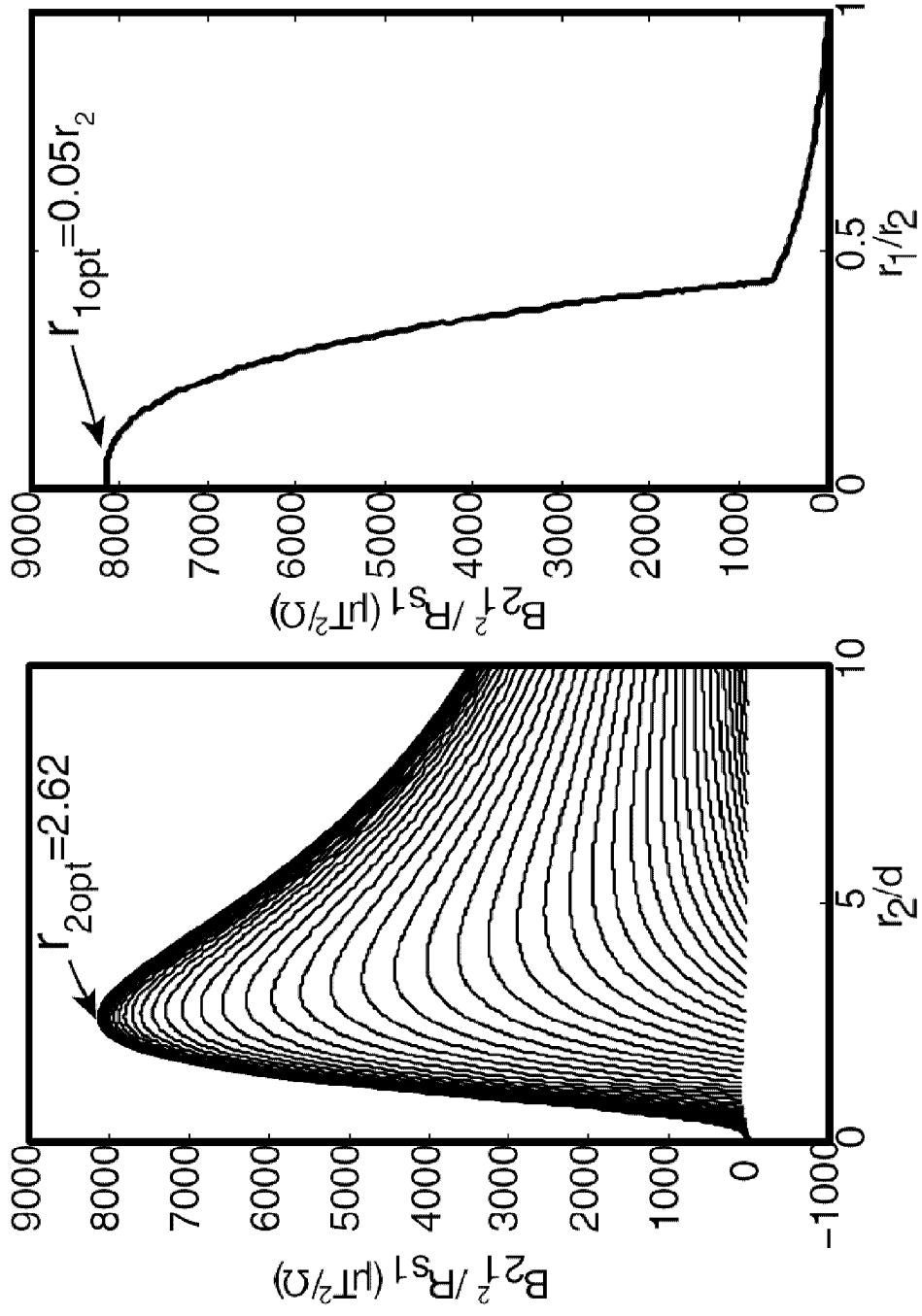
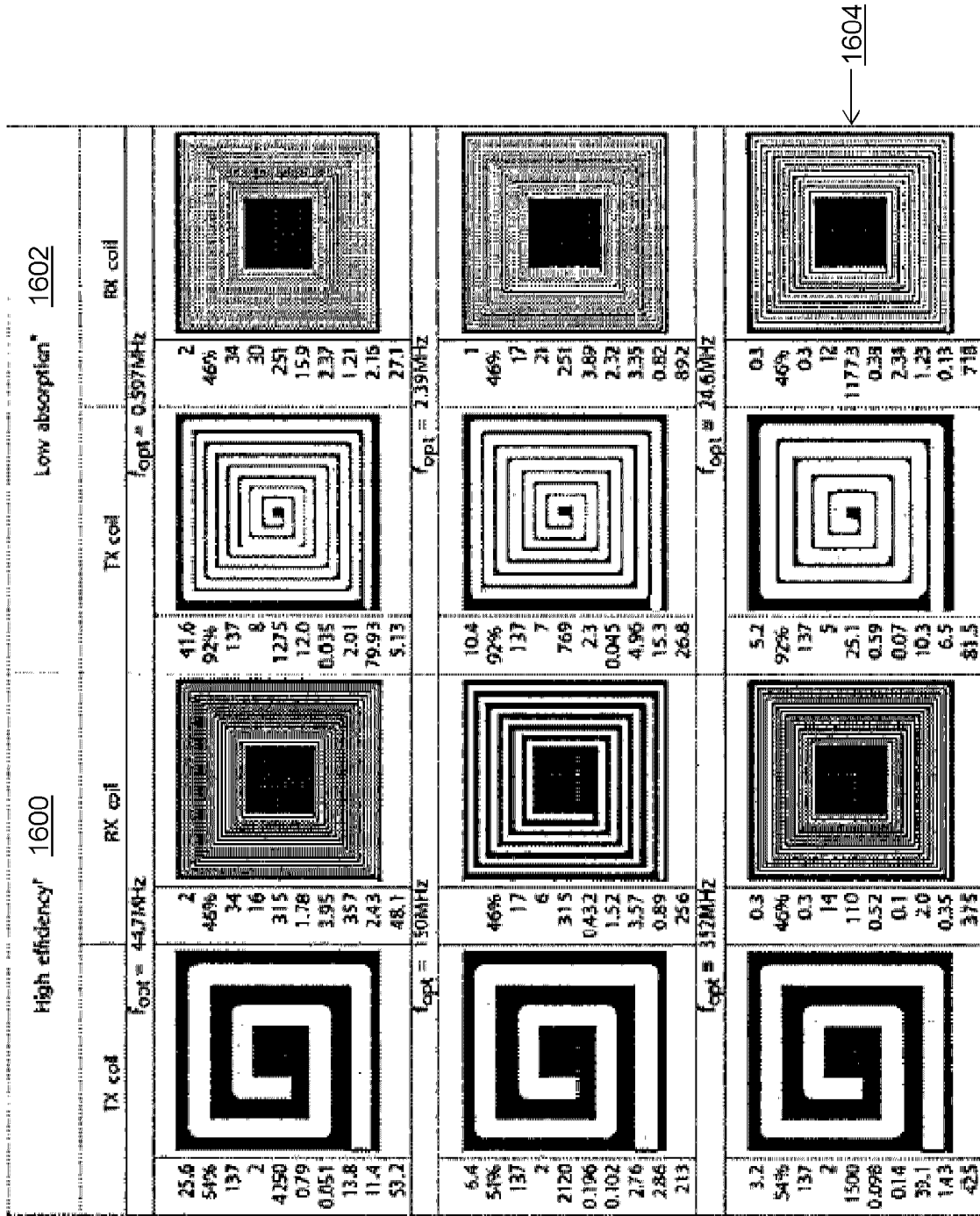


FIG. 15



1604

FIG. 16

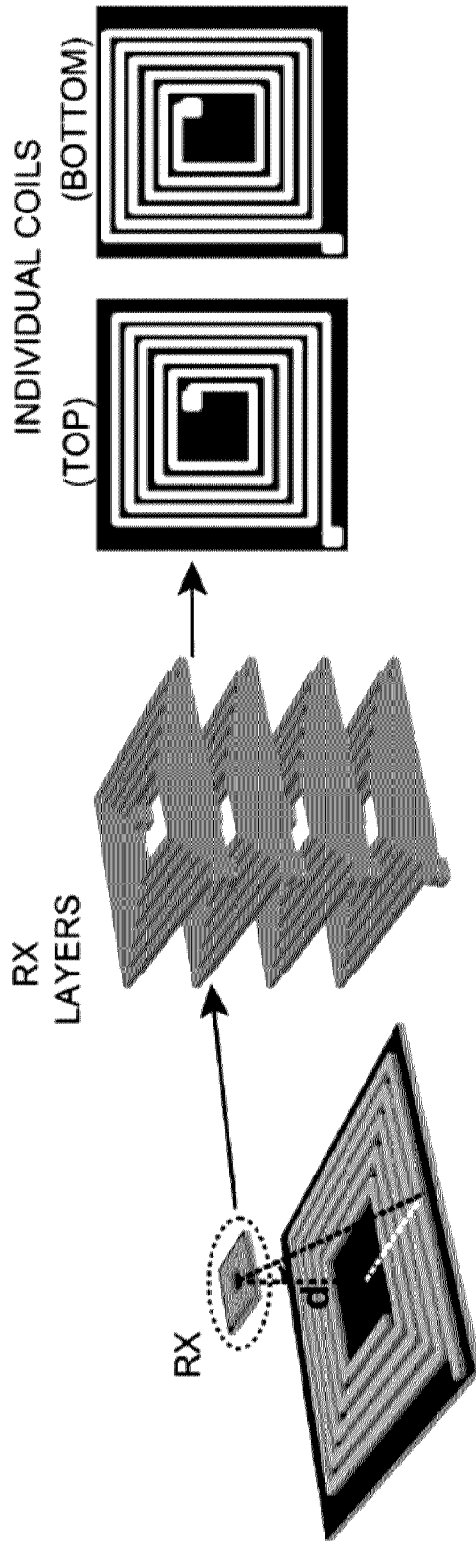


FIG. 17

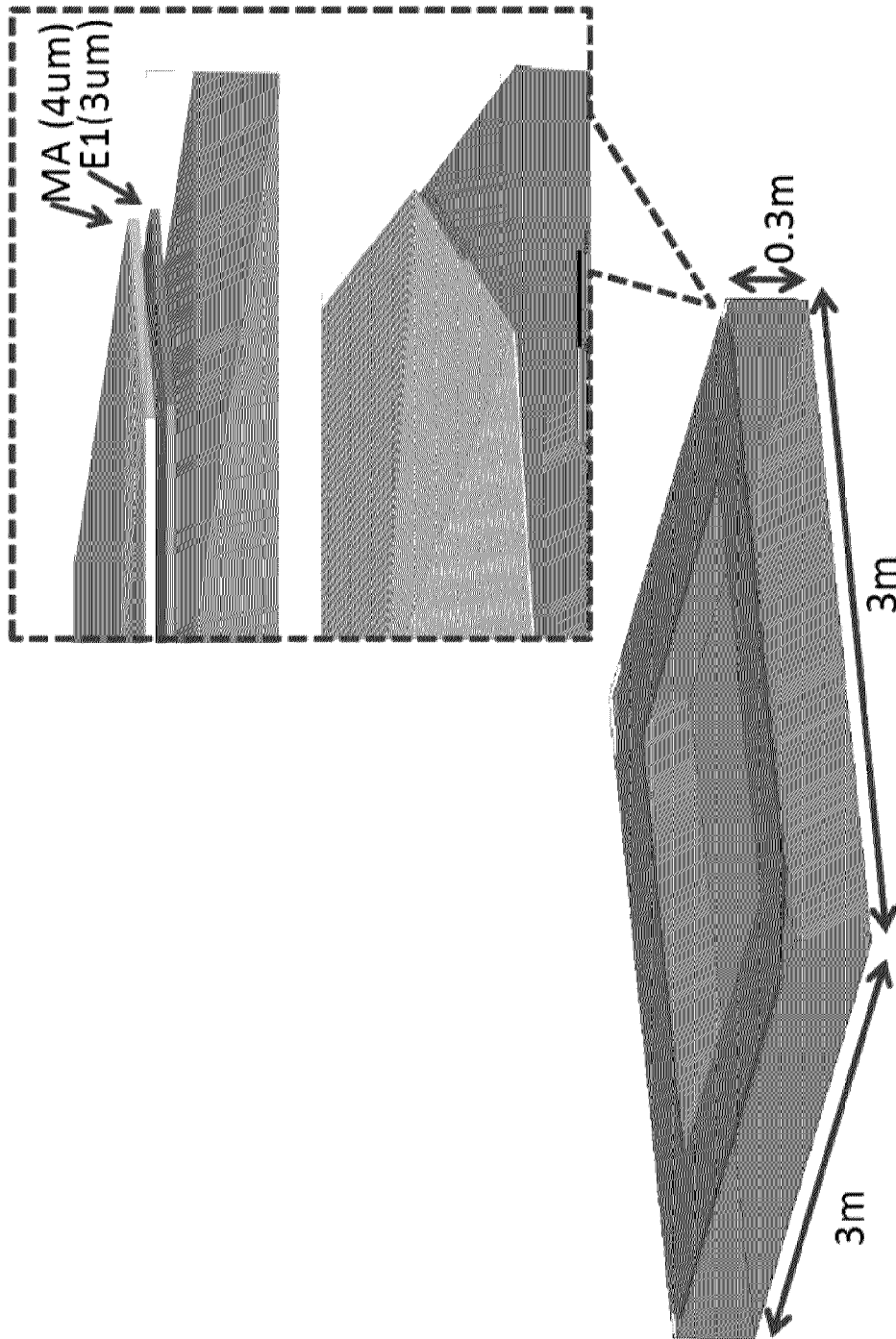


FIG. 18

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2016/051169

A. CLASSIFICATION OF SUBJECT MATTER
 IPC: **H02J 50/10** (2016.01), **A61B 90/00** (2016.01), **A61N 1/378** (2006.01), **G06F 1/26** (2006.01), **H02J 50/12** (2016.01),
H02J 50/80 (2016.01), **H04B 5/00** (2006.01), **H01Q 7/00** (2006.01)

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)
H02J* (2016.01), **A61B*** (2016.01), **A61N*** (2006.01), **G06F*** (2006.01), **H04B***, **H01Q*** (2006.01)

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

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

Databases searched: Canadian Patent Database, Questel Orbit, European Patent Database, Patent Abstracts of Japan (PAJ), US Patent Database, WIPO-PCT Publications (Full text), IEEE publications, Google Patents and Patents.com

Keywords: (implantable OR wearable) AND processor AND signal AND charging AND ("radio frequency" OR RF) and transmission coil

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US7212110 (Martin et al.), 01 May 2007 (01-05-2007) -see abstract; -see cols. 4, lines 36-42, 45-62; col. 11, lines 32-33, 62; -see figs. 2, 7.	1 - 19
Y	CN102157989 (Wang et al.), 17 August 2011 (17-08-2011) -see abstract; -see section [0033] and figs. 1-7; -see whole document.	1 - 19
Y	US8180452 (Shaquer), 15 May 2012 (15-05-2012) -see abstract; -see col. 1, line 67; -see figs. 1-5; -see whole document.	1 - 19

Further documents are listed in the continuation of Box C.

See patent family annex.

* "A" "E" "L" "O" "P"	Special categories of cited documents: document defining the general state of the art which is not considered to be of particular relevance earlier application or patent but published on or after the international filing date 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) document referring to an oral disclosure, use, exhibition or other means document published prior to the international filing date but later than the priority date claimed	"T" "X" "Y" "&"	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 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 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
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Date of the actual completion of the international search
05 January 2017 (05-01-2017)

Date of mailing of the international search report
13 January 2017 (13-01-2017)

Name and mailing address of the ISA/CA
 Canadian Intellectual Property Office
 Place du Portage I, C114 - 1st Floor, Box PCT
 50 Victoria Street
 Gatineau, Quebec K1A 0C9
 Facsimile No.: 819-953-2476

Authorized officer

Rajiv Agarwal
 (819) 639-1761

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of the 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. Claim Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. Claim 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. Claim 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:

The claims 1-27 lack single general inventive concept or technical relationship among various independent claims. The independent claims do not define special technical features, which can be considered as a contribution for each of the claimed inventions as a whole. Therefore, claims 1-27 do not meet the requirements of the Rule 13 of the PCT as described below:

Group I: Claims 1-19 are directed to an apparatus and a method for wireless power and data communication incorporating an implantable or wearable electronic device, the apparatus comprising a powering medium comprising a transmission coil electrically coupled to a source providing a power signal and a data signal, the powering medium generating a magnetic field for transmitting the power signal and the data signal wirelessly by the transmission coil; an implantable or wearable inductively powered device comprising a wireless interface communicatively coupled to an application circuit, the wireless interface comprising an inductive receiving circuit including an inductive data receiver and inductive power receiver, and a pulse radio transmitter, the inductive power receiver configured to receive the wirelessly transmitted power signal and data signal and provide the received power signal and data signal to the application circuit, and to transmit data received from the application circuit by an antenna; a receiver in communication with a computer for receiving the data and providing the data to a processor; and a computer comprising the source and the processor.

Group II: Claims 20-24 are directed to an electronic device for continuous and simultaneous powering and data transfer, the electronic device comprising an inductive power receiver comprising a resonator having a coil for receiving an externally induced magnetic field and correspondingly generating a resonating current; a rectifier electrically coupled to the inductive power receiver to convert and store a portion of the resonating current to a DC voltage; a limiter electrically coupled to the rectifier for limiting the DC voltage to a threshold voltage to produce a clipped signal thereof; and an antenna electrically coupled to the limiter and configured to emit a pulse-train

corresponding to the clipped signal.

Group III: Claims 25-26 are directed to a method for optimizing the geometries of magnetic coils and their stacking arrangement to optimize the power loss.

Group IV: Claim 27 is directed to a data transmission circuit comprising an input for receiving a pulse train at a first frequency; an oscillator comprising a switch toggling a digitally-controlled cross-coupled LC tank and a diode pair to produce a clipped pulse train; and a data transmitter configured to receive, from an application circuit, a baseband data stream for transmission, a delay lock loop and to align the baseband data stream to the pulse train, and a stream generator to generate a transmission stream by operating on the data stream with the pulse train.

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 claim 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 claim Nos.: 1 - 19

- 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.

INTERNATIONAL SEARCH REPORT

International application No.

PCT/CA2016/051169

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO2015092747 (Haim), 25 June 2015 (25-06-2015) -see abstract; -see figs. 1-21; -see whole document.	1 - 19

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CA2016/051169

Patent Document Cited in Search Report	Publication Date	Patent Family Member(s)	Publication Date
US7212110B1	01 May 2007 (01-05-2007)	US7212110B1 US7782190B1	01 May 2007 (01-05-2007) 24 August 2010 (24-08-2010)
CN102157989A	17 August 2011 (17-08-2011)	None	
US8180452B2	15 May 2012 (15-05-2012)	US2007118185A1 AU3949800A CA2406158A1 EP1294329A1 EP1294329A4 JP2003530960A US6810289B1 US2005131491A1 US7171273B2 WO0180795A1	24 May 2007 (24-05-2007) 07 November 2001 (07-11-2001) 01 November 2001 (01-11-2001) 26 March 2003 (26-03-2003) 31 March 2004 (31-03-2004) 21 October 2003 (21-10-2003) 26 October 2004 (26-10-2004) 16 June 2005 (16-06-2005) 30 January 2007 (30-01-2007) 01 November 2001 (01-11-2001)
WO2015092747A2	25 June 2015 (25-06-2015)	WO2015092747A2 WO2015092747A3	25 June 2015 (25-06-2015) 17 September 2015 (17-09-2015)