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(54) **ADAPTIVE MATCHING AND TUNING OF HF WIRELESS POWER TRANSMIT ANTENNA**

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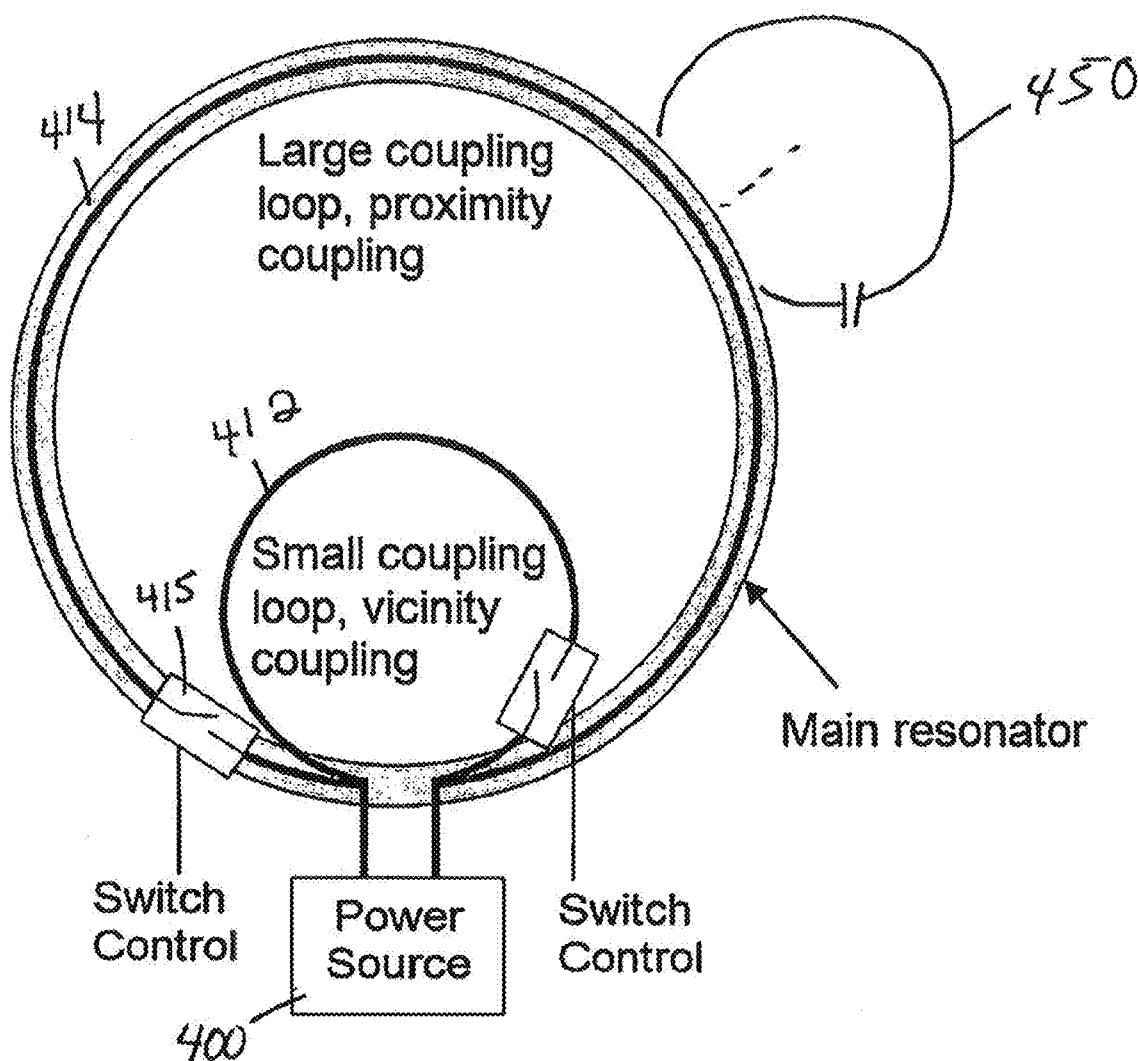
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(57) **ABSTRACT**

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Exemplary embodiments of the invention s are directed to a wireless power system with different coupling loops, such as two loops. The coupling loops are switched. One can be used for vicinity coupling, e.g., greater than a distance away, the other for proximity coupling, e.g., less than a distance away.

(21) Appl. No.: **12/505,353**



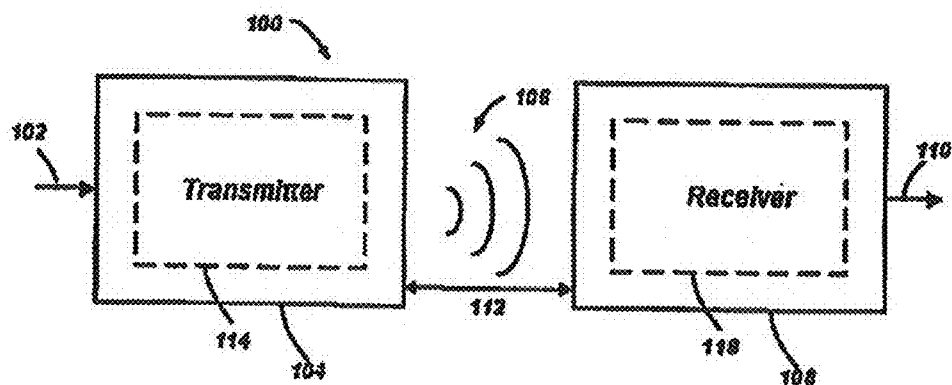


FIG. 1

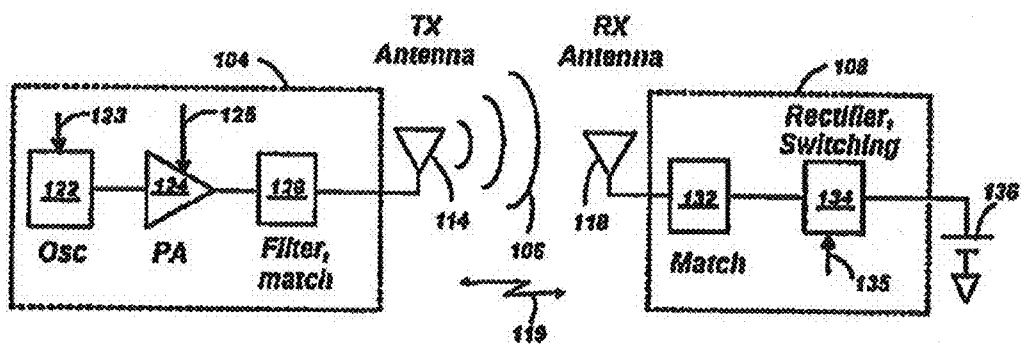


FIG. 2

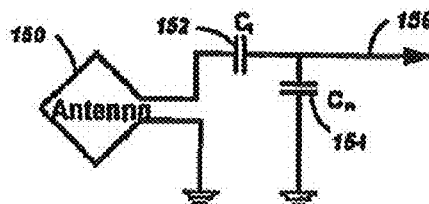


FIG. 3

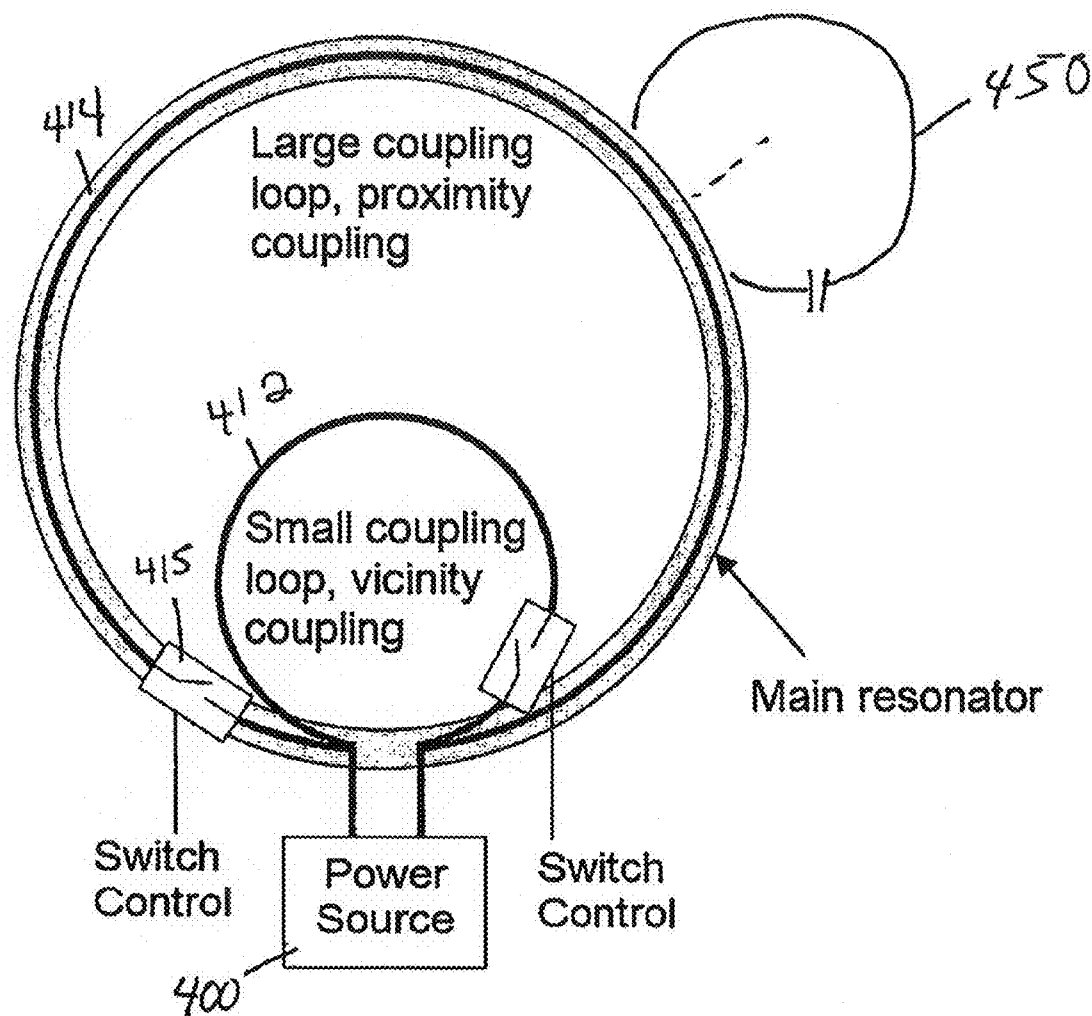


FIG 4

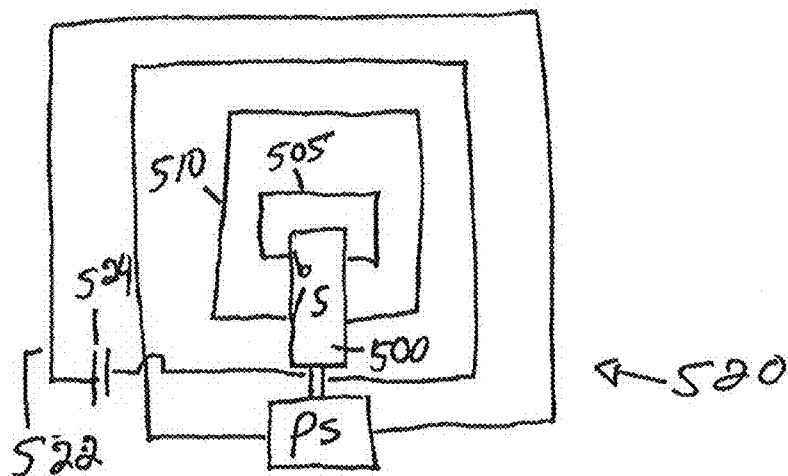


FIG 5

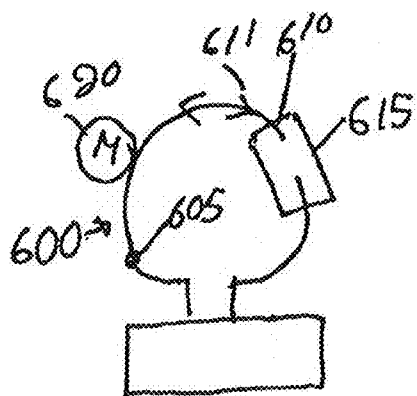


FIG 6

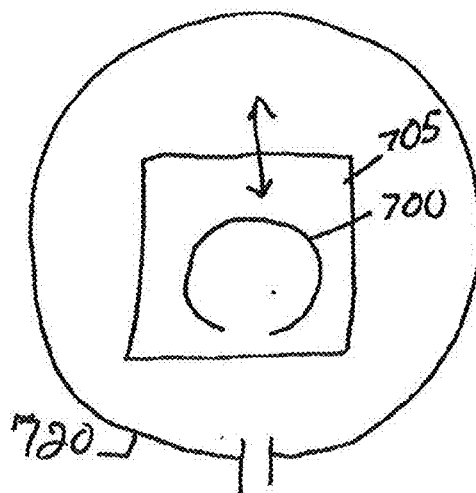
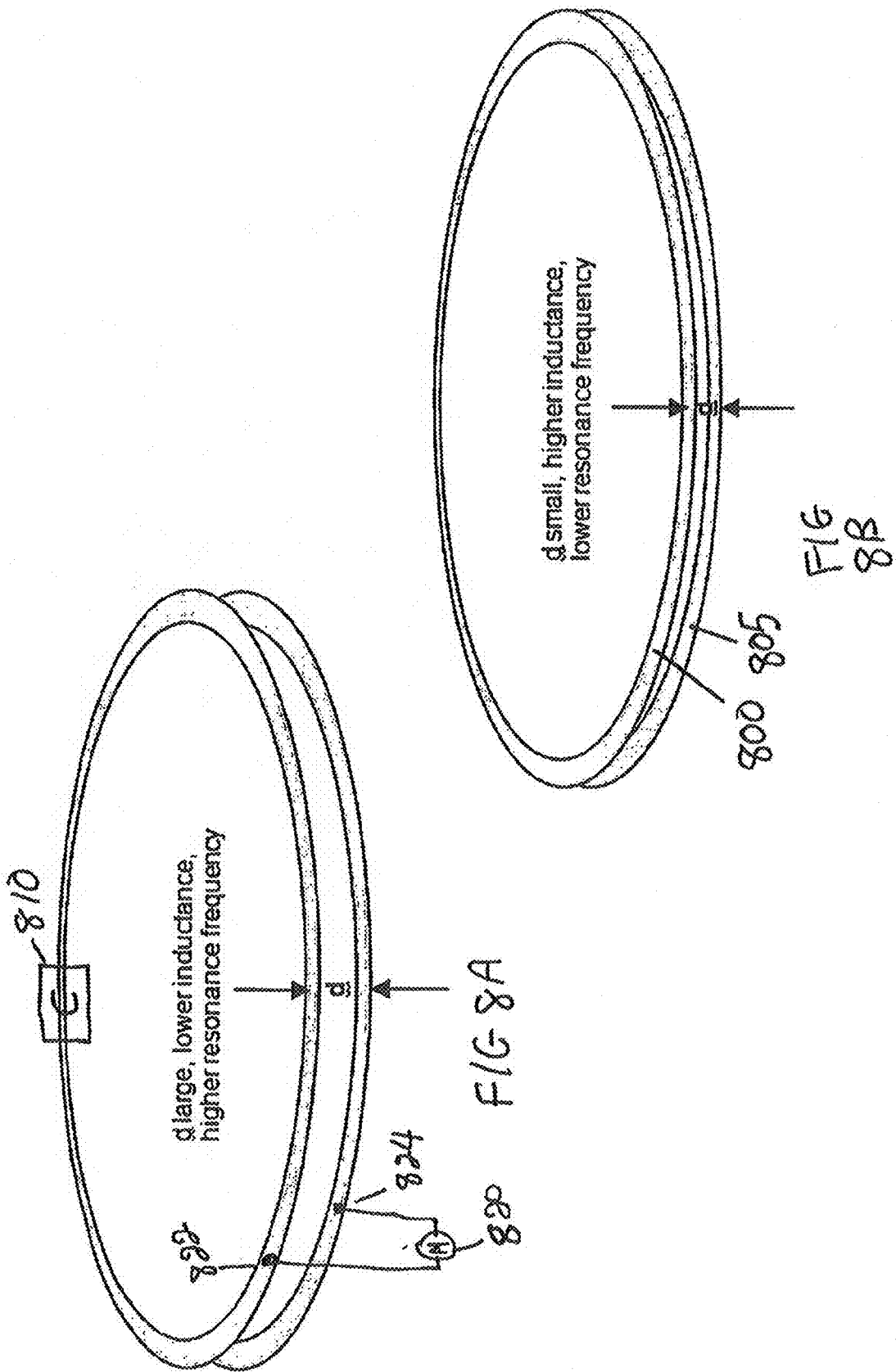


FIG 7



ADAPTIVE MATCHING AND TUNING OF HF WIRELESS POWER TRANSMIT ANTENNA

[0001] The present Application for Patent claims priority to Provisional Application No. 61/081,719, entitled “ADAPTIVE MATCHING AND TUNING OF HF WIRELESS POWER TRANSMIT ANTENNA” filed Jul. 17, 2008, and assigned to the assignee hereof and hereby expressly incorporated by reference herein.

BACKGROUND

[0002] Previous applications assigned to this assignee describe magnetically resonant transfer of power between antennas. The antennas may be capacitively loaded wire loops or multi-turn coils. These form a resonant antenna that efficiently couples energy from a primary structure (a transmitter) to a distal positioned secondary structure (a receiver) via a magnetic field. Both primary and secondary are tuned to a common resonance frequency.

[0003] These previous applications describe a major issue of wireless power as electromagnetic interference and radiation exposure for human safety. Energy transfer via magnetic field coupling may be mainly constrained by the specified H-field limits. Compliance with these limits may be tested at a defined distance, e.g., 10 m, from the radiating structure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] FIG. 1 shows a simplified block diagram of a wireless power transfer system.

[0005] FIG. 2 shows a more detailed block diagram of a wireless power transfer system.

[0006] FIG. 3 shows a schematic diagram of a loop antenna for use in exemplary embodiments of the present invention.

[0007] FIG. 4 shows a multiple part coupling loop;

[0008] FIG. 5 shows an embodiment on a PC board;

[0009] FIG. 6 shows a sliding part embodiment;

[0010] FIG. 7 shows a moving antenna embodiment; and

[0011] FIGS. 8A and 8B show a tunable solenoid.

DETAILED DESCRIPTION

[0012] The word “exemplary” is used herein to mean “serving as an example, instance, or illustration.” Any embodiment described herein as “exemplary” is not necessarily to be construed as preferred or advantageous over other embodiments.

[0013] The detailed description set forth below in connection with the appended drawings is intended as a description of exemplary embodiments of the present invention and is not intended to represent the only embodiments in which the present invention can be practiced. The detailed description includes specific details for providing a thorough understanding of the exemplary embodiments of the invention. It will be apparent to those skilled in the art that the exemplary embodiments of the invention may be practiced without these specific details. In some instances, well-known structures and devices are shown in block diagram form in order to avoid obscuring the novelty of the exemplary embodiments presented herein.

[0014] The words “wireless power” is used herein to mean any form of energy associated with electric fields, magnetic fields, electromagnetic fields, or otherwise that is transmitted from a transmitter to a receiver without the use of physical electromagnetic conductors.

[0015] FIG. 1 illustrates wireless transmission or charging system 100, in accordance with various exemplary embodiments of the present invention. Input power 102 is provided to a transmitter 104 for generating a radiated field 106 for providing energy transfer. A receiver 108 couples to the radiated field 106 and generates an output power 110 for storing or consumption by a device (not shown) coupled to the output power 110. Both the transmitter 104 and the receiver 108 are separated by a distance 112. In one exemplary embodiment, transmitter 104 and receiver 108 are configured according to a mutual resonant relationship. When the resonant frequency of receiver 108 and the resonant frequency of transmitter 104 are identical, transmission losses between the transmitter 104 and the receiver 108 are minimal when the receiver 108 is located in the “near-field” of the radiated field 106.

[0016] Transmitter 104 further includes a transmit antenna 114 for providing a means for energy transmission and receiver 108 further includes a receive antenna 118 for providing a means for energy reception. The transmit and receive antennas are sized according to applications and devices to be associated therewith. As stated, an efficient energy transfer occurs by coupling a large portion of the energy in the near-field of the transmitting antenna to a receiving antenna rather than propagating most of the energy in an electromagnetic wave to the far field. A coupling mode may be developed between the transmit antenna 114 and the receive antenna 118 when in this near-field. The area around the antennas 114 and 118 where this near-field coupling may occur is referred to herein as a coupling-mode region.

[0017] FIG. 2 shows a simplified schematic diagram of a wireless power transfer system. The transmitter 104 includes an oscillator 122, a power amplifier 124 and a filter and matching circuit 126. The oscillator 122 is configured to generate at a desired frequency, such as 13.5 MHz, which may be adjusted in response to adjustment signal 123. An alternative uses LF frequencies, e.g., 135 KHz. The oscillator signal may be amplified by the power amplifier 124 with an amplification amount responsive to control signal 125. The filter and matching circuit 126 may be included to filter out harmonics or other unwanted frequencies and match the impedance of the transmitter 104 to the transmit antenna 114.

[0018] The receiver 108 may include a matching circuit 132 and a rectifier and switching circuit 134 to generate a DC power output to charge a battery 136 as shown in FIG. 2 or power a device coupled to the receiver (not shown). The matching circuit 132 may be included to match the impedance of the receiver 108 to the receive antenna 118.

[0019] As illustrated in FIG. 3, antennas used in exemplary embodiments may be configured as a “loop” antenna 150, which may also be referred to herein as a “magnetic” antenna. Loop antennas may be configured to include an air core or a physical core such as a ferrite core. Using a ferrite core may decrease the effect of extraneous objects. However, ferrite cores may need a certain length to be effective, which may be difficult when used in a vehicle. Air disk coils are considered more suitable for integration in car and for embedding in the ground. LF Ferrites may be used as magnetic shield to prevent fields generating eddy currents in metallic parts of the antenna surrounding.

[0020] Efficiency may be improved by keeping other devices outside of the core area. Air core loop antennas may be more tolerable to extraneous physical devices placed in the vicinity of the core. Furthermore, an air core loop antenna allows the placement of other components within the core

area. In addition, an air core loop may more readily enable placement of the receive antenna **118** (FIG. 2) within a plane of the transmit antenna **114** (FIG. 2) where the coupled-mode region of the transmit antenna **114** (FIG. 2) may be more powerful.

[0021] As stated, efficient transfer of energy between the transmitter **104** and receiver **108** occurs during matched or nearly matched resonance between the transmitter **104** and the receiver **108**. However, even when resonance between the transmitter **104** and receiver **108** are not matched, energy may be transferred at a lower efficiency. Transfer of energy occurs by coupling energy from the near-field of the transmitting antenna to the receiving antenna residing in the neighborhood where this near-field is established rather than propagating the energy from the transmitting antenna into free space.

[0022] The resonant frequency of the loop or magnetic antennas is based on the inductance and capacitance. Inductance in a loop antenna is generally simply the inductance created by the loop, whereas, capacitance is generally added to the loop antenna's inductance to create a resonant structure at a desired resonant frequency. As a non-limiting example, capacitor **152** and capacitor **154** may be added to the antenna to create a resonant circuit that generates resonant signal **156**. Accordingly, for larger diameter loop antennas, the size of capacitance needed to induce resonance decreases as the diameter or inductance of the loop increases. Furthermore, as the diameter of the loop or magnetic antenna increases, the efficient energy transfer area of the near-field increases. Of course, other resonant circuits are possible. As another non-limiting example, a capacitor may be placed in parallel between the two terminals of the loop antenna. In addition, those of ordinary skill in the art will recognize that for transmit antennas the resonant signal **156** may be an input to the loop antenna **150**.

[0023] Exemplary embodiments of the invention include coupling power between two antennas that are in the near-fields of each other. As stated, the near-field is an area around the antenna in which electromagnetic fields exist but may not propagate or radiate away from the antenna. They are typically confined to a volume that is near the physical volume of the antenna. In the exemplary embodiments of the invention, magnetic type antennas such as single and multi-turn loop antennas are used for both transmit (Tx) and receive (Rx) antenna systems because magnetic near-field amplitudes tend to be higher for magnetic type antennas in comparison to the electric near-fields of an electric-type antenna (e.g., a small dipole). This allows for potentially higher coupling between the pair. Furthermore, "electric" antennas (e.g., dipoles and monopoles) or a combination of magnetic and electric antennas is also contemplated.

[0024] The Tx antenna can be operated at a frequency that is low enough and with an antenna size that is large enough to achieve good coupling (e.g., >-4 dB) to a small Rx antenna at significantly larger distances than allowed by far field and inductive approaches mentioned earlier. If the Tx antenna is sized correctly, high coupling levels (e.g., -2 to -4 dB) can be achieved when the Rx antenna on a host device is placed within a coupling-mode region (i.e., in the near-field) of the driven Tx loop antenna.

[0025] It should be noted that the foregoing approach is applicable to variety of communication standards such as CDMA, WCDMA, OFDM, and so forth. Those of skill in the art would understand that information and signals may be represented using any of a variety of different technologies

and techniques. For example, data, instructions, commands, information, signals, bits, symbols, and chips that may be referenced throughout the above description may be represented by voltages, currents, electromagnetic waves, magnetic fields or particles, optical fields or particles, or any combination thereof.

[0026] Exemplary embodiments of the invention are directed to (or include) the following.

[0027] A wireless power antenna and its operation is disclosed. In an exemplary embodiment, the wireless power antenna is a high frequency ("HF") transmit antenna. By adjusting matching to the antenna from or to wireless power circuitry, this may enable this system to be used for both proximity and vicinity coupling.

[0028] A high Q HF transmit antenna usually has a very low series resonance-impedance. It has been believed that these antennas should not be fed directly from a power source, because the low impedance could prevent the transmitter system from working efficiently.

[0029] Our previous applications described use of a coupling. The coupling loop transforms the low impedance of the transmit antenna to a suitable impedance for the power source e.g. 5 to 50 Ohms.

[0030] In an exemplary embodiment, the loaded and unloaded Q will determine the size of the coupling for the transmit antenna. A larger coupling loop can be used to increase coupling efficiency to feed power to a loaded antenna. A smaller coupling loop in the same plane as the main resonator may be sufficient to feed power to an unloaded antenna.

[0031] For a vicinity system, the transmit antenna is nearly unloaded, so the Q is very high. A good antenna can achieve an unloaded Q for example between 800 and 1000. A smaller coupling loop in the same plane as the main resonator is sufficient to feed power to the unloaded antenna.

[0032] For a proximity system, the Q of the transmit antenna drops due to the strong coupling to the receiver and due to the eddy-current losses in the metallic parts of the receiver. The loaded Q can be in the range of 100 to 200. To feed power to the loaded antenna, a larger coupling loop may be advantageous increase the coupling to the antenna.

[0033] A first exemplary embodiment is shown in FIG. 4 shows power source **400** as connected to a wireless power coupling loop **410**. That coupling loop, in turn, couples to a wireless power antenna **450**, which is magnetically resonant at the frequency of interest.

[0034] In an exemplary embodiment, the coupling loop **410** has two different coupling loops **412**, **414** of different sizes. The coupling loops can separately be activated. In an embodiment as shown, the small coupling loop **412** is used for vicinity (distance) coupling. The larger coupling loop **414** is used for proximity (close up) coupling. Each of the coupling loops has an embedded switch. For example, the vicinity coupling loop **412** includes an embedded switch **413** which is remotely controllable by a controller that is associated with the power source. Analogously the larger coupling loop **414** includes a switch **415**.

[0035] Only one of the switches **413** or **415** is closed at any one time. When a switch such as **415** is closed, this renders the loop **414** active, and the loop **412** inactive.

[0036] In an exemplary embodiment, this coupling loop can be formed on a printed circuit board, as shown in the exemplary embodiment of FIG. 5. In this printed circuit board embodiment, a switch **500** controls which of the two coupling

loops **505**, **510** be used as the coupling loop to transmit or receive wireless power. The switched coupling loop **505** or **510** is then used to connect to the magnetically resonant antenna **520** formed of an inductive element **522** in series with a capacitor **524**. While FIG. 5 shows an antenna **520** with two turns, it should be understood that the antenna can have any number of turns.

[0037] According to another exemplary embodiment, the coupling loop is mechanically resizable. For example, FIG. 6 shows a mechanically resizable coupling loop **600**. A hinge **605** allows a portion of the coupling loop **610** to move backwards and forwards as shown by the arrows **611**. This portion of the coupling loop is located on a contact pad **615** which extends over a remote area. In operation, a controllable mover **620**, e.g. a motor or hydraulic device, can be used to move the portion **610** to make the coupling loop either larger or smaller as desired.

[0038] FIG. 7 shows an alternative exemplary embodiment, in which the coupling loop **700** is located on a carrier **705**. That carrier **705** can be moved by action of the mover **715**. For example, the carrier **705** can be move towards or away from the main resonator **720**. This has the effect of changing the coupling between the coupling loop **700** in the main resonator **720**. In each of these exemplary embodiments, the mover can be electrical, pneumatic, or can use any other techniques.

[0039] In addition to matching to the transmit antenna being influenced by the position of the receiver, the resonance frequency can also be influenced. A device that is in close proximity to the coupling loop de-tunes the coupling loop due to its electrical and dielectric closeness. This in turn influences the inductance in capacitance of the transmit antenna.

[0040] FIGS. 8A and 8B illustrate an embodiment which addresses this issue. In the embodiment of FIG. 8A, a solenoid antenna is used which has two turns **800**, **805**. The rear portion of the antenna may include a capacitor element **810** attached thereto, and may be stable or hinged. However, the front portion of the spiral antenna can be compressed and decompressed to change the distance d between the loops **800**, **805**. By compressing the two loops **800**, **805** relative to one another, the inductance of this resonator increases, causing a lowered resonance frequency. Uncompressing these loops causes the inductance to decrease, alternatively raising the resonance frequency. This technique will allow a tuning range between 5 and 10%. In an embodiment, a mover **820** can be used to compress and decompress the loops. The mover can be a servomotor, pneumatic motor, or piezoelectric device, for example. This connects to the loops via brackets **822**, **824**.

[0041] In one exemplary embodiment, those brackets may be connected with Teflon to avoid changing the Q of the antenna. However, any material that does not destroy the high Q , typically a material with low dielectric losses, can be used for this purpose.

[0042] In an exemplary embodiment, the antenna itself **800**, **805** is formed of copper, and the elasticity of the copper is used to change the distance between the two materials. FIG. 8B illustrates the antenna in its more compressed scenario, where there is a distance of d_0 between the loops **800**, **805**.

[0043] While the above describes the use of two turns, the coil can be used with any number of turns. For example, this can be used with a five turn coil, while adjusting the spacing between only two of the loops.

[0044] These techniques can be used for transmit or receive antennas, and allow adapting to multiple load situations and can be used for both, proximity and vicinity power transfer.

[0045] Those of skill would further appreciate that the various illustrative logical blocks, modules, circuits, and algorithm steps described in connection with the embodiments disclosed herein may be implemented as electronic hardware, computer software, or combinations of both. To clearly illustrate this interchangeability of hardware and software, various illustrative components, blocks, modules, circuits, and steps have been described above generally in terms of their functionality. Whether such functionality is implemented as hardware or software depends upon the particular application and design constraints imposed on the overall system. Skilled artisans may implement the described functionality in varying ways for each particular application, but such implementation decisions should not be interpreted as causing a departure from the scope of the exemplary embodiments of the invention.

[0046] The various illustrative logical blocks, modules, and circuits described in connection with the embodiments disclosed herein may be implemented or performed with a general purpose processor, a Digital Signal Processor (DSP), an Application Specific Integrated Circuit (ASIC), a Field Programmable Gate Array (FPGA) or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A general purpose processor may be a microprocessor, but in the alternative, the processor may be any conventional processor, controller, microcontroller, or state machine. A processor may also be implemented as a combination of computing devices, e.g., a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration.

[0047] The steps of a method or algorithm described in connection with the embodiments disclosed herein may be embodied directly in hardware, in a software module executed by a processor, or in a combination of the two. A software module may reside in Random Access Memory (RAM), flash memory, Read Only Memory (ROM), Electrically Programmable ROM (EPROM), Electrically Erasable Programmable ROM (EEPROM), registers, hard disk, a removable disk, a CD-ROM, or any other form of storage medium known in the art. An exemplary storage medium is coupled to the processor such that the processor can read information from, and write information to, the storage medium. In the alternative, the storage medium may be integral to the processor. The processor and the storage medium may reside in an ASIC. The ASIC may reside in a user terminal. In the alternative, the processor and the storage medium may reside as discrete components in a user terminal.

[0048] In one or more exemplary embodiments, the functions described may be implemented in hardware, software, firmware, or any combination thereof. If implemented in software, the functions may be stored on or transmitted over as one or more instructions or code on a computer-readable medium. Computer-readable media includes both computer storage media and communication media including any medium that facilitates transfer of a computer program from one place to another. A storage media may be any available media that can be accessed by a computer. By way of example, and not limitation, such computer-readable media can comprise RAM, ROM, EEPROM, CD-ROM or other

optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium that can be used to carry or store desired program code in the form of instructions or data structures and that can be accessed by a computer. Also, any connection is properly termed a computer-readable medium. For example, if the software is transmitted from a website, server, or other remote source using a coaxial cable, fiber optic cable, twisted pair, digital subscriber line (DSL), or wireless technologies such as infrared, radio, and microwave, then the coaxial cable, fiber optic cable, twisted pair, DSL, or wireless technologies such as infrared, radio, and microwave are included in the definition of medium. Disk and disc, as used herein, includes compact disc (CD), laser disc, optical disc, digital versatile disc (DVD), floppy disk and blu-ray disc where disks usually reproduce data magnetically, while discs reproduce data optically with lasers. Combinations of the above should also be included within the scope of computer-readable media.

[0049] The previous description of the disclosed exemplary embodiments is provided to enable any person skilled in the art to make or use the present invention. Various modifications to these exemplary embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other embodiments without departing from the spirit or scope of the invention. Thus, the present invention is not intended to be limited to the embodiments shown herein, but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

What is claimed is:

1. A transmitter system for wireless power, comprising:
 - a antenna, comprising of an inductive element and a capacitor that are collectively magnetically resonant at a first frequency; and
 - a coupling loop assembly, comprising of a first coupling loop part of a first smaller size and a first switch to activate said first coupling loop, and a second coupling loop part of a second larger size with a second switch to activate said second coupling loop.
2. A system as in claim 1, further comprising a controller that detects a coupling to the antenna, and automatically selects either said first coupling loop or said second coupling loop based on said coupling.
3. A system as in claim 2, wherein said controller detects proximity coupling and selects said first coupling loop upon detecting proximity coupling.
4. A system as in claim 2, wherein said controller detects vicinity coupling and selects said second coupling loop upon detecting vicinity coupling.
5. A system as in claim 1, wherein said coupling loops are formed on a PC board.
6. A system as in claim 1, wherein said antenna includes multiple loops.
7. A system as in claim 6, wherein said multiple loops include a mechanism that moves positions of said loops relative to one another.
8. A system as in claim 2, wherein said antenna includes multiple loops.
9. A system as in claim 8, wherein said controller adjusts a resonance frequency of said antenna by moving said multiple loops relative to one another.
10. A system as in claim 2, wherein said coupling loop is unconnected to said antenna and coupling is performed via magnetic induction.
11. A receiver system for wireless power, comprising:
 - a circuit that receives a signal at a first frequency and produces an electrical output based on said first frequency;
 - a antenna, comprising of an inductive element and a capacitor that are collectively magnetically resonant at said first frequency; and
 - a coupling loop assembly, comprising of a first coupling loop part of a first smaller size and a first switch to activate said first coupling loop, and a second coupling loop part of a second larger size with a second switch to activate said second coupling loop.
12. A system as in claim 11, further comprising a controller that detects a coupling to the antenna, and automatically selects either said first coupling loop or said second coupling loop based on said coupling.
13. A system as in claim 12, wherein said controller detects proximity coupling and selects said first coupling loop upon detecting proximity coupling.
14. A system as in claim 12, wherein said controller detects vicinity coupling and selects said second coupling loop upon detecting vicinity coupling.
15. A system as in claim 11, wherein said coupling loops are formed on a PC board.
16. A system as in claim 11, wherein said antenna includes multiple loops.
17. A system as in claim 16, wherein said multiple loops include a mechanism that moves positions of said loops relative to one another.
18. A system as in claim 12, wherein said antenna includes multiple loops.
19. A system as in claim 18, wherein said controller adjusts a resonance frequency of said antenna by moving said multiple loops relative to one another.
20. A system as in claim 12, wherein said coupling loop is unconnected to said antenna and coupling performs via magnetic induction.
21. An antenna, comprising:
 - multiple loops forming an inductive part;
 - a capacitor, in series with said multiple loops; and
 - a mover, that moves said multiple loops relative to one another, to move the loops closer to one another to raise a resonance frequency of said antenna, and to move the loops further from one another to lower the resonance frequency of said antenna.
22. A system as in claim 21, wherein said mover includes an electric motor.
23. A system as in claim 21, wherein said mover includes a pneumatic motor.
24. A system as in claim 21, wherein said mover includes a piezoelectric device.
25. A method of coupling electric power, comprising:
 - detecting wireless power transfer with a proximity that is less than a first distance away, and switching to a smaller coupling loop to transfer power with the proximity; and
 - detecting wireless power transfer with a vicinity that is greater than the first distance away, and switching to a larger coupling loop to transfer power with the vicinity.
26. A method as in claim 25, wherein said switching comprises switching to use one coupling loop or a different coupling loop.

27. A method of coupling electric power, comprising:
configuring a circuit into a first configuration to transfer power wirelessly with a vicinity that is greater than a first distance away; and

configuring the circuit into a second configuration to transfer power with a proximity that is less than the first distance away.

28. A method as in claim **25**, wherein said configuring comprises switching to use one coupling loop or a different coupling loop.

29. A transmitter system as in claim **1**, further comprising a first circuit that produces a signal at a first frequency, coupled to said antenna.

30. A system for wireless power, comprising:

means for transmitting or receiving wireless power, said means, comprising of an inductive element and a capacitor that are collectively magnetically resonant at a first frequency; and

means for coupling wireless power to and from said means for transmitting or receiving, said coupling means including a means that first couples wireless power to said means, said first means of a first smaller size and a means for activating said first coupling loop means, and

a means for second coupling wireless power to said means for transmitting or receiving wireless power, said second means being of a second larger size than said first size, and means for activating said second means.

31. A system as in claim **30**, further comprising means for detecting a coupling to the means for transmitting or receiving wireless power, and automatically selecting either said first means or said second means based on said coupling.

32. A system as in claim **31**, wherein said means for detecting a coupling detects proximity coupling and selects said first means upon detecting said proximity coupling.

33. A system as in claim **31**, wherein said means for detecting a coupling detects vicinity coupling and selects said second means upon detecting said vicinity coupling.

34. A system as in claim **30**, wherein said first and second means are formed on a PC board.

35. A system as in claim **30**, wherein said means for transmitting and receiving includes multiple loops.

36. A system as in claim **35**, wherein said multiple loops include a means for moving positions of said loops relative to one another.

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