



UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

APPLICATION NUMBER	FILING or 371(c) DATE	GRP ART UNIT	FIL FEE REC'D	ATTY. DOCKET NO	TOT CLAIMS	IND CLAIMS
61/433,883	01/18/2011		110	AFPA-01029US0		

CONFIRMATION NO. 9465

23910

FLIESLER MEYER LLP
650 CALIFORNIA STREET
14TH FLOOR
SAN FRANCISCO, CA 94108

FILING RECEIPT



0C000000045718136

Date Mailed: 02/03/2011

Receipt is acknowledged of this provisional patent application. It will not be examined for patentability and will become abandoned not later than twelve months after its filing date. Any correspondence concerning the application must include the following identification information: the U.S. APPLICATION NUMBER, FILING DATE, NAME OF APPLICANT, and TITLE OF INVENTION. Fees transmitted by check or draft are subject to collection. Please verify the accuracy of the data presented on this receipt. **If an error is noted on this Filing Receipt, please submit a written request for a Filing Receipt Correction. Please provide a copy of this Filing Receipt with the changes noted thereon. If you received a "Notice to File Missing Parts" for this application, please submit any corrections to this Filing Receipt with your reply to the Notice. When the USPTO processes the reply to the Notice, the USPTO will generate another Filing Receipt incorporating the requested corrections**

Applicant(s)

Afshin Partovi, Sunnyvale, CA;

Power of Attorney:

Karl Kenna--45445

If Required, Foreign Filing License Granted: 01/27/2011

The country code and number of your priority application, to be used for filing abroad under the Paris Convention, is **US 61/433,883**

Projected Publication Date: None, application is not eligible for pre-grant publication

Non-Publication Request: No

Early Publication Request: No

**** SMALL ENTITY ****

Title

SYSTEM AND METHOD FOR MODULATING THE PHASE AND AMPLITUDE OF AN
ELECTROMAGNETIC WAVE IN MULTIPLE DIMENSIONS

PROTECTING YOUR INVENTION OUTSIDE THE UNITED STATES

Since the rights granted by a U.S. patent extend only throughout the territory of the United States and have no effect in a foreign country, an inventor who wishes patent protection in another country must apply for a patent in a specific country or in regional patent offices. Applicants may wish to consider the filing of an international application under the Patent Cooperation Treaty (PCT). An international (PCT) application generally has the same effect as a regular national patent application in each PCT-member country. The PCT process **simplifies** the filing of patent applications on the same invention in member countries, but **does not result** in a grant of "an international

page 1 of 3

patent" and does not eliminate the need of applicants to file additional documents and fees in countries where patent protection is desired.

Almost every country has its own patent law, and a person desiring a patent in a particular country must make an application for patent in that country in accordance with its particular laws. Since the laws of many countries differ in various respects from the patent law of the United States, applicants are advised to seek guidance from specific foreign countries to ensure that patent rights are not lost prematurely.

Applicants also are advised that in the case of inventions made in the United States, the Director of the USPTO must issue a license before applicants can apply for a patent in a foreign country. The filing of a U.S. patent application serves as a request for a foreign filing license. The application's filing receipt contains further information and guidance as to the status of applicant's license for foreign filing.

Applicants may wish to consult the USPTO booklet, "General Information Concerning Patents" (specifically, the section entitled "Treaties and Foreign Patents") for more information on timeframes and deadlines for filing foreign patent applications. The guide is available either by contacting the USPTO Contact Center at 800-786-9199, or it can be viewed on the USPTO website at <http://www.uspto.gov/web/offices/pac/doc/general/index.html>.

For information on preventing theft of your intellectual property (patents, trademarks and copyrights), you may wish to consult the U.S. Government website, <http://www.stopfakes.gov>. Part of a Department of Commerce initiative, this website includes self-help "toolkits" giving innovators guidance on how to protect intellectual property in specific countries such as China, Korea and Mexico. For questions regarding patent enforcement issues, applicants may call the U.S. Government hotline at 1-866-999-HALT (1-866-999-4158).

LICENSE FOR FOREIGN FILING UNDER

Title 35, United States Code, Section 184

Title 37, Code of Federal Regulations, 5.11 & 5.15

GRANTED

The applicant has been granted a license under 35 U.S.C. 184, if the phrase "IF REQUIRED, FOREIGN FILING LICENSE GRANTED" followed by a date appears on this form. Such licenses are issued in all applications where the conditions for issuance of a license have been met, regardless of whether or not a license may be required as set forth in 37 CFR 5.15. The scope and limitations of this license are set forth in 37 CFR 5.15(a) unless an earlier license has been issued under 37 CFR 5.15(b). The license is subject to revocation upon written notification. The date indicated is the effective date of the license, unless an earlier license of similar scope has been granted under 37 CFR 5.13 or 5.14.

This license is to be retained by the licensee and may be used at any time on or after the effective date thereof unless it is revoked. This license is automatically transferred to any related applications(s) filed under 37 CFR 1.53(d). This license is not retroactive.

The grant of a license does not in any way lessen the responsibility of a licensee for the security of the subject matter as imposed by any Government contract or the provisions of existing laws relating to espionage and the national security or the export of technical data. Licensees should apprise themselves of current regulations especially with respect to certain countries, of other agencies, particularly the Office of Defense Trade Controls, Department of State (with respect to Arms, Munitions and Implements of War (22 CFR 121-128)); the Bureau of Industry and

Security, Department of Commerce (15 CFR parts 730-774); the Office of Foreign Assets Control, Department of Treasury (31 CFR Parts 500+) and the Department of Energy.

NOT GRANTED

No license under 35 U.S.C. 184 has been granted at this time, if the phrase "IF REQUIRED, FOREIGN FILING LICENSE GRANTED" DOES NOT appear on this form. Applicant may still petition for a license under 37 CFR 5.12, if a license is desired before the expiration of 6 months from the filing date of the application. If 6 months has lapsed from the filing date of this application and the licensee has not received any indication of a secrecy order under 35 U.S.C. 181, the licensee may foreign file the application pursuant to 37 CFR 5.15(b).

SYSTEM AND METHOD FOR MODULATING THE PHASE AND AMPLITUDE OF AN ELECTROMAGNETIC WAVE IN MULTIPLE DIMENSIONS

Inventor: Afshin Partovi

Copyright Notice

A portion of the disclosure of this patent document contains material which is subject to copyright protection. The copyright owner has no objection to the facsimile reproduction by anyone of the patent document or the patent disclosure, as it appears in the Patent and Trademark Office patent file or records, but otherwise reserves all copyright rights whatsoever.

Field of Invention:

[0001] The invention is generally related to modulating the phase and amplitude of an electromagnetic wave in multiple (e.g. two or three) dimensions. Applications include inductive charging, and particularly usage in mobile, electronic, electric, lighting, or other devices, batteries, power tools, kitchen, industrial applications, vehicles, and other usages. The invention can also be applied generally to multiple dimensional power supplies and other power sources and chargers, including systems and methods for improved ease of use and compatibility and transfer of wireless power to mobile, electronic, electric, lighting, or other devices, batteries, power tools, kitchen, industrial applications and/or vehicles.

Background:

[0002] Wireless technologies for powering and charging mobile and other electronic or electric devices, batteries and vehicles have been developed. These systems generally use a wireless charger or transmitter system and a wireless receiver in combination to provide a means for transfer of power across a distance. For safe and efficient operation the two coil parts of the system are typically aligned and of comparable or similar size. The operation in this system requires the users to place the device or battery to be charged in a specific location. To enable better ease of use, it is important that the receiver can be placed on a charger without specific alignment between the coils. It is further highly desirable to be able to charge or power multiple devices of similar or different power requirements on the same surface. This is the general area that embodiments of the invention are intended to address

Summary:

[0003] Described herein are systems and methods of modulating the phase and amplitude

of an electromagnetic wave in multiple (e.g. one, two or three) dimensions. Applications include beam shaping, beam forming, phase array radar, beam steering, etc. and inductive charging, and particularly usage in mobile, electronic, electric, lighting, or other devices, batteries, power tools, kitchen, industrial applications, vehicles, and other usages. Embodiments of the invention can also be applied generally to power supplies and other power sources and chargers, including systems and methods for improved ease of use and compatibility and transfer of wireless power to mobile, electronic, electric, lighting, or other devices, batteries, power tools, kitchen, industrial applications and/or vehicles.

Detailed Description:

[0004] With the proliferation of electrical and electronic devices and vehicles (which are considered examples of devices herein), simple and universal methods of providing power and or charging of these devices is becoming increasingly important. The term device, product, or battery is used herein to include any electrical, electronic, mobile, lighting, or other product, batteries, power tools, industrial, kitchen, or medical products and vehicles whereby the product, part, or component is powered by electricity or an internal or external battery and/or can be powered or charged externally or internally by a generator. A product or device can also include an attachable or integral skin, case, battery door or attachable or add-on component to enable the user to power or charge the product or device. An induction power transmitter employs a magnetic induction coil(s) transmitting energy to a receiving coil(s) in a device or product or battery placed near the power platform. The receiver can be an incomplete device intended for installation in or on the product, battery or device to be powered or charged, or the receiver can be a complete device intended for connection to a device, product or battery. Herein, the term wireless power, charger, or inductive power and charger are used interchangeably. Examples of products or devices powered or charged by the induction transmitter and receiver include but are not limited to cell phones, cordless phones, communication devices, personal data assistants, portable media players, global positioning (GPS) devices, Bluetooth headsets and other devices, shavers, tooth brushes, calculators, cameras, optical scopes, infrared viewers, computers, laptops, netbooks or email devices, computer monitors, televisions, music or movie players and recorders, speakers, laptops, gaming devices, game controllers, toys, remote controllers, power tools, office equipment, robots, industrial tools, mobile vacuum cleaners, medical tools, military equipment or tools, kitchen appliances, food or beverage heaters or coolers such as electrically powered beverage mugs, massagers, adult toys, lights or light fixtures, printers, fax machines, vehicles, automobiles, buses, or other vehicles, and similar

battery or electrically powered devices or products. It is important to note that the product or device does not necessarily have to be portable and/or contain a battery to take advantage of induction or wireless power transfer. For example, a lighting fixture or a computer monitor that are typically powered by an AC outlet or a DC power supply may be placed on a table top and receive power wirelessly.

[0005] Many of these devices contain internal batteries, and the device may or may not be operating during receipt of power. Depending on the degree of charge status of the battery or its presence and the system design, the applied power may provide power to the device, charge its battery or a combination of the above. The terms charging and/or power are used interchangeably herein to indicate that the received power can be used for either of these cases or a combination thereof. Unless specifically described, these terms are therefore used interchangeably. Also, unless specifically described herein, in accordance with various embodiments the terms charger and transmitter are used interchangeably.

[0006] As shown in **Figure 1**, in accordance with an embodiment, a wireless charger or power system comprises a charger or transmitter part, and a receiver part. The charger or transmitter can generate a repetitive power signal pattern (such as a sinusoid or square wave from 10's of Hz to several MHz or even higher, but typically in the 100 kHz to several MHz range) with its coil drive circuit and a coil or antenna for transmission of the power. The charger or transmitter typically also includes a communication and regulation / control system that detects a receiver and/or turns the applied power on or off and/or modify the amount of applied power by mechanisms such as changing the amplitude, frequency or duty cycle, etc. or a combination thereof of the applied power signal to the coil or antenna.

[0007] The second part of the system is a receiver that includes a coil or antenna to receive power, a method for change of the received AC voltage to DC voltage, such as rectification and smoothing with one or more rectifiers or a bridge or synchronous rectifier, etc. and one or more capacitors, and optionally a method for the receiver to communicate with the charger.

[0008] The optional method of communication between the charger and receiver can be through the same coils as used for transfer of power, through a separate coil, through an RF or optical link, through RFID, Bluetooth, WiFi, Wireless USB, Zigbee, or other communication protocol or combination thereof. It is also possible to develop systems whereby there is no communication between the charger and receiver. In case of communication through the power transfer coil, one method for the communication is to modulate the load in the receiver to affect the voltage in the receiver coil and therefore create a modulation in the charger coil parameters

that can be detected through monitoring of its voltage or current. Other methods can include frequency modulation by combining the received frequency with a local oscillator signal or inductive, capacitive, or resistive modulation of the output of the receiver coil.

[0009] The communicated information can be the output voltage, current, device or battery status, validation ID for receiver, end of charge or various charge status information, receiver battery, device, or coil temperature, or user data such as music, email, voice, photos or video, or other form of digital or analog data used in a device.

[0010] The data communicated can be any one or more of the information detailed herein, or the difference between these values and the desired value or simple commands to increase or decrease power or simply one or more signals that would confirm presence of a receiver or a combination of the above. In addition, the receiver can include other elements such as a dc to dc converter or regulator such as a switching, buck, boost, buck / boost, or linear regulator. The receiver can also include a switch between the DC output of the receiver coil and its output to a device or battery or a device case or skin and in cases where the receiver is used to charge a battery, the receiver may also include a battery charger IC or circuitry and/or battery protection circuit and associated transistors, etc. The receiver and/or charger and/or their coils can also include elements such as thermistors, magnetic shields or magnetic cores, magnetic sensors, and input voltage filters, etc. for safety and/or emission compliance reasons. In addition, the charger and or receiver can include means to provide more precise alignment between the charger and receiver coils or antennas. These can include visual, physical, or magnetic means to assist the user in alignment of parts. To implement more positioning freedom of the receiver on the charger, the size of the coils can also be mismatched. For example, the charger can comprise a larger coil size and the receiver a smaller one or vice versa, so that the coils do not have to be precisely aligned for power transfer.

[0011] In simpler architectures, there may be minimal or no communication between the charger and receiver. For example, a charger can be designed to be in a standby power transmitting state, and any receiver in close proximity to it can receive power from the charger. The voltage, power, or current requirements of the device or battery connected to the receiver circuit can be regulated or controlled completely at the receiver or by the device attached to it. In this instance, no regulation or communication between the charger and receiver may be necessary. In a variation of this, the charger may be designed to be in a state where a receiver in close proximity would bring it into a state of power transmission. Examples of this would be a resonant system where inductive and/or capacitive components are used, so that when a receiver of appropriate design is in proximity to a charger, power is transmitted from the charger

to a receiver; but without the presence of a receiver, minimal or no power is transmitted from the charger. In a variation of the above, the charger can periodically be turned on to be driven with a periodic pattern (a ping process) and if a receiver in proximity begins to draw power from it, it can detect power being drawn from it and stay in a transmitting state. If no power is drawn during the ping process, the charger can be turned off to conserve power and turned on and off again periodically to continue seeking a receiver.

[0012] In accordance with an embodiment, the power section (coil drive circuit and receiver power section) can be a resonant converter, resonant, zero switching, flyback, or any other appropriate power supply topology. **Figure 2** shows a more detailed view of the wireless charger system with a resonant converter geometry, wherein a pair of transistors Q1 and Q2 (such as FETs, MOSFETs, or other types of switch) are driven by a half-bridge driver IC and the voltage is applied to the coil L1 through one or more capacitors shown as C1. The receiver includes a coil and an optional capacitor (for added efficiency) shown as C2 that may be in series or in parallel with the receiver coil L2. The charger and/or receiver coils may also include appropriate magnetic material layers behind (on the side opposite to the coil surfaces facing each other) them to increase their inductance and/or to shield the magnetic field leakage to surrounding area.

[0013] In accordance with an embodiment, the charger also includes a circuit that measures the current through and/or voltage across the charger coil (in this case a current sensor is shown in the figure as an example). Various demodulation methods for detection of the communication signal on the charger current or voltage are available. This demodulation mechanism can be, for example, an AM or FM receiver (depending on whether amplitude or frequency modulation is employed in the receiver modulator) similar to a radio receiver tuned to the frequency of the communication or a heterodyne detector, etc.

[0014] In accordance with an embodiment, the microcontroller unit (MCU) in the charger (MCU2) is responsible for understanding the communication signal from the detection / demodulation circuit and, depending on the algorithm used, making appropriate adjustments to the charger coil drive circuitry to achieve the desired output voltage, current or power from the receiver output. In addition, MCU1 is responsible for processes such as periodic start of the charger to seek a receiver at the start of charge, keeping the charger on when a receiver is found and accepted as a valid receiver, continuing to apply power and making necessary adjustments, and/or monitoring temperature or other environmental factors, providing audio or visual indications to the user on the status of charging or power process, etc. or terminating charging or application of power due to end of charge or customer preference or over

temperature, over current, over voltage, or some other fault condition or to launch or start another program or process. For example, the charger can be built into a car, and when a valid receiver integrated into or on a mobile device, its case or skin, or battery is found, the charger may activate some other functions such as Bluetooth connectivity to the device, displaying the device identity or its status or state of charge on a display, etc. More advanced functions can also be activated or enabled by this action. Examples can include routing a mobile phone call or music from a smart phone to the speakers and microphones in a car, etc. Other similar actions or different actions can be provided in other environments. It may be useful in addition to the communication signal to detect the dc value of the current through the charger coil. For example, faults may be caused by insertion or presence of foreign objects such as metallic materials between the charger and receiver. These materials may be heated by the application of the power and can be detected through detection of the charger current or temperature or comparison of input voltage, current, or power to the charger and output voltage, current, or power from the receiver and concluding that the ratio is out of normal range and extra power loss due to unknown reasons is occurring. In these conditions or other situations such as abnormal charger and/or receiver heating, the charger may be programmed to declare a fault condition and shut down and/or alert the user or take other actions.

[0015] In accordance with an embodiment, once the charger MCU has received a signal and decoded it, it can take action to provide more or less power to the charger coil. This can be accomplished through known methods of adjusting the frequency, duty cycle or input voltage to the charger coil or a combination of these approaches. Depending on the system and the circuit used, the MCU can directly adjust the bridge driver or an additional circuit such as a frequency oscillator may be necessary to drive the bridge driver or the FETs.

[0016] A typical circuit for the receiver in accordance with an embodiment is also shown in Figure 2. In accordance with an embodiment, the receiver circuit can include a capacitor C2 in parallel or series with the receiver coil to produce a tuned receiver circuit. This circuit is known to increase the efficiency of a wireless power system. The rectified and smoothed (through a bridge rectifier and capacitors) output of the receiver coil and optional capacitor is either directly or through a switch or regulator applied to the output. A microcontroller is used to measure various values such as output voltage, current, temperature, state of charge, battery full status, end of charge, etc. and to report back to the charger to provide a closed loop system with the charger as described above. In the circuit shown in Figure 2, the receiver MCU communicates back to the charger by modulating the receiver load by rapidly closing and opening a switch in series with a modulation load at a pre-determined speed and coding pattern. This rapid load

modulation technique at a frequency distinct from the power transfer frequency can be easily detected by the charger. A capacitor and/or inductor can also be placed in parallel or in series with this load.

[0017] For example, if one assumes that the maximum current output of the receiver is 1000 mA and the output voltage is 5 V for a maximum output of 5W; in this case, the minimum load resistance is 5 ohms. A modulation load resistor of several ohms (20, or 10 ohms or smaller) would be able to provide a large modulation depth signal on the receiver coil voltage. Choosing a 5 ohm resistor would modulate the output between a maximum current of 1 Amp or larger and a smaller value defined by the device load at the output. Such a large modulation can be easily detected at the charger coil current or voltage as described above. Alternatively the modulation can be achieved capacitively, by replacing the resistor with a capacitor. In this instance, the modulation by the switch in the receiver provides the advantage that by choosing the modulation frequency appropriately, it is possible to achieve modulation and signal communication with the charger coil and circuitry, with minimal power loss (compared to the resistive load modulation).

[0018] The receiver in Figure 2 also shows an optional dc regulator that is used to provide constant stable voltage to the receiver MCU. This voltage supply may be necessary to avoid drop out of the receiver MCU during startup conditions where the power is varying largely or during changes in output current and also to enable the MCU to have a stable voltage reference source so it can measure the output voltage accurately. Alternatively, a switch to connect or disconnect the load can be used or combined with the regulator.

[0019] In the above description, a uni-directional communication (from the receiver to the charger) is described. However, this communication can also be bi-directional, and data can be transferred from the charger to the receiver through modulation of the voltage or current in the charger coil and read back by the microcontroller in the receiver detecting a change in the voltage or current, etc.

[0020] In accordance with other embodiments, and other geometries where position independence on placement of the receiver on the charger surface is achieved by having multiple charger coils in an array or pattern, similar drive and communication circuits in the charger and receiver can be implemented. To detect the appropriate coil to activate in the charger, the coils can be activated in a raster or zigzag fashion or other geometry and current drawn from a charger coil, strength of voltage, current, power or signal from the receiver or other methods can be used to determine the closest match between position of one or more of the charger coils and a receiver coil and the appropriate charger coil or coils can be activated

and modulated to provide optimum power transfer to the receiver.

[0021] While a system for communication between the charger and receiver through the power transfer coil or antenna is described above, in accordance with an embodiment the communication can also be implemented through a separate coil, a radio frequency link (am or fm or other communication method), an optical communication system or a combination of the above. The communication in any of these methods can also be bi-directional rather than uni-directional as described above. As an example, **Figure 3** shows a system in accordance with an embodiment, wherein a dedicated RF channel for uni-directional or bi-directional communication between the charger and receiver is implemented for validation and/or regulation purposes. This system is similar to the system shown in Figure 2, except rather than load modulation being the method of communication, the MCU in the receiver transmits the necessary information over an RF communication path. A similar system with LED or laser transceivers or detectors and light sources can be implemented. Advantages of such system include that the power received is not modulated and therefore not wasted during communication and/or that no noise due to the modulation is added to the system.

[0022] One of the disadvantages of the circuit shown in Figure 2 is that in the receiver circuit shown therein, the current path passes through 2 diodes and suffers 2 voltage drops resulting in large power dissipation and loss. For example, for Schottky diodes with forward voltage drop of 0.4 V, at a current output of 1 A, each diode would lose 0.4 W of power for a combined power loss of 0.8 W for the two in a bridge rectifier configuration. For a 5 V, 1 A output power (5W), this 0.8 W of power loss presents a significant amount of loss (16%) just due to the rectification system.

[0023] In accordance with an embodiment, an alternative is to use a center-tapped receiver as shown in **Figure 4**, wherein during each cycle current passes only through one part of the coil and one diode in the receiver and therefore halves the rectification losses. Such a center tapped coil can be implemented in a wound wire geometry with 2 sections of a wound wire or a printed circuit board coil or with a double or multi-sided sided PCB coil or a combination or even a stamped, etched or otherwise manufactured coil or winding.

[0024] In any of the systems described above, as shown in **Figure 5**, the charger and receiver coils can be represented by their respective inductances by themselves (L_1 and L_2) and the mutual inductance between them M which is dependent on the material between the two coils and their position with respect to each other in x, y, and z dimensions. The coupling coefficient between the coils k is given by:

$$k = M / (L1 * L2)^{1/2}$$

[0025] The coupling coefficient is a measure of how closely the 2 coils are coupled and may range from 0 (no coupling) to 1 (very tight coupling). In coils with small overlap, large gap between coils or dissimilar coils (in size, number of turns, coil winding or pattern overlap, etc.), this value can be smaller than 1.

[0026] **Figure 6** shows a wirelessly powered battery pack and receiver in accordance with an embodiment. The components of a typical common battery pack (battery cell and protection circuit, etc.) used in a battery device used in applications such as mobile phone, etc. are shown inside the dashed lines. The components outside the dashed lines are additional components that are included to enable safe wireless and wired charging of a battery pack. A battery pack may have four or more external connector points that interface with a mobile device pins in a battery housing or with an external typical wired charger. In accordance with an embodiment, the battery cell is connected as shown in **Figure 7** to two of these connectors (shown in the figure as Batt+ and Batt-) through a protection circuit comprising a battery protection IC that protects a battery from over-current and under or over voltage. A typical IC can be Seiko 8241 IC that uses 2 external Field Effect Transistors (FETs) as shown in Figure 7 to prevent current going from or to the battery cell (on the left) from the external battery pack connectors if a fault condition based on over current, or battery cell over or under voltage is detected. This provides safety during charging or discharging of the battery. In addition, a battery pack can include a PTC conductive polymer passive fuse. These devices can sense and shut off current by heating a layer inside the PTC if the amount of current passing exceeds a threshold. The PTC device is reset once this current falls and the device cools.

[0027] In addition, in accordance with an embodiment, the battery pack can contain a thermistor that the mobile device checks through one other connector on the battery pack to monitor the health of the pack, and in some embodiments an ID chip or microcontroller that the mobile device interrogates through another connector to confirm an original battery manufacturer or other information about the battery. Other connectors and functions can be included in a battery pack to provide accurate battery status and/or charging information to a device being powered by a battery pack or a charger charging the battery pack.

[0028] In addition to the components described above, the receiver circuit comprises a receiver coil that can be a wound wire and/or PCB coil as described above, optional electromagnetic shielding between the coil and the metal body of the battery, optional alignment assisting parts such as magnets, etc., a receiver communication circuit (such as the resistor and

FET for load modulation shown in Figures 2 and 4), a wireless power receiver (such as rectifiers and capacitors as discussed above), and an optional Battery charger IC that has a pre-programmed battery charging algorithm. Each type of battery and chemistry requires a pre-determined optimized profile for charging of that battery type. A typical charge cycle for a Lithium Ion (Li-Ion) is shown in **Figure 8**. Such a battery can be charged up to a value of 4.2 V at full capacity. The battery should be charged according to the guidelines of the manufacturer. For a battery of capacity C, the cell can typically be charged at the rate 1C. In Stage 1, the maximum available current is applied and the cell voltage increases until the cell voltage reaches the final value (4.2 V). In that case, the charger IC switches to Stage 2 where the charger IC switches to Constant Voltage charging where the cell voltage does not change but current is drawn from the source to further fill up the battery. This second Stage may take 1 or more hours and is necessary to fully charge the battery. Eventually, the battery will draw little (below a threshold) or no current. At this stage, the battery is full and the charger may discontinue charging. The charger IC can periodically seek the condition of the battery and top it off further if the battery has drained due to stand-by, etc.

[0029] Such multiple stages of battery charging can be implemented in firmware with the wireless power charger and receiver microcontrollers monitoring the battery cell voltage, current, etc. and working in tandem and to provide appropriate voltage, current, etc. for safe charging for any type of battery. In another approach as shown in Figure 6, a battery charger IC chip that has specialized battery charging circuitry and algorithm for a particular type of battery can be employed. These charger ICs (with or without fuel gauge capability to accurately measure battery status, etc.) are available for different battery chemistries and are included in most mobile devices with mobile batteries such as mobile phones. They can include such safety features as a temperature sensor, open circuit shut off, etc. and can provide other circuits or microcontrollers such useful information as end of charge signal, signaling for being in constant current or voltage (stage 1 or 2 above, etc.). In addition, some of these ICs allow the user to program and set the maximum output current to the battery cell with an external resistor across 2 pins of the IC.

[0030] In accordance with an embodiment, the wirelessly charged battery pack in addition includes a micro-controller that coordinates and monitors various points and may also include thermal sensors on the wireless power coil, battery cell and/or other points in the battery pack. The microcontroller also may communicate to the charger and can also monitor communication from the charger (in case of bi-directional communication). Typical communication through load modulation is described above.

[0031] In accordance with an embodiment, another aspect of a wirelessly charged battery pack is the optional external / internal switch. A battery pack can receive power and be charged wirelessly or through the connectors of a battery pack. For example when such a battery pack is used in a mobile phone, the user may wish to place the phone on a wireless charger or plug the device in to a wired charger for charging or charge the device as well as synchronize or upload and/or download data or other information. In the second case, it may be important for the battery pack to recognize current incoming to the battery pack and to take some sort of action. This action can include, e.g. notifying the user, shutting off the wired charger by a switch or simply shutting down the charger IC and sending a signal back through the microcontroller and modulating the current back to the charger that a wired charger is present (in case priority is to be given to the wired charger) or conversely to provide priority to the wireless charger and shut off wired charger access to battery when the wireless charger is charging the battery. At either case, a protocol for dealing with presence of two chargers simultaneously should be pre-established and implemented in hardware and firmware.

[0032] As shown in Figure 6, the wireless charging of battery occurs with current flowing into the battery through the battery contacts from the mobile device. Typically, such current is provided by an external DC supply to the mobile device (such as an AC/DC adaptor for a mobile phone) and the actual charging is handled by a charger IC chip or power management IC inside the mobile device that in addition to charging the battery, measures the battery's state of charge, health, verifies battery authenticity, and displays charge status through LEDs, display, etc. to a user. It may be therefore be advantageous to include a current sense circuit at one of the battery pack contacts to measure and sense the direction of current flow into or out of the battery. In situations where the current is flowing inwards (i.e. the battery is being externally charged through a wired charging connection, and/or through a mobile device), the microcontroller can take the actions described above and shut off wireless charging or conversely, provide priority to wireless charging and if it is present, allow or disallow wired charging as the implementation requires.

[0033] In many applications, it is important to include a feature that can inform a mobile device user about the state of charge of a battery pack in the device. To enable an accurate measurement of the remaining battery charge, several gas gauging techniques can be implemented, in general by incorporating a remaining charge IC or circuitry in the battery or in the device. In accordance with an embodiment, the mobile device can also include a Power Management Integrated Circuit (PMIC) or a fuel or battery gauge that communicates with the wirelessly chargeable battery and measures its degree of charge and display this status on the

mobile device display or inform the user in other ways. In typical circumstances, a typical fuel gauge or PMIC may use battery voltage / impedance, etc. as well as measurement of the current and time for the current entering the mobile device (coulomb counting) to determine the status of the battery charge. However in a wirelessly charged system, this coulomb counting may have to be carried out in the battery rather than in the mobile device, and then communicated to the mobile device, since the charge is entering the battery directly through the onboard wireless power receiver and circuitry. The communication between the mobile device and the battery is through the connectors of the battery and may involve communication with an on-board microcontroller in the battery pack. In accordance with an embodiment, the wirelessly chargeable battery pack can include appropriate microcontroller and/or circuitry to communicate with the mobile device circuitry and update its state of charge, even though no current may be externally applied (through a wired power supply or charger) to the mobile device and the battery is charged wirelessly. In simpler fuel gauge techniques, the battery voltage, impedance, etc. can be used to determine battery charge status, and that in turn can be accomplished by performing appropriate measurements by the mobile device circuitry through battery connector points or by appropriate circuitry that may be incorporated in the wirelessly chargeable battery pack and/or in the mobile device or its PMIC or circuitry. Figure 6 shows an embodiment where a microcontroller or circuit inside the battery pack is included to accomplish the fuel gauge task and report the state of charge to the device. This circuitry can be the same, or different, from an ID chip to identify the battery, and can communicate through a common battery connector a separate one.

[0034] In accordance with an embodiment, the firmware in the receiver micro-controller plays a key role in the operation of this battery pack. The micro-controller can measure voltages and currents, flags, and temperatures at appropriate locations for proper operation. In accordance with one embodiment, by way of example, the micro-controller can measure the value of V_{out} from the rectifier circuit and attempt to keep this constant throughout the charging cycle thereby providing a stable regulated DC supply to the charger IC chip. The microcontroller can report the value of this voltage or error from a desired voltage (for example 5V) or simply a code for more or less power back to the charger in a binary or multi-level coding scheme through a load modulation or other scheme (for example RF communication, NFC, Bluetooth, etc. as described earlier) back to the charger. The charger can then take action through adjustment of input voltage to the charger coil, adjustment of the frequency or duty cycle of the ac voltage applied to the charger coil to bring the V_{out} to within required voltage range or a combination of these actions or similar methods. The micro-controller throughout the

charging process, in addition, may monitor the end of charge and/or other signals from charger and/or protection circuit and the current sense circuit (used to sense battery pack current direction and value) to take appropriate action. Li-ion batteries for example need to be charged below a certain temperature for safety reasons. In accordance with an embodiment, it is therefore desirable to monitor the cell, wireless power receiver coil or other temperature and to take appropriate action, such as to terminate charging or lower charging current, etc. if a certain maximum temperature is exceeded.

[0035] It will be noted that during charging, as shown in Figure 8, the battery cell voltage increases from 3 V or lower, to 4.2 V, as it is charged. The V_{out} of the wireless power receiver is input to a charger IC and if this V_{out} is kept constant (for example 5V), a large voltage drop (up to 2 V or more) can occur across this IC especially during Stage 1 where maximum current is applied. With charging currents of up to 1 A, this may translate to up to 2 Watts of wasted power / heat across this IC that may contribute to battery heating. In accordance with an embodiment, it is therefore desirable to implement a strategy whereby the V_{out} into the charger IC tracks the battery voltage thereby creating a smaller voltage drop and therefore loss across the charger IC. This can provide a significant improvement in performance, since thermal performance of the battery pack is very important.

[0036] In accordance with an embodiment, the communication between the receiver and charger needs to follow a pre-determined protocol, baud rate, modulation depth, etc. and a pre-determined method for hand-shake, establishment of communication, and signaling, etc. as well as optionally methods for providing closed loop control and regulation of power, voltage, etc. in the receiver.

[0037] In accordance with an embodiment, a typical wireless power system operation can be as follows: as shown in **Figure 9**, the charger periodically activates the charger coil driver and powers the charger coil with a drive signal of appropriate frequency. During this 'ping' process, if a receiver coil is placed on top or close to the charger coil, power is received through the receiver coil and the receiver circuit is energized. The receiver microcontroller is activated by the received power and begins to perform an initiation process whereby the receiver ID, its presence, power or voltage requirements, receiver or battery temperature or state of charge and/or other information is sent back to the charger. If this information is verified and found to be valid, then the charger proceeds to provide continuous power to the receiver. The receiver can alternately send an end of charge, over-temperature, battery full, or other messages that will be handled appropriately by the charger and actions performed. The length of the ping process should be configured to be of sufficient length for the receiver to power up its

microcontroller and to respond back and for the response to be received and understood. The length of time between the pings can be determined by the implementation designer. If the ping process is performed often, the stand-by power use of the charger is higher. Alternately, if the ping is performed infrequently, the system will have a delay before the charger discovers a receiver nearby. So in practice, a balance must be achieved.

[0038] Alternately, the ping operation can be initiated upon discovery of a nearby receiver by other means. This provides a very low stand-by power use by the charger and may be performed by including a magnet in the receiver and a magnet sensor in the charger or through optical, capacitive, weight, NFC or Bluetooth or other RF communication or other methods for detection. Alternatively, the system can be designed or implemented to be always ON (i.e. the charger coil is powered at an appropriate drive frequency) or pinged periodically and presence of the receiver coil brings the coil to resonance with the receiver coil and power transfer occurs. The receiver in this case may not even contain a microcontroller and act autonomously and simply have a regulator in the receiver to provide regulated output power to a device, its skin or case, or battery. In those embodiments that periodic pingging is performed, the presence of a receiver can be detected by measuring a higher degree of current flow or power transfer or other means and the charger can simply be kept on to continue transfer of power until either the power drawn falls below a certain level or an end of charge and/or no device present is detected. In another embodiment, the charger may be in an off or standby, or low or no power condition, until a receiver is detected by means of its presence through a magnetic, RF, optical, capacitive or other methods. For example, in accordance with an embodiment the receiver can contain an RFID chip and once it is present on or nearby the charger, the charger would turn on or begin pingging to detect a receiver.

[0039] In accordance with an embodiment, the protocol used for communication can be any of, e.g. common RZ, NRZ, Manchester code, etc. used for communication. An example of the communication process and regulation of power and/or other functions is shown in **Figure 10**. As described above, the charger can periodically start and apply a ping voltage of pre-determined frequency and length to the charger coil (as shown in the lower illustration in Figure 10). The receiver is then activated, and may begin to send back communication signals as shown in top of Figure 10. The communication signal can include an optional preamble that is used to synchronize the detection circuit in the charger and prepare it for detection of communication. A communication containing a data packet may then follow, optionally followed by checksum and parity bits, etc. Similar processes are used in communication systems and similar techniques can be followed. In accordance with an embodiment, the actual data packet

can include information such as an ID code for the receiver, received voltage, power, or current values, status of the battery, amount of power in the battery, battery or circuit temperature, end of charge or battery full signals, presence of external wired charger, or a number of the above. Also this packet may include the actual voltage, power, current, etc. value or the difference between the actual value and the desired value or some encoded value that will be useful for the charger to determine how best to regulate the output.

[0040] Alternatively, the communication signal can be a pre-determined pattern that is repetitive and simply lets the charger know that a receiver is present and/or that the receiver is a valid device within the power range of the charger, etc. Any combination of systems can be designed to provide the required performance.

[0041] In response to the receiver providing information regarding output power or voltage, etc. the charger can modify voltage, frequency, duty cycle of the charger coil signal or a combination of the above. The charger can also use other techniques to modify the power out of the charger coil and to adjust the received power. Alternatively the charger can simply continue to provide power to the receiver if an approved receiver is detected and continues to be present. The charger may also monitor the current into the charger coil and/or its temperature to ensure that no extra-ordinary fault conditions exist. One example of this type of fault may be if instead of a receiver, a metal object is placed on the charger.

[0042] In accordance with an embodiment, the charger can adjust one or more parameters to increase or decrease the power or voltage in the receiver, and then wait for the receiver to provide further information before changing a parameter again, or it can use more sophisticated Proportional Integral Derivative (PID) or other control mechanism for closing the loop with the receiver and achieving output power control. Alternatively, as described above, the charger can provide a constant output power, and the receiver can regulate the power through a regulator or a charger IC or a combination of these to provide the required power to a device or battery.

[0043] Various manufacturers may use different codings, and also bit rates and protocol. The control process used by different manufacturers may also differ, further causing interoperability problems between various chargers and receivers. A source of interoperability differences may be the size, shape, and number of turns used for the power transfer coils. Furthermore, depending on the input voltage used, the design of a wireless power system may step up or down the voltage in the receiver depending on the voltage required by a device by having appropriate number of turns in the charger and receiver coils. However, a receiver from one manufacturer may then not be able to operate on another manufacturer charger due to these differences in designs employed. It is therefore beneficial to provide a system that can

operate with different receivers or chargers and can be universal.

[0044] In accordance with an embodiment, to be able to detect and power / charge various receivers, the charger can be designed such that the initial ping signal is at such a frequency range to initially be able to power and activate the receiver circuitry in any receiver during the ping process. After this initial power up of the receiver, the charger communication circuit should be able to detect and understand the communication signal from the receiver. Many microcontrollers are able to communicate in multiple formats and may have different input pins that can be configured differently to simultaneously receive the communication signal and synchronize and understand the communication at different baud rates and protocols. In accordance with an embodiment, the charger firmware can then decide on which type of receiver is present and proceed to regulate or implement what is required (end of charge, shut-off, fault condition, etc.). Depending on the message received, the charger can then decide to change the charger driver voltage amplitude, frequency, or duty cycle, or a combination of these or other parameters to provide the appropriate regulated output.

[0045] In accordance with an embodiment, the charger's behavior can also take into account the difference in the coil geometry, turns ratio, etc. For example, a charger and receiver pair from one or more manufacturers may require operation of the charger drive voltage at 150 kHz. However, if the same receiver is placed on a charger from another manufacturer or driven with different coil / input voltage combination, to achieve the same output power, the charger frequency may need to be 200 kHz. The charger program may detect the type of receiver placed on it and shift the frequency appropriately to achieve a baseline output power and continue regulating from there. In accordance with an embodiment, the charger can be implemented so that it is able to decode and implement multiple communication and regulation protocols and respond to them appropriately. This enables the charger to be provided as part of a multi-protocol system, and to operate with different types of receivers, technologies and manufacturers.

[0046] As shown in Figure 10, after the receiver sends back a communication signal back to the charger, in response to it, the charger adjusts its frequency and then awaits further information from the receiver. The receiver acknowledges the change and as shown in the second data packet in the receiver signal, has modified its state and communicates back to the charger. This closed loop continues during the charging process.

[0047] For receivers that contain an onboard regulator for the output power, stability of the input voltage to the regulator is not as critical since the regulator performs a smoothing function and keeps the output voltage at the desired level with any load changes. It is however,

important not to exceed the maximum rated input voltage of the regulator or to drop below a level required so that the output voltage could no longer be maintained at the required value. However, in general, inclusion of a regulator and/or a charger IC chip (for batteries) reduces the power / voltage regulation requirements of the wireless power receiver portion of the circuit at the expense of the additional size and cost of this component. In accordance with some embodiments, simpler voltage limiting output stages such as Zener diodes or other voltage limiting or clamping ICs or circuits, can be used.

[0048] While the system above describes a system wherein the communication is primarily through the coil, as described earlier, communication can also be implemented through a separate coil, RF, optical system or a combination of the above. In such circumstances, a multi-protocol system can also be used to interoperate between systems with different communication and/or control protocols or even means of communication.

[0049] Alternately, the receiver can be designed or implemented to accommodate different types of chargers. For example, once a receiver is awakened by a charger, it can try to detect the ping frequency used by the charger. This can be done by any number of phase locking or other techniques. Alternately, the receiver can send back a variety of trial communication signals during ping process to establish which type of device is performing the ping. Once the type of the charger is established, the receiver can proceed and communicate with the appropriate communication protocol and frequency with the charger.

[0050] The multi-protocol approach described above is important for development of a universal system that can operate amongst multiple systems and provide user convenience.

[0051] The description for the systems above may use discreet electronics components or some or all of the functions described above may be integrated into an Application Specific Integrated Circuit (ASIC) to achieve smaller footprint, better performance / noise, etc. and/or cost advantages. Such integration is common in the Electronics industry and can provide additional advantages here.

[0052] In general, for the systems described above, the transmitter and receiver coils are of similar, although not necessarily same, sizes and are aligned laterally to be able to transfer power efficiently. For coils of similar size, this would typically require the user to place the device and/or receiver close to alignment with respect to the transmitter coil. For example, for a transmitter / receiver coil of 30 mm diameter, this would require lateral (x,y) positioning within 30 mm so there is some degree of overlap between the coils. In practice, a considerable degree of overlap is necessary to achieve high output powers and efficiencies. This may be achieved by providing mechanical or other mechanisms such as indentations, protrusions, walls, holders,

fasteners, etc. to align the parts.

[0053] However for a universal charger / power supply that is going to be used for charging or powering a range of devices, a design able to accept any device and receiver is desirable. For this reason, in accordance with an embodiment, a flat or somewhat curved charger / power supply surface that can be used with any type of receiver may be used. To achieve alignment in this case, markings, small protrusions or indentations and/or audio and/or visual aids or similar methods can be used. Another method includes using two magnets, or a magnet and another magnetic or ferrite magnetic attractor material that can be attracted to a magnet in the transmitter / charger and receiver. In these methods, typically a single charger / transmitter and receiver are in close proximity and aligned to each other.

[0054] However, for even greater ease of use, it may be desirable to be able to place the device to be charged / powered over a larger area, without requiring precise alignment of coils. There are several methods that have been previously used for this.

[0055] Several other methods that address the topic of position independence have been described previously. For example in U.S. Patent Publication No. 2007/0182367 and U.S. Patent Publication No. 2009/0096413, incorporated herein by reference, an embodiment comprising multiple transmitter coils arranged in a two-dimensional array to cover and fill the transmitter surface is described. When a receiver is placed on the surface of such a coil array, the transmitter coil with the largest degree of overlap with the receiver is detected and activated to allow optimum power transmission and position independent operation. The detection mechanism can be through, e.g. detection of weight, capacitive, optical, mechanical, magnetic RFID, RF, or electrical sensing of the receiver. In accordance with an embodiment, the coils in the charger / power supply are sequentially powered (pinged) and the charger / power supply waits for any possibly receivers to be powered up and reply to the ping. If no reply is detected back within a time window, the next coil is activated, etc. until a reply is detected in which case the charger / power supply initiates power up of the appropriate transmitter coil(s) and proceeds to charge / power the receiver.

[0056] In another geometry, each transmitter (or charger) coil center includes a sensor inductor (for example, E. Waffenschmidt, and Toine Staring, 13th European Conference on Power Electronics and Applications, Barcelona, 2009. EPE '09. pp. 1 – 10). The receiver coil includes a soft magnetic shield material that shifts the resonance frequency response of the system and can be sensed by a sensor in the transmitter to switch the appropriate coil on. The drawback of this system is that 3 layers of overlapping coils with a sensor and detection circuit at the center of each is required adding to the complexity and cost of the system. Other

variations of the above or a combination of techniques can be used to detect the appropriate transmitter coil.

[0057] In accordance with other embodiments, described in .U.S. Patent Publication Nos. 2007/0182367 and 2009/0096413, the charger / power supply may contain one or more transmitter coils that are suspended and free to move laterally in the x-y plane behind the top surface of the charger / power supply. When a receiver coil is placed on the charger / power supply, the closest transmitter coil would move laterally to position itself to be under and aligned with the receiver coil. One passive method of achieving this may be to use a pair of magnets (one attached to the transmitter coil and one to the receiver coil) that would attract and passively align the two coils appropriately. In another embodiment, a system that detects the position of the receiver coil on the charger / power supply surface and uses this information to move the transmitter coil to the appropriate location actively using motors, piezo or other actuators, etc. is possible.

[0058] In general the systems above describe use coils that are of similar size / shape and in relatively close proximity to create a wireless power system.

[0059] As described above, the coupling coefficient k is an important factor in design of the wireless power system. In general, wireless power systems can be categorized into two types. One category which is called tightly coupled operates in a parameter space where the k value is 0.5 or larger. This type of system is characterized by coils that are typically similar and/or spatially close together in distance (z axis) and with good lateral (x,y) overlap. This so called tightly coupled system is typically associated with high power transfer efficiencies defined as the ratio of output power from the receiver coil to input power to transmitter coil. The methods described above for position independent operation (array of transmitter coils and moving coils), typically may use tightly coupled coils.

[0060] In contrast, for coils of dissimilar size or design or larger transmitter to receiver distance or smaller lateral coil overlap, the system coupling coefficient is lower. Another important parameter, the quality factor of a transmitter (tx) and receiver (rx) coil is defined as:

$$Q_{tx} = 2 \pi f L_{tx} / R_{tx}$$

$$Q_{rx} = 2 \pi f L_{rx} / R_{rx}$$

where f is the frequency of operation, L_{tx} and L_{rx} the inductances of the transmitter and receiver coils and R_{tx} and R_{rx} their respective resistances. The system quality factor can be calculated as follows:

$$Q = (Q_{tx} \cdot Q_{rx})^{1/2}$$

[0061] In general, the loosely coupled systems may have smaller power transfer efficiencies. However, it can be shown (see for example, E. Waffenschmidt, and Toine Staring, 13th European Conference on Power Electronics and Applications, Barcelona, 2009. EPE '09. pp. 1 – 10) that an increase of Q can compensate for smaller k values, and reasonable or similar power transfer efficiencies can be obtained. Such systems with dissimilar coil sizes and higher Q values are sometimes referred to as Resonant Coupled or Resonant systems. However, resonance is also often used in the case of similar-size coil systems. Others, (such as André Kurs, Aristeidis Karalis, Robert Moffatt, J. D. Joannopoulos, Peter Fisher, and Marin Soljac, Science, 317, P. 83-86, 2007; and <http://newsroom.intel.com/docs/DOC-1119>) have shown that with systems with k of <0.2 due to large distance between coils (up to 225 cm), sizeable reported power transfer efficiencies of 40% - 70% can be obtained. Other types of loosely coupled system appear to use mis-matched coils where the transmitter coil is much larger than the receiver coil (see for example, J. J. Casanova, Z.N. Low, J. Lin, and Ryan Tseng, in Proceedings of Radio Wireless Symposium, 2009, pp. 530-533 and J. J. Casanova, Z. N. Low, and J. Lin, IEEE Transactions on Circuits and Systems – II: Express Briefs, Vol. 56, No. 11, Nov. 2009, pp. 830-834 and a Fujitsu System described at <http://www.fujitsu.com/global/news/pr/archives/month/2010/20100913-02.html>).

[0062] Such systems may have a larger transmitter coil and a smaller receiver coil and operate with a small k value (possibly between 0 and 0.5 depending on coil size mismatch and gap between coils / offset of coils). Of course the opposite case of a small transmitter coil and larger receiver coil is also possible.

[0063] **Figure 11** shows configurations for a tightly coupled power transfer system with 2 individual transmitter coils of different size powering a laptop and a phone (left) and a loosely coupled wireless power system with a large transmitter coil powering 2 smaller receiver coils in mobile phones (right).

[0064] An ideal system with largely mis-matched (i.e. dissimilar in size / shape) coils can potentially have several advantages:

1. Power can be transferred to the receiver coil placed anywhere on the transmitter coil.
2. Several receivers can be placed and powered on one transmitter allowing for simpler and lower cost of transmitter.
3. The system with higher Q can be designed so the gap between the transmitter and

receiver coil can be larger than a tightly coupled system leading to design of systems with more design freedom. In practice, power transfer in distances of several cm or even higher have been demonstrated.

4. Power can be transferred to multiple receivers simultaneously. In addition, the receivers can potentially be of differing power rating or be in different stages of charging or require different power levels and/or voltages.

[0065] In order to achieve the above characteristics and to achieve high power transfer efficiency, the lower k value is compensated by using a higher Q through design of lower resistance coils, etc. The power transfer characteristics of these systems may differ from tightly coupled systems and other power drive geometries such as class E amplifier or Zero Voltage Switching (ZVS) or Zero Current Switching (ZCS) or other power transfer systems may operate more efficiently in these situations. In additions, impedance matching circuits at the charger / transmitter and/or receiver may be required to enable these systems to provide power over a range of load values and output current conditions. General operation of the systems can, however be quite similar to the tightly coupled systems and one or more capacitors in series or parallel with the transmitter and/or receiver coil is used to create a tuned circuit that may have a resonance for power transfer. Operating near this resonance point, efficient power transfer across from the transmitter to the receiver coil can be achieved. Depending on the size difference between the coils and operating points, efficiencies of over 50% up to near 80% have been reported.

[0066] To provide more uniform power transfer across a coil, methods to provide a more uniform magnetic field across a coil can be used. One method for achieving this uses a hybrid coil consisting of a combination of a wire and pcb coils (see, for example, X. Liu and S. Y. R. Hui, "Optimal design of a hybrid winding structure for planar contactless battery charging platform," IEEE Transactions on Power Electronics, vol. 23, no. 1, pp. 455–463, 2008). In another method, the transmitter coil is constructed of Litz wire and has a pattern that is very wide between successive turns at the center and is more tightly wound as one gets closer to the edges (see, for example, J. J. Casanova, Z. N. Low, J. Lin, and R. Tseng, "Transmitting coil achieving uniform magnetic field distribution for planar wireless power transfer system," in Proceedings of the IEEE Radio and Wireless Symposium, pp. 530–533, January 2009). **Figure 12** shows a coil demonstrated therein, while **Figure 13** shows the resulting calculated magnetic field. In a geometry described in U.S. Patent Publication No. 2008/0067874, also incorporated herein by reference, a planar spiral inductor coil is demonstrated, wherein the width of the

inductor's trace becomes wider as the trace spirals toward the center of the coil to achieve a more uniform magnetic field allowing more positioning flexibility for a receiver across a transmitter surface. In yet other embodiments, the coil can be a meandering type of coil wherein the wire is stretched along x direction and then folds back and makes a back and forth pattern to cover the surface. Combining this with a wire pattern stretched along the y direction provides orthogonal resulting magnetic fields that are independent of orientation of the receiver pickup coil.

[0067] In accordance with an embodiment, the charger can operate continuously, and any receiver placed on or near its surface will bring it to resonance and will begin receiving power. The regulation of power to the output can be performed through a regulation stage at the receiver. Advantages of such a system include that multiple receivers with different power needs can be simultaneously powered in this way. The receivers may also have different output voltage characteristics. To achieve this, the number of turns on the receiver coil can be changed to achieve different receiver output voltages. Without any receivers nearby, such a charger would not be in resonance and would draw minimal power. At end of charge, the receiver can include a switch that will detect the minimal current draw by a device connected to the receiver, and disconnect the output altogether and/or disconnect the receiver coil so that the receiver is no longer drawing power. This will bring the charger out of resonance and minimal input current is drawn at this stage.

[0068] In accordance with another embodiment, the charger can periodically ping for receivers, and initiate and maintain power transfer if sufficient current draw from a receiver is detected. Otherwise, the charger can return to standby and continue pinging. Such a system would have even lower stand by power usage.

[0069] In a more complex system, similar communication and control and/or receiver detection as described for the tightly coupled situation earlier can be applied for such loosely coupled systems. However, a wireless power system designed to power multiple receivers placed on a single transmitter (see, for example, "Qualcomm Universal Charging" available at http://www.qualcomm.com/common/documents/articles/eZone_052609.pdf) may need to regulate the power transfer and the voltage at each receiver differently depending on the status of the load / device that the power is being delivered to. In cases where multiple receivers are placed on one transmitter coil and it is desired to power / charge all devices, all receivers may try to communicate with the transmitter and the transmitter will need to distinguish between receivers and operate differently (e.g. at different power level, or switching frequency, etc.) with each one. Since the transmitter coil emits power to all the receivers, it may be difficult to

regulate power delivered to each receiver differently. Therefore in a practical system, some degree of regulation of power to be delivered to a load or device may be performed in the receiver circuitry. In another method of regulation, each receiver may time-share the transmitter power. Each receiver placed on a transmitter may synchronize and communicate with the transmitter and/or with other receivers through wireless RF communication or RFID or Near Field Communication, Bluetooth, WiFi, or communication through power transfer and/or separate coils or through optical or other methods. The transmitter may then power each receiver sequentially and deliver the appropriate power level through adjustment of the transmitter frequency, pulse width modulation, or adjustment of input voltage, or a combination of above methods. In order for this system to operate, it may be necessary for all or some of the receivers to disconnect from receipt of power during the time period when one receiver is receiving power. This can be accomplished by implementing and opening a switch in the path of the receiver coil circuit or disabling the receiver's output or its associated optional regulator or alike. In this way, only one receiver coil (or more depending on design and architecture) is at any given time magnetically coupled to the transmitter and receives power. After some period of time, that receiver may be disconnected by opening its appropriate switch and the next receiver powered, etc. Alternatively, one or more receivers may be powered at the same time. In this case, the receivers may need to share the available power so for example, while with one receiver 5 W of output power may be available, with 2 receivers, each can only output only 2.5 W, etc. This may be acceptable in many charging and/or power applications.

[0070] In any practical system, in addition to the power transfer and communication system, appropriate electromagnetic shielding of the transmitter and receiver is necessary and may be similar or different to the tightly coupled systems.

[0071] The ratio of the size of the transmitter coil to the receiver coil may be decided depending on design considerations such as the desired number of receivers to be powered / charged at any given time, the degree of positioning freedom needed, the physical size of device being charged / powered, etc. In the case that the transmitter coil is designed to be of a size to accommodate one receiver at a time, the transmitter and receiver coils may of similar size thereby bringing the loosely coupled system to the tightly coupled limit in this case.

[0072] While the loosely coupled system may have distinct advantages and in some ways may overcome the complexities of the multiple coil / moving coil systems employed in tightly coupled systems to achieve position independence, traditional systems suffer from some several issues:

1. Since a large area transmitter coil and smaller receiver coil may be used,

Electromagnetic emission in areas of the transmitter coil not covered by the receiver coil is present. This emission is in the near field and drops rapidly away from the coil. Nevertheless, it can have adverse effects on devices and/or people in the vicinity of the transmitter.

2. The receiver may be incorporated or attached to Electronic and electrical devices or batteries that often contain metallic components and/or circuits and/or parts / shells, etc. Such metallic sections that are not shielded may absorb the emitted EM field from the transmitter and create destructive and undesirable eddy currents and/or heating in these parts.

3. The Electromagnetic field emitted may also affect the operation of the device being powered or charged or even nearby devices that are not on the transmitter / charger. Such interference with device operation / reception or a drop in sensitivity of a radio transmitter / receiver (desense) is quite important in design of mobile or electronic devices such as mobile phones or communication devices. To avoid this effect, the portions of the device being charged or powered that may be exposed to the Electromagnetic (EM) field with the exception of the receiver coil area may need to be shielded causing severe restrictions on the device design.

4. In many situations, an after-market receiver such as a case, skin, carrier, battery or attachment with a receiver built in is desired to enable a mobile or electronic / electric device to be powered or charged wirelessly. To shield the entire device from EM radiation at locations beside the receiver coil, such an after-market receiver will require shielding in all other locations of the device thereby severely limiting the design and choices in after-market products possible. For example, a battery with a built in receiver circuit and shielding may not be sufficient to protect a mobile device to be charged wirelessly. For example, in the case of a mobile phone, such a battery would cover only a small area of a mobile phone's back's surface area leaving the rest of the phone exposed to EM radiation which could have serious effects on its performance and operation.

5. Metallic objects such as keys or coins that are placed on a charger / transmitter may affect the operation of the transmitter and draw power from it due to eddy currents. This may result in excessive heating of such objects that is highly undesirable.

6. The EM field emitted from the transmitter further may be sufficiently physically close to a user as to be affecting and incident on the user. Such exposure to EM radiation may result in unwanted or unacceptable levels of exposure.

7. Many regulatory guidelines regarding the safe exposure limits for human and electrical / electronic device operation exists and awareness and concern regarding this issue is increasing. Any unnecessary exposure from an uncovered and operating area of a transmitter is highly undesirable.
8. A substantial amount of power from the transmitter may be lost from the area that is not physically covered by the receiver leading to lower efficiencies and wastage of power.
9. To capture the most amount of power and to achieve higher efficiencies, the receiver coil area must be maximized. This often leads to a larger receiver coil area than tightly coupled implementations.

[0073] It is therefore desired to benefit from the advantages of a loosely coupled system while minimizing or avoiding problems related to it.

[0074] In accordance with various embodiments described herein, through appropriate design of the system and use of a novel technique referred to herein as Magnetic Aperture, the benefits of the use of a mismatched (in size) coil system can be retained, while overcoming the problems and issues raised above, leading to an ideal system for wireless power transfer.

[0075] As described above, a position independent system may be implemented by use of a large area transmitter coil upon which a smaller receiver coil may be placed on a variety or any location and receive power. Typically, a system such as shown in Figure 2 includes capacitors in series and/or parallel with the transmitter and/or receiver coils to provide a resonant circuit that shows strong power transfer characteristics at particular frequencies. (See for example S.Y. Hui, H.S.H Chung, and S.C. Tang, IEEE Transactions on Power Electronics, Vol. 14, pp.422-430 (1999), which shows an analysis method for such a system). Using values of $L_1 = 46 \mu\text{H}$ for the transmitter coil and $L_2 = 4 \mu\text{H}$ for the receiver (based on a 16 cm x 18 cm 13-turn transmitter coil and a 4 cm x 5 cm, 6-turn receiver coil (J. Casanova, Z.N. Low, and J. Lin, IEEE Trans. On Circuits and Systems – II, Express Briefs, Vol. 56, pp. 830-834 (2009)), and using 12 nF for the receiver capacitance, the impedance to the input supply of the transmitter can be calculated as shown in **Figure 14**, clearly showing the resonance in power transfer.

[0076] In practice, a transmitter operating on or near resonance frequency does not draw much power until a receiver of appropriate inductance and capacitance is nearby thereby shifting its operating point and bringing it into resonance at which point, significant power can be drawn from the transmitter supply and enabling large power transfer and high power transfer efficiencies. But as discussed above, a large area transmitter typically would also then emit

power into areas not covered by the receiver coil, which could cause EMI and accompanying health issues.

[0077] In accordance with embodiments of the present invention, the techniques described herein allow operation of a position-independent power transfer system, while reducing or eliminating undesirable radiation from other areas of the transmitter coil. To achieve this, it is necessary to achieve the seemingly mutually exclusive conditions of low-to-no emission from a transmitter coil, with high-efficiency and position-independence operation at positions with the presence of the receiver coil. Ideally, this system is passive in that no complicated detection of receiver location and switching and control of the power transfer is necessary.

[0078] In accordance with one embodiment, a large transmitter coil and smaller receiver coil or coils similar to a loosely coupled system are used. However, to reduce or eliminate radiation from the transmitter coil, the transmitter coil is covered with a thin soft magnetic layer.

[0079] **Figure 15** shows the magnetization curves of a number of Ferromagnetic materials. They include 1.Sheet steel, 2.Silicon steel, 3.Cast steel, 4.Tungsten steel, 5.Magnet steel, 6.Cast iron, 7.Nickel, 8.Cobalt, and 9.Magnetite. In the linear regime of operation, the magnetic field strength H is related to the magnetic flux density B through the permeability of the material μ :

$$B = \mu H + M$$

where M is the magnetization of a material. It must be noted that B , H , and M are vectors and μ is a scalar in isotropic materials and a tensor in anisotropic ones. In anisotropic materials, it is therefore possible to affect the magnetic flux in one direction with a magnetic field applied in another direction. The permeability of Ferromagnetic materials is not constant, but depends on H . In saturable materials as shown in Figure 15, the permeability increases with H to a maximum, then as it approaches saturation it decreases by orders of magnitude toward one.

[0080] Different materials have different saturation levels. For example, high permeability iron alloys used in transformers reach magnetic saturation at 1.6 - 2.2 Tesla (T), whereas ferromagnets saturate at 0.2 - 0.5 T. One of the Metglass amorphous alloy saturates at 1.25 T. Many materials that are typically used in transformer cores may be candidates for this application. They include materials described above, soft iron, Silicon steel, laminated materials (to reduce eddy currents), Silicon alloyed materials, Carbonyl iron, Ferrites, Vitreous metals, alloys of Mn, Zn, and many other materials used in transformers or power transfer applications.

[0081] **Figure 16** shows the hysteresis curve for a hard ferromagnetic material such as

steel. As the magnetic field is increased, the magnetic flux saturates at some point, therefore no longer following the linear relation above. If the field is then reduced and removed, in some media, some value of B called the remanence (B_r) remains, giving rise to a magnetized behavior. By applying an opposite field, the curve can be followed to a region where B is reduced to zero. The level of H at this point is called the coercivity of the material.

[0082] Many magnetic shield layers consist of soft magnetic material made of high permeability ferromagnets or metal alloys such as large crystalline grain structure Permalloy and Mu-metal, or with nanocrystalline grain structure Ferromagnetic metal coatings. These materials do not block the magnetic field, as with electric shielding, but instead draw the field into themselves, providing a path for the magnetic field lines around the shielded volume. The effectiveness of this type of shielding decreases with the decrease of material's permeability, which generally drops off at both very low magnetic field strengths, and also at high field strengths where the material becomes saturated as described above. The permeability of a material is in general a complex number:

$$\mu = \mu' + j\mu''$$

where μ' and μ'' are the real and imaginary parts of the permeability providing the storage and loss component of the permeability respectively. **Figure 17** shows the real and imaginary part of the permeability of a Ferromagnetic material layer.

[0083] In accordance with an embodiment, the present invention provides a method for shielding of the EM field emitted from the transmitter coil while providing a path for transfer of power from this field to a receiver coil placed arbitrarily on the surface of the transmitter. To achieve this, as shown in an embodiment in **Figure 18**, a large area transmitter coil (of wire, Litz wire, or PCB type, or a combination thereof) is covered by a ferromagnetic or other magnetic material that acts to guide and contain any field due to its high permeability.

[0084] With a ferromagnetic layer of sufficient thickness and/or permeability, any receiver coil placed on or a distance to such a Ferromagnetic layer on top of the transmitter coil will not have an effect on the transmitter and will not receive any power.

[0085] In accordance with an embodiment, one can create a magnetic aperture in such a shield or ferroelectric layer at any desired location, so that the magnetic field confined in such a layer is efficiently coupled to a receiver coil and can provide power transfer to such a receiver. At any other location on the transmitter coil, the confinement of the field prevents unnecessary radiation, thereby providing low EMI and adverse health effects.

[0086] Several methods to enable local change of the characteristics of the ferromagnet material are described herein. In accordance with one embodiment, the local characteristics of the ferromagnet are altered by saturating the layer through application of a DC and/or AC magnetic field such as through a permanent magnet or electromagnet, etc. For example, a magnet or electromagnet can be incorporated behind, in front, around or at the center of the receiver coil such that it has sufficient magnetic field to saturate or alter the magnetization curve of the ferromagnet layer locally on or near where the receiver coil is placed. Examples of magnets that can be used include, e.g. one or more disc, square, rectangular, oval, curved, ring, or any other shape of magnet and with appropriate magnetization orientation and strength that can provide sufficient DC magnetic field to shift the operating position of the magnetization curve (as shown in Figure 12), so that the combination of the transmitter coil, the affected ferromagnet layer and the receiver coil move to a resonance condition at a given frequency for power transfer. At this point, a local 'magnetic aperture' is opened up in the ferromagnet layer, allowing the transmitter coil electromagnetic field to be transmitted through this local aperture without affecting any areas nearby. In this manner, by reducing the permeability of the ferromagnet layer locally through saturation or reduction with the DC and/or AC field, one can determine at what location the power and energy coupling occurs while keeping the field confined in other areas. This effect can be used to meet the goal of simultaneously transferring power efficiently to a receiver at any location while keeping the field from emitting at other locations and causing problems. At the same time, since the field is directed towards the generated aperture, this provides an efficient method for transfer of power to an arbitrarily positioned receiver.

[0087] In accordance with an embodiment, to provide shielding from the EM field below the transmitter coil (the side opposite to the charging / power side of the transmitter) and above the receiver coil (on the side of the coil that may be in close contact with a device, battery, or electrical part being powered or charged wirelessly), further shielding layers such as ferromagnet and/or metallic layers can be added below the transmitter coil and/or above the receiver coil as necessary. Furthermore, these layers can be integrated into the coil design (such as metal shield layers integrated into a PCB multi-layer design that includes a PCB coil). The choice of material and thickness, etc. can be chosen such that even though a magnet in the receiver may be used to saturate the top layer of the transmitter (the switchable layer), the permeability of the shield layers would not be affected. For example, the switchable layer can comprise material with low saturation field density while the other shield layers have higher saturation field densities.

[0088] To test the above embodiment, a transmitter coil with Litz wire with dimensions of 10 cm x 10 cm was constructed. The coil was constructed similar to earlier work (J. J. Casanova, Z.N. Low, J. Lin, and Ryan Tseng, in Proceedings of Radio Wireless Symposium, 2009, pp. 530-533 and J. J. Casanova, Z. N. Low, and J. Lin, IEEE Transactions on Circuits and Systems – II: Express Briefs, Vol. 56, No. 11, Nov. 2009, pp. 830-834). The receiver consisted of a Litz wire coil of 35 mm radius and 10 turns and the signal was fed to a rectifier and capacitor circuit to provide a DC output. The transmitter coil was then driven with a resonant converter circuit similar to Figure 2 and the frequency of the system was adjusted for test purposes. It is important to realize that different power delivery mechanisms and receiver systems as well as different shape, geometry, winding, and construction of coils such as wire, Litz wire, or a combination can be used and this setup is used only as an example.

[0089] To test the transmission capability of the loosely coupled system itself first, the drive circuit was powered from a DC supply at 20 V input voltage and the receiver coil was placed on the transmitter with a coil to coil vertical (z-direction) gap of 5 mm. Power level in excess of 20 W with a DC output to DC input power efficiency of over 70% could be achieved. Moving the receiver coil laterally across the surface of the transmitter coil confirms that high power transfer and efficiencies can be obtained across the transmitter coil surface. Placing a metal object, such as a metal disk, on the transmitter coil at a location laterally away from the receiver coil confirms that strong magnetic field emissions exist on the entire surface of the transmitter coil as expected since the coin heats up within seconds to very high levels confirming heating by eddy currents. Similarly, a receiver circuit connected to some Light Emitting Diodes (LEDs) shows significant power being emitted from all areas of the transmitter coil as expected.

[0090] Next, a sheet of Hitachi material MS-F comprising 18 μm of FineMET[®] FT-3M material on an adhesive tape substrate was used as a Ferromagnet / Ferrite material (switchable layer) and placed on the entire top of the transmitter coil surface. This material has a saturation flux density of 1.23 T. Placing a receiver coil 5 mm away from the transmitter coil and the switchable layer and adjusting the transmitter frequency, no power was transferred to the receiver at any frequency. Next, a Nd rare-earth ring magnet (of material N45H) of inner diameter of 32 mm and outer diameter of 36 mm and 2.5 mm thickness and magnetized along its axis (with North and South pole on top and bottom of the ring) was placed behind in the center of the receiver coil. The ring magnet as shown in **Figure 19** includes a cut or gap in its circumference. This cut or gap is optional and can be manufactured during casting of the magnet to avoid or reduce generation of any eddy currents from stray magnetic fields in the receiver during operation in the wireless power system. By breaking the circular pattern of the

ring, any potentially generated currents would not be able to circulate and heat the magnet. The overall geometry for operation with the switchable layer and the receiver and magnet is shown in **Figure 20** for 2 receivers of dissimilar size and possibly power ratings and/or voltage outputs.

[0091] **Figure 21** shows a simplified side view of a wireless power system in accordance with an embodiment, showing a charger (transmitter) and receiver coil, switching layer, and switching magnet. In this instance, a ring magnet is shown and the coils are described as circular ring coils. However, in accordance with other embodiments, other geometries and designs can be used to achieve similar results. For example, as described above, the coil can be configured to achieve a more uniform field pattern and/or the magnet can be of a different shape and magnetization orientation. In addition, the magnet can be placed in front of, behind, or on the same plane as the coil and/or the coils can be made of wires, PCB, free standing metal parts or a combination thereof or other geometries and materials.

[0092] The flux densities and the magnetic field orientation are shown in Figure 21. The magnetic field flows in the switching layer and is funneled or directed to the receiver location by the presence of the receiver magnet. In an isotropic material, the switching magnetic field (from the switching or permanent magnet or electromagnet shown here) should have a component in an orientation along the direction of the AC (wireless power transfer) magnetic field to saturate the permeability in that orientation and affect its behavior. However in an anisotropic material, different orientations of switching magnetic field can affect the permeability affecting the AC magnetic power transfer field, giving rise to interesting combinations of switching layer materials and magnet designs to achieve enhanced performance.

[0093] In the embodiment shown in Figure 21, due to overlap of the radial orientation of the magnetic field from the ring magnet magnetized axially (North and South pole along its axis), the DC switching magnetic field is parallel to the x-y plane and oriented to direct the AC wireless power magnetic field towards the created aperture for power transfer. However, alternate geometries such as an arc, radially magnetized ring or cylinder or multi-pole magnets can be used to provide optimal power coupling. A multi-pole magnet can provide a tighter external magnetic field pattern and reduce any potential unwanted effect of magnet on nearby devices / materials while providing sufficient magnetic flux density to saturate the switching layer. In addition, use of appropriately designed magnets and/or anisotropic or multi-layer switching layers can result in enhanced switching performance and coupling of power with minimal switching magnet strength.

[0094] In accordance with another embodiment, multi-pole magnets that have strong magnetic field strengths near the surface of the magnet with rapidly decreasing magnetic field

strength can be used. Some examples of multi-pole magnets are shown in **Figure 22**. Such magnets can provide magnetic aperture switching nearby, while maintaining weak magnetic field strengths farther away, thereby minimizing the effect on other materials, devices, etc. This feature may be especially be important for use with devices such as GPS or compasses that use the weak magnetic field of the earth to detect the device orientation. In accordance with one embodiment that uses a ring magnet as shown in **Figure 23**, the magnet can be magnetized radially or along its axis, but can comprise multiple alternating poles.

[0095] In addition to reduce or eliminate eddy currents, a cut or gap in the circumference of a ring or other type of magnet can be introduced to prevent circular current from flowing due to the alternating magnetic field. **Figure 24** shows two examples of multi-pole ring magnets with cuts or gaps in the circular pattern, in accordance with various embodiments.

[0096] In accordance with an embodiment, to bring the system to resonance, the frequency of the applied power to the charger coil can be adjusted to observe power transfer through the switchable layer. Experimentally, with a single magnet for switching no power transfer is observed. Doubling the magnet strength by double stacking the magnets provided sufficient magnetic field strength to saturate the switchable layer and adjusting the frequency, large amounts of power were transmitted through the opened aperture. Over 10 W of power and efficiencies in excess of up to 50 % were achieved. To achieve optimum power transfer, it is necessary to move the magnets some distance (e.g. about 25 mm vertically in the z-direction) away from the transmitter surface. This may be due to the magnet size (diameter) being much smaller than the receiver coil and to saturate the switchable layer with sufficient size to optimally couple power to the receiver coil, it was necessary to move the magnets away to allow their fringing fields to be larger in area than the size of the magnets itself and thereby open an optimally sized aperture for power transfer. In accordance with other embodiments, a larger diameter magnet that is matched with the receiver coil size can be used and can be at the same plane as the receiver coil (inside, outside or behind the receiver coil).

[0097] The magnetic flux density of each magnet was estimated to be around 1.3 T by the manufacturer. In practice, we noticed that doubling up the magnets by stacking on top of each other and moving the magnets away to optimally match the aperture size to the receiver coil was optimal. This is understandable in view of the fact that while the single magnet should have sufficient magnetic flux density to saturate the layer close to its surface, the resulting aperture when the magnet is on the plane of the receiver coil and close to the transmitter coil and switchable layer (5 mm distance between magnet and the switchable layer) is comparable in size to the magnet and smaller than the 40 x 50 mm size of the receiver coil. To achieve the

best coupling, the magnet had to be further away (25 mm between magnet and transmitter switchable layer) in this example and therefore 2 magnets were required to provide sufficient flux density in this example. Even with the magnet co-planar with the receiver coil, doubling the magnets was necessary to provide sufficient fringing fields to open a sufficiently dimensionally large aperture for efficient power transfer.

[0098] In accordance with an embodiment, changing the receiver coil size so that it is comparable to the switching magnet diameter provides more efficient coupling, with output to input power efficiencies of 50% or more, and output power levels of over 25 W achieved with one or more magnets.

[0099] In accordance with an embodiment, due to the circular symmetry of the geometry used, the receiver can be rotated in the plane without any change in the received power or system efficiency. Rotation of the receiver out of the plane also demonstrated sizeable power transfer.

[00100] To test emission levels from other areas of the transmitter, the test with metallic object was repeated by placing a metallic object at a location close to the receiver coil on top of the transmitter surface. No appreciable heating was detected. Similarly, when the magnets were removed from the center of the receiver coil, the power transfers stopped and the transmitter only drew very minimal current (less than 100 m A). While with the magnets at the center of the receiver coil, the transmitter drew 1 A or more of current. This is a very dramatic and large confirmation of the principle described here.

[00101] As a further test, the magnet and receiver were placed on a location on the transmitter coil with a switching layer on top of it. Large current draw from the transmitter power supply can be observed at an adjusted resonant frequency. This is due to the power being emitted through the generated magnetic aperture into the receiver. Next, another receiver coil without a magnet was placed on the transmitter at a location near the first receiver and magnet. No discernible power transfer was detected. Confirming that the power transfer is localized to the area of the transmitter where the Ferrite layer above the transmitter coil is saturated.

[00102] To confirm that the effect observed is due to the magnetic field and not the presence of the Ferrite material in the magnets, the ring magnets were replaced with a ring constructed of the same material as the ring but not magnetized. No power transfer was observed with such a set up.

[00103] As a further confirmation, the receiver coil was placed on the transmitter coil and switchable layer but the magnet was removed. Next the magnets were brought close to the transmitter coil from below (the side opposite to the receiver coil). At about 25 mm distance to

the switchable layer, with the magnets aligned with the lateral location of the receiver coil, strong power transfer and high power transfer efficiency was observed. Moving the magnets laterally away from lateral alignment with the receiver coil, the aperture closed and no power was transferred further confirming the effect as being due to the field.

[00104] As a final confirmation, with the receiver coil and the ring magnets placed on the transmitter coil and transmitter frequency optimized for high power transfer, a single ring magnet was brought to lateral alignment from below the transmitter coil with the top magnets. With the magnetic poles oriented so that the flux density from the below magnet was opposing the magnetic flux from the magnet above, lower amounts of power transfer were achieved. Demonstrating that the net magnetic flux density was reduced by half and therefore the aperture was partially closed. Doubling the magnet below the transmitter coil, with the 2 magnetic flux densities from the magnets above and below the transmitter coil and the switchable layer cancelling each other out, the aperture could be closed and no power transfer was observed. Flipping the magnets below the transmitter coil so that the fields from magnets above and below would add up on the plane of the ferromagnetic layer, the power transfer would resume.

[00105] The multiple tests above consistently confirm that the principle of operation is the saturation of the Ferromagnetic switchable layer and this combination of materials and geometry performs as planned. Namely, safe (no EM emission), efficient power transmission to a receiver placed at any location on the transmitter coil can be achieved with minimal side effect and residual emission. The communication and control of such a system can be similar to the tightly coupled systems described earlier providing regulation and control between transmitter and receiver. Alternately, the system can be designed with no regulation at the charger, and all the regulation instead at the receiver, or any combination of architectures as described earlier for loosely-coupled or tightly-coupled wireless power transfer systems above. The novel wireless power transmission systems and methods described herein have ideal characteristics for this application.

[00106] In practice, with the thin layer of the Hitachi switchable material used, some heating of the switchable layer was observed. This can be due to the material being lossy (imaginary permeability) and/or being extremely thin. Use of Ferrites with minimal or no loss at the frequency of interest would improve this effect. Also, as noted above and shown in Figure 15, Ferrite material would have significantly lower saturation flux densities (0.2-0.5 T) compared to the thin sheet of the FineMET[®] material used. Thus, smaller magnetic flux densities (smaller or weaker magnets) can be used for switching.

[00107] Next 60 x 60 x 0.5 mm plates of material 78 (a MnZn Ferrite) from Fair-Rite

corporation were used to cover the transmitter coil surface as the switchable material while the same tests above were performed. This material has a low loss up to about 100 kHz and a real permeability of about 2000 up to 100 kHz. Similar switching results were obtained. However, with such thicker and lower loss material, no significant switching layer heating was observed. Many Ferrite materials with differing magnetic properties exist and optimizing the various fundamental properties and dimensions of the switchable layer can be performed with more detailed modeling.

[00108] Similarly, a low saturation flux density switching layer can be used above the transmitter coil while a higher saturation flux density material can be used below the transmitter coil and above the receiver coil for shielding purposes. For example, Nickel, cobalt, cast iron, etc. or alloys of such material (see Figure 15) with low saturation flux densities may be used as the switching layer while Sheet Steel or FineMET[®] or other shield material with high saturation flux densities would be used for shielding. In this case, a smaller and/or weaker switching permanent magnet or electromagnet induced field may be used for switching the switchable layer. Thus, the shields would not be saturated by the magnet used for switching and would remain effective in shielding unwanted stray magnetic fields from affecting nearby devices, materials, or living tissue. In such a case, the total system would be completely shielded and safe. Power would at the same time transfer efficiently between the transmitter and receiver from the created aperture at any location desired by user where the receiver is placed.

[00109] The tests above with magnets placed above and below the switching layer also show that novel methods of switching the layer can be employed. Since the layer responds to the net magnetic flux density, for example, a bias magnetic flux density can be designed to be incident on the layer and by including a weak additional magnet into the receiver, the total flux density with the receiver present can then be designed to exceed the saturation level to switch the layer locally. For example, a bias magnet material or electromagnet in the charger / transmitter can provide a uniform or local flux density to bring the DC or average AC level close to saturation and a smaller magnet material or electromagnet in the receiver can be used to exceed the required saturation level locally to open an aperture for power transfer.

[00110] In addition, it must be noted that when power is being transferred through the aperture, a sizeable ac magnetic field due to the inductive field is present. This field is in fact quite large since with a resonant geometry with a high Q, the power resonating between the coils is larger than the transferred power by a factor of Q (quality factor).

[00111] So it may be possible to open an aperture with a DC or AC magnetic flux density from a permanent magnet or electromagnet from the receiver or a bias DC or AC magnetic flux

density plus a magnet and/or electromagnet from the transmitter / charger and start the power transfer through an aperture. Once power transfer is achieved through such an aperture, the saturating magnetic field can be removed or reduced and if the average value of the AC magnetic flux density is sufficiently high to saturate the layer, power transfer will continue. It must be noted that once an aperture is opened, due to resonance and local change of the permeability, the magnetic flux density at this location is much higher than neighboring areas and with proper design and choice of materials and flux density, Q, etc, this aperture may be designed to remain open while the rest of the Ferromagnetic layer will remain in a high permeability state and continue to provide shielding at other locations and limit radiation from these locations as desired. Such a behavior was observed experimentally with another type thin layer Ferromagnetic material with lower saturation flux density.

[00112] In yet another embodiment, the transmitter periodically or continually applies a DC or AC magnetic flux generated by a coil (the same or different from the power transmitter coil) and sufficient magnetic flux density to bias the switching layer near or above its saturation value. The presence of the receiver coil with or without additional magnetic flux density from a permanent magnet or electromagnetic near the transmitter at a location on the surface may then be sufficient to bring the system to resonance, open the aperture and start power transfer as described above. Once power transfer starts, then the bias field may be removed or lowered to save energy. The locations on the switchable layer of transmitter away from the receiver will remain at high permeability and therefore contain the magnetic flux and would not emit power.

[00113] Such an application of a magnetic field to bring the magnetic flux density close to or above the saturation level can be achieved by pulsing a magnetic field from an electromagnet such as the transmitter coil and/or a separate electromagnet or coil and may be at the same time that the ping process discussed earlier occurs. Basically, through application of a magnetic field created by this bias electromagnet (can be the same as power transmitter coil or separate), the switchable layer is brought close to or over the saturation level. Then the power transmitter coil provides an additional AC magnetic field that may be detected through an opened aperture by any receiver coil present to start communication. Once this response is detected by the charger / transmitter, then continuous power is transmitted from the charger / transmitter and the regulation / control loop is established and power is transmitted until the receiver sends an end of charge signal or is removed so no feedback signal is detected at the charger / transmitter. As described above, during the transfer of power, the bias flux density to the switchable layer may or may not be applied depending on the design and principle of operation.

[00114] In yet another embodiment, the receiver can contain a permanent magnet and/or

electromagnet (which in some instances can be the same coil as for the receiver coil for power transfer) that is pulsed or turned on to apply a bias flux density to the switchable layer to saturate it to open the aperture and start power transfer. As described above, it may be possible to turn this bias off or remove the permanent magnet once the power transfer has started without affecting operation.

[00115] It must be noted that as discussed earlier the permeability is a tensor and the permeability of the material to magnetic field in one orientation may be affected by a flux density in another orientation in anisotropic material. So, novel single or multi-layer material and field geometries may be employed to take advantage of the magnetic aperture concept.

[00116] It may be further possible or desirable to switch the magnetic aperture on and keep it open in a certain location of the switchable layer. An example would be a charger / power supply layer where a particular area for power coupling is opened and kept open without continued presence of an AC or DC magnetic flux until the user desires to close this aperture. For these cases, it may be desirable to use a hard magnetic switching layer where the magnetic state of a region is changed by applying a sufficiently large flux density to switch the magnetic domains in that area and change the permeability permanently to a state that allows transfer of power through the aperture until reset by an opposing flux density. An application of this may be for example a charger / power supply table or surface of large area where at will, by application of a high magnetic flux through the switching layer with a permanent or electromagnet or a combination thereof, a region is modified and serves essentially as a power outlet for inductive power until the user chooses to close it by application of a reverse field.

[00117] An analogy for the above method of regulation and control of the amount of the power transferred can be seen in a product called the Saturable Reactor or Magnetic Amplifier (shown in **Figure 25**) where the amount of an AC current flowing through a lamp (L) from an AC source (G) is controlled by the inductor T made of a Ferrite core such as iron that is saturable. Another winding of the coil nearby is connected to a battery (B) or a DC power source and the current through the winding (i.e. the magnetic field and flux density incident on the core) are varied through a variable resistor (R) to change the permeability of the iron core or saturate it to modify the inductance value along the current path to the lamp (see Wikipedia entry for Saturable Reactor). While this is a very different application of modifying the permeability of a material with application of a magnetic field, it shows that the basic concept is solid and can be used in products.

[00118] Another method for achieving the goal of modifying the permeability of the switchable layer locally is to use the Curie temperature property of a Ferromagnet to alter its

properties. Curie temperature or point is the temperature at which a Ferromagnetic or a Ferrimagnetic material becomes paramagnetic upon heating. An iron magnet will lose its magnetism if heated above the Curie temperature and the effect is reversible. In optical recording, a laser light is focused on a data track to be written and the local temperature is raised over the Curie temperature. At the same time, a nearby coil will create an alternating magnetic field that mimics the data to be recorded. As the location under the laser beam is heated, the data is erased and the magnetization is changed to the direction dictated by the applied external magnetic field. Once the laser beam is passed and the material cools, that modified location of material is fixed and the up / down magnetization is frozen into the material to be stored and/or read back through magneto optic detection of polarization change of an incident optical beam when the track is read back.

[00119] Nickel (Curie Temperature of 358 °C) and Iron (Curie Temperature of 770 °C) or alloys of these materials are often used for this type of recording application. Lower Curie temperature Ferromagnetic material can also be designed. As an example, material 78 from Fair-Rite corporation has a Curie temperature of 200 °C. Similarly, in the wireless power case described above, in one embodiment, the receiver may locally heat a switchable layer optically or through resistive heating or a combination of the above to locally modify the permeability and affect the amount of power transfer by opening a magnetic aperture while leaving the rest of the area of a switchable layer unmodified to shield the transmitter coil magnetically and reduce or eliminate emission.

[00120] Use of the Curie temperature effect and the magnetic saturation may be combined or used individually to design an optimized system as discussed above and to achieve best performance.

[00121] In another implementation of this concept for other applications, a Ferromagnetic layer that has an EM field incident on it, may be modified in a one or 2 dimensional manner as desired by placing pixels or arrays of electromagnets such as printed or assembled coils or alike along the front and/or back or inside such a material. This may be combined with field from one or more permanent magnets to bias the operation near the saturation level. By locally activating the electromagnets, the local permeability may be modified affecting the phase and amplitude transmission and/or reflection properties of the EM wave at that location.

[00122] While the above descriptions relate to modifying the amount and location of power transmitted from a 2 dimensional wireless power system, the concept can be used for modulating the transmitted and/or reflected amplitude and/or phase of any electromagnetic and/or magnetic wave by using a Ferromagnetic layer. In a general sense, the description

above is for the first time describing the concept of locally modifying the shielding and/or magnetic properties of a Ferromagnetic layer by application of one or more or a combination of permanent and/or electromagnets and/or temperature to modify the magnitude and/or phase of the reflected and/or transmitted electromagnetic or magnetic field at any location in the 2 dimensional space while passing through or reflecting from such a layer. Beyond wireless power, this may have applications in shielding or modulating the amplitude and/or phase of a 2 dimensional electromagnetic or magnetic wave spatially. Applications may include phased array radar, beam steering, EM cloaking, beam forming and shaping, etc.

[00123] One advantage of use of a magnetic aperture in a wireless power transmission system is that the amount of power transferred and characteristics of the system are determined by the size of the receiver coil and associated magnet. So using a large transmitter coil, a designer may have flexibility in powering a variety of receivers and associated devices / power levels with the same transmitter coil. For example, a large receiver coil and associated magnet or electromagnet or heater (for curie temperature operation), may open a large aperture for providing relatively large power and to charge or power a laptop, power tool, or lamp, etc. while a smaller coil and magnet may be used to power or charge a mobile phone or Bluetooth headset. Such flexibility is very advantageous in many applications.

[00124] In a loosely coupled system, two or more receivers may be placed on and powered or charged from one transmitter coil simultaneously due to the size mismatch. The inventors have tested placement of two or more receivers on the type of charger surface described here, and shown that both receivers can be powered simultaneously while detecting no emission from any other area on the surface. This allows for the development of multiple charger systems where multiple (2 or more) receivers can be powered or charged simultaneously. In accordance with various embodiments, the receivers can provide different power levels and/or voltages to different products or parts. The sizes of the receiver coil, number of turns of the receiver coil, the regulation mechanism and overall system design can also be optimized to address a particular design requirement. This allows for the development of power surfaces with little or no power dissipation or emission (since the system is not in resonance and in low current draw state without a receiver). The same surface can also power or charge multiple devices including lamps, kitchen appliances, laptops, mobile phones, power tools, batteries, etc. as needed by simple placement on the surface. Experimentally, the inventors have found that, depending on the degree of resonance that can be adjusted by adjusting the Q of the system, the receiver can also be some distance (up to an inch or more) from the charger surface and receive power. This also allows placement of the charger pad under a table or surface if

necessary. In such a system, power transferred to each receiver may or may not be individually adjusted since any adjustment would affect operation and power received at all receivers. Methods for adjustment of power to each receiver may include serially or alternate powering of each receiver whereby the receiver disconnects its coil for a period allowing only one or a number of receivers to receive power or regulation of power at the receiver or a combination of the above.

[00125] Alternately, a power transmitter / charger / power supply may consist of a number of transmitter coils and associated control and communication circuits operating in tandem or independently. The charger / power supply / transmitter surface may thus be divided (and identified to the user) to contain independent sections so that the user may place one receiver on or near each section of the charger / power supply / transmitter to be powered and regulated by its associated electronics. Each section may operate as a position independent charger / power supply through use of the techniques and geometries described here so that the user may place the receiver in any position on the charger / power supply / transmitter for operation. Another device to be powered and/or charged may be placed in another section and similarly operate in a position independent manner in that section. **Figure 26** shows a geometry where multiple transmitter coils cover different areas of a multi-charger / power supply. Within each section, devices with different power rating and/or coil size can receive the appropriate voltage and power required. Each section has an independent power driver and/or communication system to operate with the receiver nearby. In this way, control and regulation of individual devices and position independence can both be achieved. However, placement of more than one device in each section is not permitted. In practice, this may not be a significant disadvantage.

[00126] In any of the examples given above, the ring magnet and its variations including the gap are described only by way of example. In accordance with other embodiments, it is also possible to achieve the same or a similar effect with use of any appropriate one or several permanent magnets or electromagnets of arc, disc, cylinder, square, rectangular, triangular, oval, or ring, etc. shape, magnetization orientation and magnetic flux density pattern. As discussed above, it is important to optimize the type and structure of the material and the DC switching magnetic field appropriately to achieve optimum saturation. The use of anisotropic or multi-layer switching layer also provides further flexibility and design possibilities. Since a particular type of magnet and field strength may be required to open the aperture (in conjunction with the magnetic layer), it is therefore unlikely that a casual or accidental placement of a magnet by a user will open this aperture. Furthermore, if such an aperture is opened, the

system with receiver communication and/or feedback can be designed to require a communication signal to verify presence of a receiver and continue providing power. Therefore, the systems described here can be implemented in an extremely robust and safe manner.

[00127] For ease of illustration, the switching layer was described above as one layer in many of the above descriptions. In accordance with various embodiments, such as for manufacturing and/or performance reasons, it may be desirable for the switching layer to be actually made of multiple active layers. For example, the FineMET[®] sheet material may consist of one, two or even 3 layers of active Ferromagnetic material sandwiched between adhesive or backing layers. This is done to accommodate the thin nature of the basic manufactured layer while providing sufficient performance and overall active layer thickness. In general, the multiple layers of the switching layer (sheet or material) of soft and/or hard magnetic material may be similar or different to improve performance and characteristics. Interesting and useful effects may be achieved by using exchange coupling between the layers as used in magnetic recording layers.

[00128] An additional observation is that with a receiver containing an appropriate magnet placed on the charger surface, the magnetic aperture is opened as described above. The inventors have experimentally observed that a second receiver (with or without magnet) placed on top of the first receiver at distances of an inch or more apart from the first receiver coil also receives substantial amount of power. In accordance with an embodiment, the amount of power received is larger than received by a receiver coil placed at such a distance from the charger surface when a magnet placed near the surface opens an aperture. This is an indication that, in accordance with some embodiments, the coil and/or circuit from the first receiver (close to the charger surface) and the second receiver coil (from the receiver not requiring a magnet farther away and above the first receiver) can be designed to interact and resonate to extend the power to larger distances from the surface. This important and useful effect demonstrates that, in accordance with various embodiments, multiple receivers can be stacked (possibly to several receivers and many inches high) from the charger surface and all the receivers may be powered and or charged simultaneously. It also demonstrates that once a magnetic aperture is opened, the power from the aperture can be effectively guided or extended far above the charger surface. By using smaller or larger dimension coils along this path, the magnetic field physical dimension can be expanded or contracted as in a column of power from the aperture. By use of different coil turns and dimensions, different power levels and/or voltages can be extracted from this column at different positions.

[00129] The system described here, thus provides a 3-dimensional power outlet that allows

the user to extract power at different locations on the surface and vertically above the charger surface. Interesting and useful applications of this approach for powering products or power distribution can be envisioned. Such a system may also be used within an electric or electronic product to distribute different power or voltages to different locations.

[00130] For example, it would also be possible to develop multi-voltage and/or multi-power power supplies where different vertically stacked power receiver coils extract the appropriate power and voltage from a common primary (charger) coil. For fixed power supplies (where the receiver does not need to be physically removed), use of a switching layer may not be necessary since the x-y dimension flexibility is not required. Thus a charger coil and multiple vertically stacked receiver coils may be used.

[00131] In accordance with some other applications, it may not be desirable to have the magnetic field extend beyond the first receiver. As described earlier, use of appropriate ferromagnetic and/or metal layer behind any of the receiver coils can suppress this field reducing any potential effect of the magnetic radiation on nearby devices, objects, or living tissue. So the field extending in the z direction can be manipulated not to produce undesirable results. In accordance with some embodiments, it may also be possible to route the magnetic field past sensitive parts and have it then extend beyond the device to the next device without affecting the parts to be shielded. For example in the case a charger for multiple mobile phones is developed that allows stacking of the phones on the charger, the first receiver coil and magnet closer to the mobile device would open the aperture in the charger and provide power to the first receiver. This can be followed by a structure of ferrite and/or metal layer that protects the sensitive electronics of the mobile phone or any metal layers from the magnetic field but routes it above the first mobile device or phone to reach a second device's receiver coil and power that and so on and so forth, thus simultaneously powering multiple stacked mobile devices and yet shielding the electronics inside them. The above description and embodiments are not intended to be exhaustive, and are instead intended to only show some examples of the rich and varied products and technologies that can be envisioned and realized by embodiments of the invention. It will be evident to persons skilled in the art that these and other embodiments can be combined to produce combinations of above techniques, to provide useful effects and products.

[00132] Some aspects of the present invention can be conveniently implemented using a conventional general purpose or a specialized digital computer, microprocessor, or electronic circuitry programmed according to the teachings of the present disclosure. Appropriate

software coding can readily be prepared by skilled programmers and circuit designers based on the teachings of the present disclosure, as will be apparent to those skilled in the art.

[00133] In some embodiments, the present invention includes a computer program product which is a storage medium (media) having instructions stored thereon/in which can be used to program a computer to perform any of the processes of the present invention. The storage medium can include, but is not limited to, any type of disk including floppy disks, optical discs, DVD, CD-ROMs, microdrive, and magneto-optical disks, ROMs, RAMs, EPROMs, EEPROMs, DRAMs, VRAMs, flash memory devices, magnetic or optical cards, nanosystems (including molecular memory ICs), or any type of media or device suitable for storing instructions and/or data.

[00134] The foregoing description of the present invention has been provided for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise forms disclosed. Many modifications and variations will be apparent to the practitioner skilled in the art. The embodiments were chosen and described in order to best explain the principles of the invention and its practical application, thereby enabling others skilled in the art to understand the invention for various embodiments and with various modifications that are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the following claims and their equivalence.

Claims:

What is claimed is:

1. A system for modifying the transmitted and/or reflected phase and/or amplitude of an electromagnetic or magnetic field incident on a magnetic material, spatially in one or more dimensions, comprising:
 - a ferromagnetic material; and
 - one or more components for applying a magnetic field to affect saturation in the ferromagnetic material, and correspondingly the local permeability at one or more regions or all of the ferromagnetic material, in one or more dimensions, to control or modify transmission or reflection of an incident electromagnetic or magnetic field.
2. The system of claim 1, wherein the ferromagnetic material is in three-dimensions, and the one or more regions or all of the ferromagnetic material are used to control, or modify the path of transmission or reflection of, electromagnetic or magnetic fields incident in multiple dimensions on the ferromagnetic material.
3. The system of claim 2, wherein the one or more regions of the ferromagnetic material that control transmission or reflection of incident electromagnetic or magnetic field act as a magnetic aperture.
4. The system of claim 1, wherein the ferromagnetic material is a generally flat ferromagnetic layer.
5. The system of claim 4, wherein the ferromagnetic layer is generally flat in the x-y direction, and wherein the one or more regions of the ferromagnetic layer are used to control, or modify the path of transmission or reflection of, electromagnetic or magnetic fields incident on the layer generally in the z direction.
6. The system of claim 5, wherein the one or more regions of the ferromagnetic layer that control transmission or reflection of incident electromagnetic or magnetic field act as a magnetic aperture.

7. The system of claim 1, wherein the magnetic field applied to the ferromagnetic material to affect the saturation therein, including increasing or reducing the saturation, is an AC or DC magnetic field.

8. The system of claim 1, wherein the magnetic field applied to the ferromagnetic material to affect the saturation therein, including increasing or reducing the saturation, is provided by a magnet.

9. The system of claim 1, wherein the system further optionally includes one or more regions of electromagnetic shielding, for further controlling or modifying the transmission or reflection of an incident electromagnetic or magnetic field incident on the ferromagnetic material.

10. A method of modifying the transmitted and/or reflected phase and/or amplitude of an electromagnetic or magnetic field incident on a layer of magnetic material, spatially in one or more dimensions, comprising the steps of:

providing a ferromagnetic material; and

applying a magnetic field to affect saturation in the ferromagnetic material, and correspondingly the local permeability at one or more regions or all of the ferromagnetic material, in one or more dimensions, to control or modify transmission or reflection of an incident electromagnetic or magnetic field.

11. A system for charging one or more mobile, electronic, or other device and/or battery, battery door, or skin for use with the device wirelessly, comprising:

a charger having a surface and including one or more transmitter coils, for use in inductively charging one or more mobile, electronic, or other device and/or battery, battery door, or skin for use with the device placed on the charger surface; and

a ferromagnetic material generally distributed over the one or more transmitter coils, the permeability of which ferromagnetic material can be selectively controlled to create magnetic apertures, or to otherwise control or modify transmission or reflection of incident electromagnetic or magnetic fields by the transmitter coils to secondary coils of one or more mobile, electronic, or other device and/or battery, battery door, or skin for use with the device placed on the charger.

12. The system of claim 11, wherein the charger includes multiple transmitter coils, and the

ferromagnetic material is generally distributed over the multiple transmitter coils.

13. The system of claim 11, wherein the charger includes an arrangement of one or more transmitter coils that can be used to provide a generally uniform magnetic flux across the charger surface.

14. The system of claim 11, wherein the ferromagnetic material is a generally flat ferromagnetic layer distributed between the transmitter coils and the charger surface.

15. The system of claim 14, wherein the ferromagnetic layer acts as a switching layer wherein, when a mobile, electronic, or other device and/or battery, battery door, or skin for use with the device having a secondary coil is placed on the charger, the permeability of the ferromagnetic material is selectively controlled to create a magnetic aperture at a region corresponding to the secondary coil.

16. The system of claim 15, wherein the secondary coil is associated with its own magnetic field, that is used to affect saturation in the region of charger surface, and to initiate creation of the magnetic aperture, when the secondary coil is placed on the charger surface.

17. The system of claim 16, wherein the secondary coil's own magnetic field is provided by a magnet generally collocated with the secondary coil.

18. The system of claim 17, wherein the magnet generally collocated with the secondary coil is a ring magnet that optionally includes a cut or gap in its circumference.

19. The system of claim 11, wherein the charger can charge multiple mobile, electronic, or other device and/or battery, battery door, or skin for use with the device simultaneously, including wherein the secondary coil of each of the multiple mobile, electronic, or other device and/or battery, battery door, or skin for use with the device initiates creation of a magnetic aperture for that device when placed on the charger surface.

20. A method of charging one or more mobile, electronic, or other device and/or battery, battery door, or skin for use with the device wirelessly, comprising the steps of:
providing a charger having a surface and including one or more transmitter coils, for use

in inductively charging one or more mobile, electronic, or other device and/or battery, battery door, or skin for use with the device placed on the charger surface; and

providing a ferromagnetic material generally distributed over the one or more transmitter coils, the permeability of which ferromagnetic material can be selectively controlled to create magnetic apertures, or to otherwise control or modify transmission or reflection of incident electromagnetic or magnetic fields by the transmitter coils to secondary coils of one or more mobile, electronic, or other device and/or battery, battery door, or skin for use with the device placed on the charger.

Abstract:

Systems and methods for modulating the phase and amplitude of an electromagnetic wave in multiple (e.g. one, two or three) dimensions. Applications include beam shaping, beam forming, phase array radar, beam steering, etc. and inductive charging, and particularly usage in mobile, electronic, electric, lighting, or other devices, batteries, power tools, kitchen, industrial applications, vehicles, and other usages. Embodiments of the invention can also be applied generally to power supplies and other power sources and chargers, including systems and methods for improved ease of use and compatibility and transfer of wireless power to mobile, electronic, electric, lighting, or other devices, batteries, power tools, kitchen, industrial applications and/or vehicles.

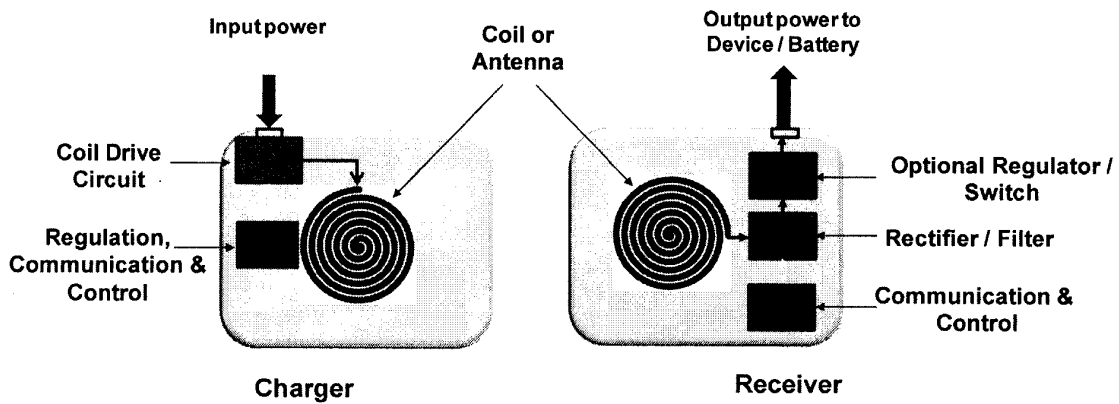


Figure 1- High level description of elements in a wireless charger and receiver.

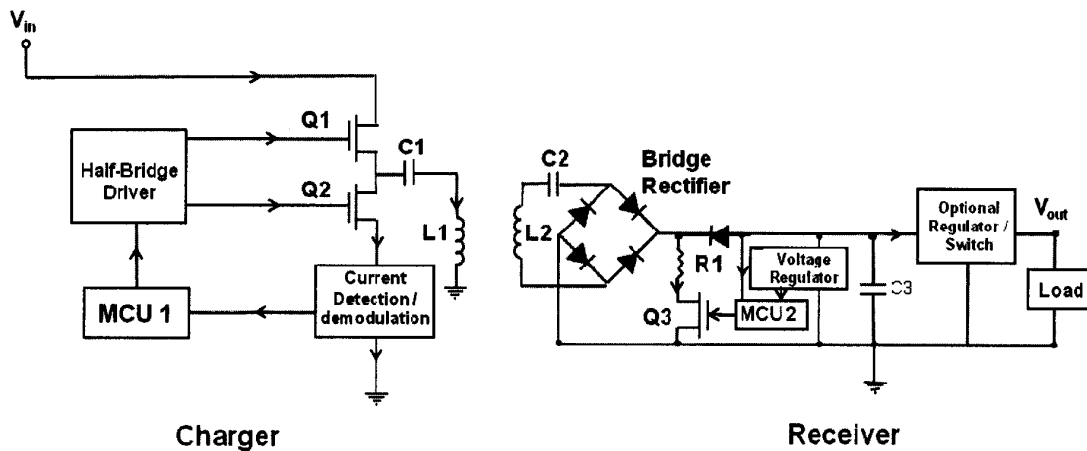


Figure 2 – Components for wireless power / charger system with communication through the coil.

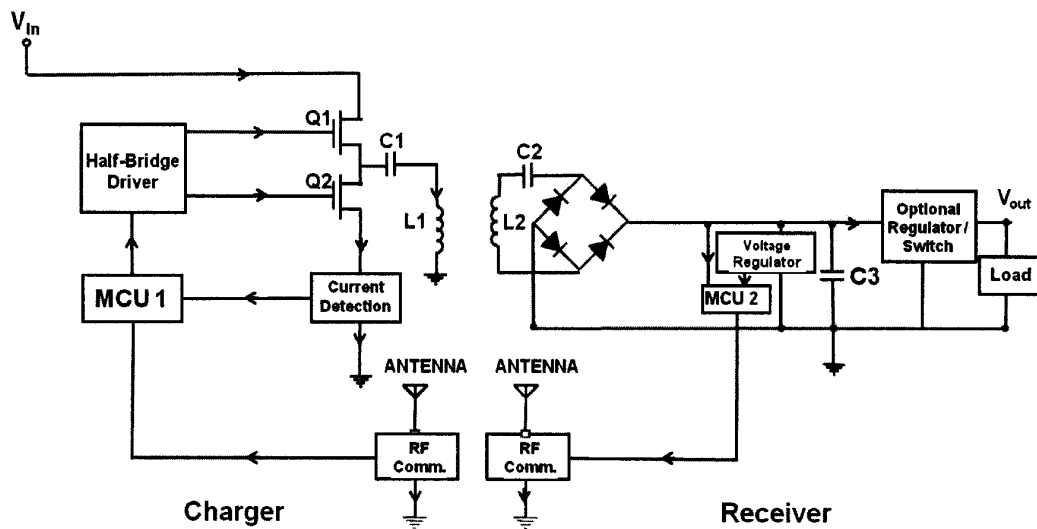


Figure 3- Wireless power system with RF communication between charger and receiver.

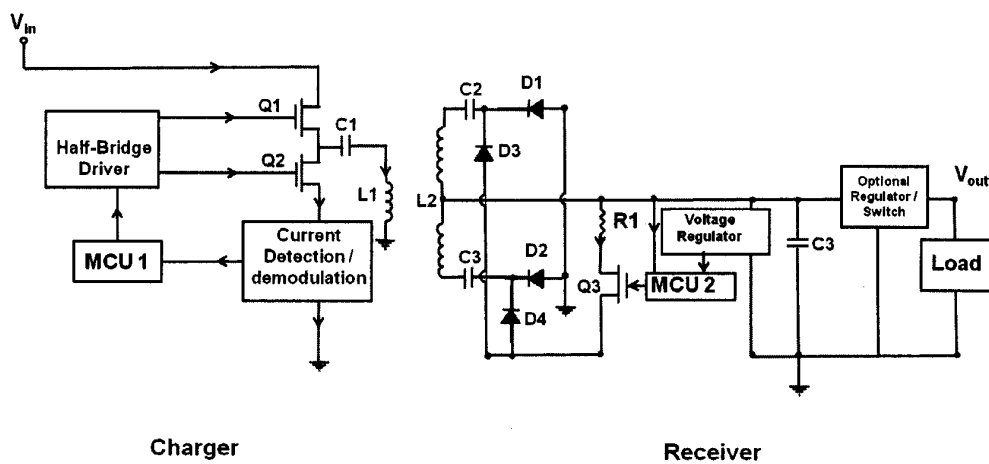


Figure 4- Wireless power system with a center-tapped receiver coil.

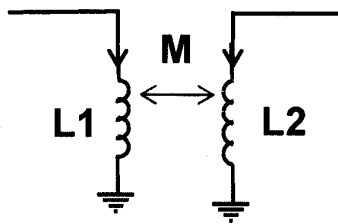


Figure 5- Inductance (L1 and L2) and mutual inductance (M) between two coils.

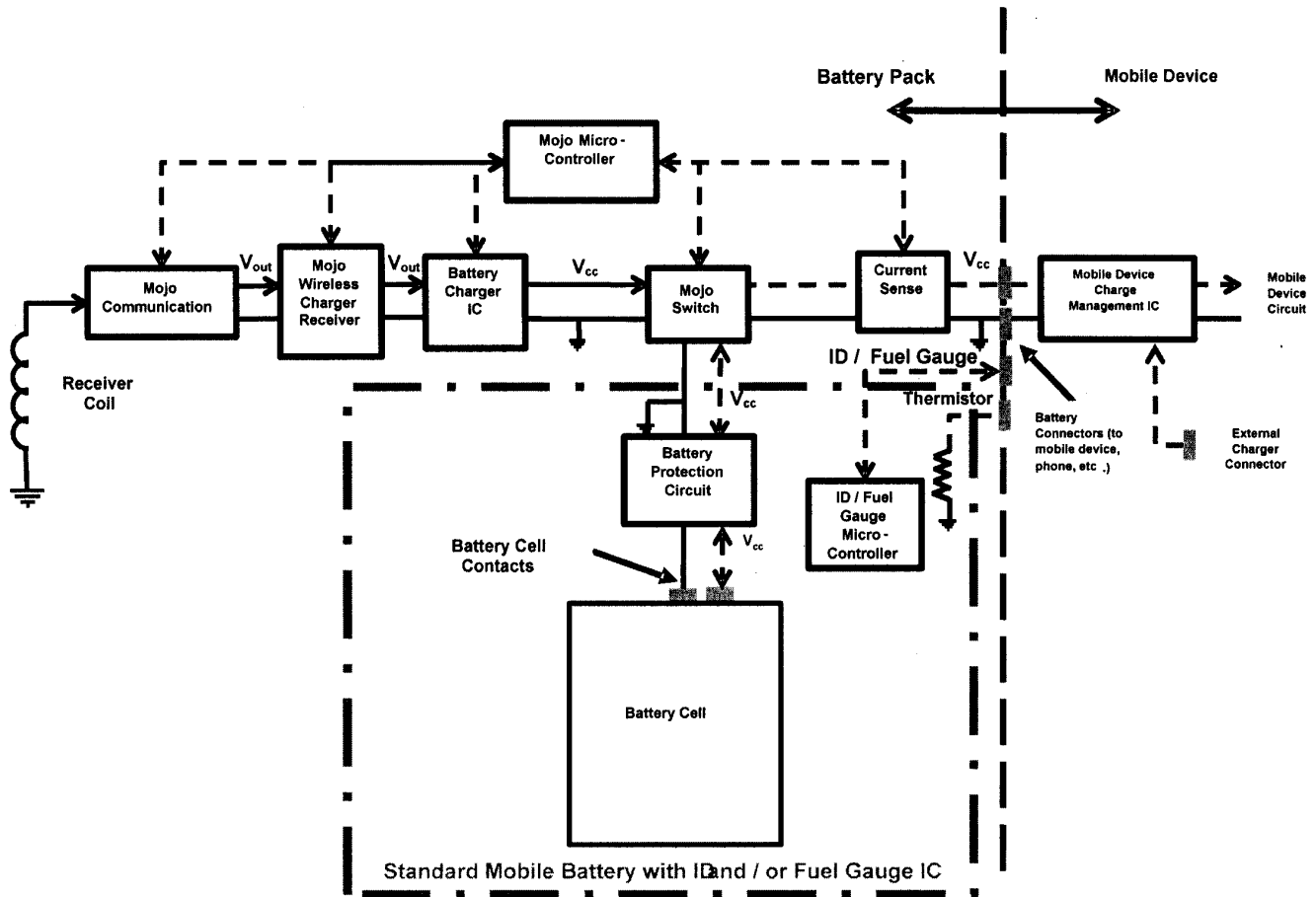


Figure 6 – Wireless power receiver for a battery circuit.

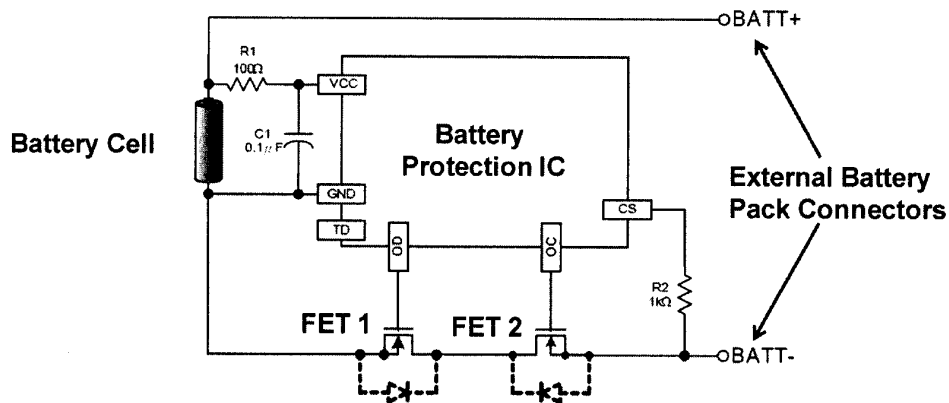


Figure 7 – Typical Lithium Ion Battery Protection Circuit

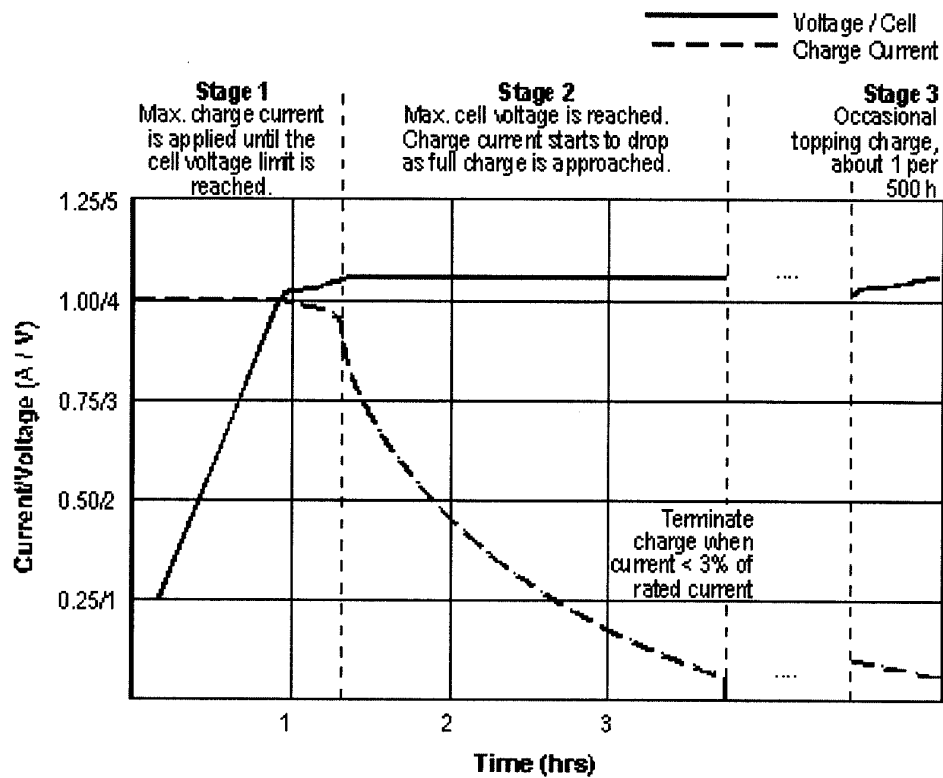


Figure 8 – Charging cycle for a Li-Ion battery.

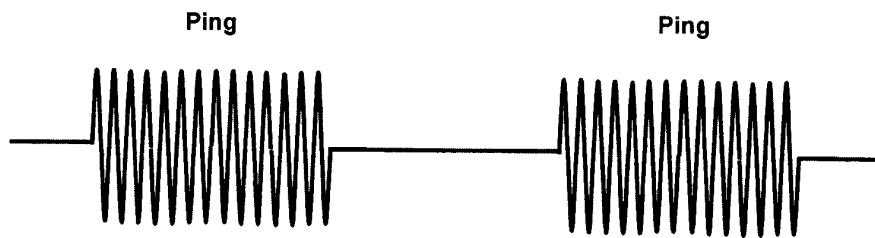


Figure 9 – Identification process by charger circuit. Charger periodically activates the charger coil by applying voltage of appropriate frequency for a period of time to find a receiver nearby.

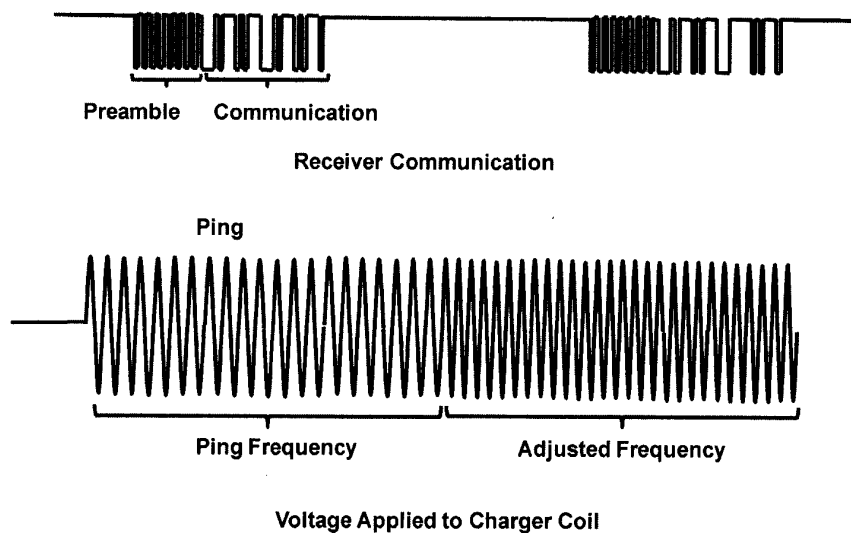


Figure 10 – Voltage applied to Charger Coil (bottom) and Signal from the Receiver (top).

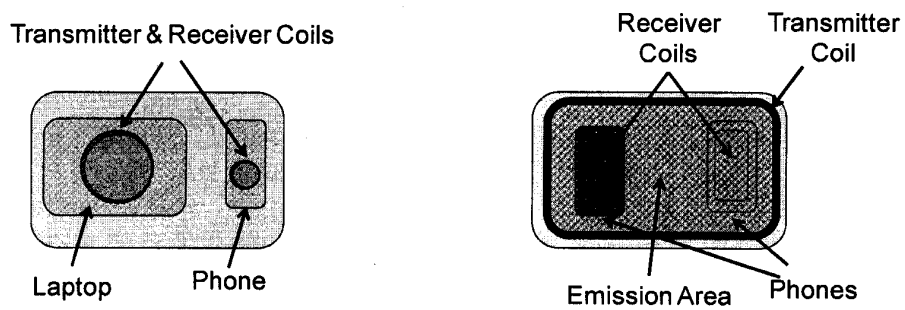


Figure 11 – Configurations for a tightly coupled power transfer system with 2 individual transmitter coils of different size powering a laptop and a phone (left) and a loosely coupled wireless power system with a large transmitter coil powering 2 smaller receiver coils in mobile phones (right).

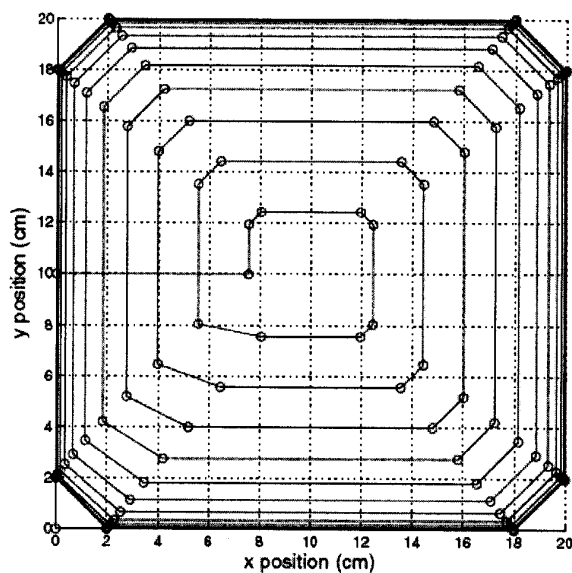


Figure 12 – Pattern as per prior art for a 20 x 20 cm area coil to produce uniform magnetic field over its surface.

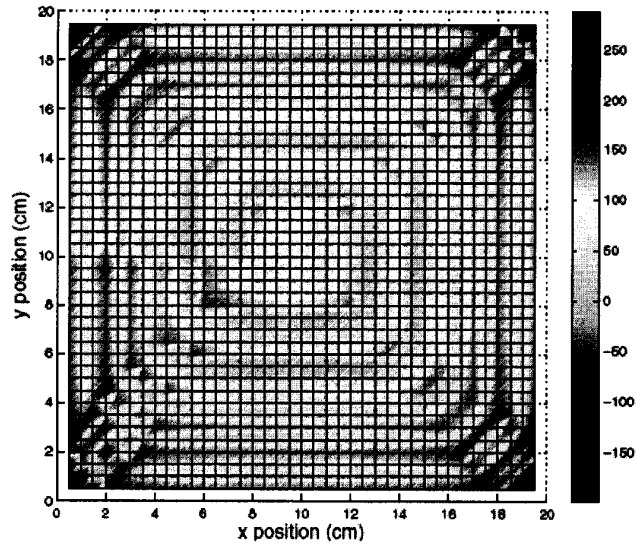


Figure 13 – Resulting calculated Magnetic field from a current of 1 A in coil of Figure 12.

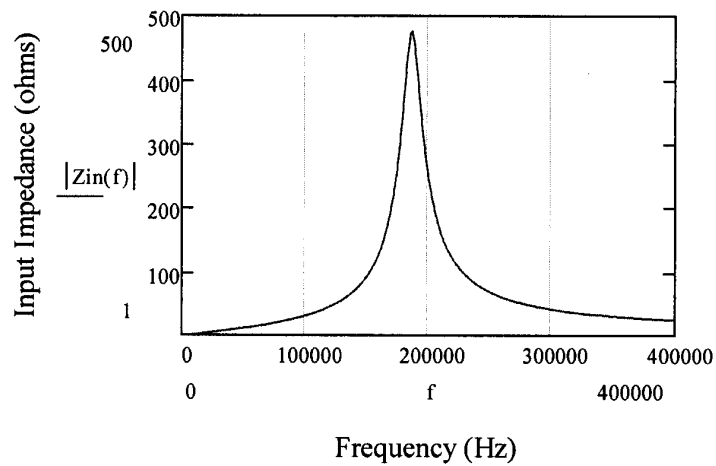


Figure 14 – Impedance at the transmitter for Figure 2 system for a loosely coupled system showing the resonance in power transfer.

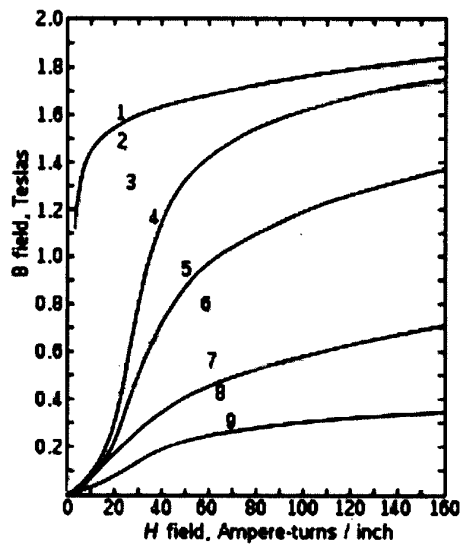


Figure 15 – Magnetization curves of 9 ferromagnetic materials, showing saturation. 1. Sheet steel, 2. Silicon steel, 3. Cast steel, 4. Tungsten steel, 5. Magnet steel, 6. Cast iron, 7. Nickel, 8. Cobalt, 9. Magnetite.

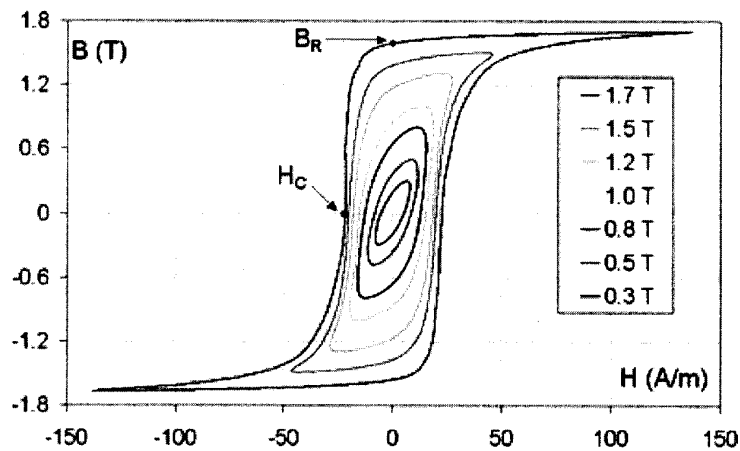


Figure 16 – Magnetic Hysteresis loop for Steel. The magnetic remanence (B_R) and coercivity of the material (H_C) are shown in this figure.

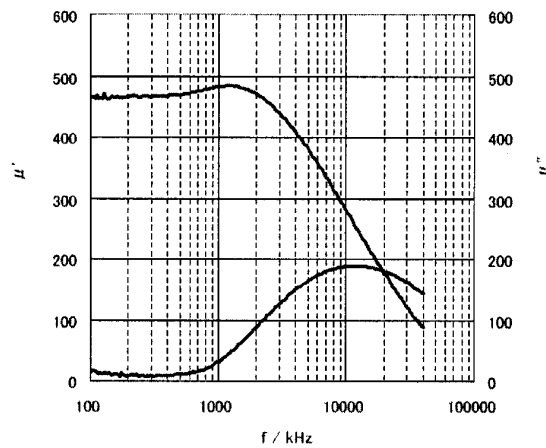


Figure 17 – Complex permeability for a Ferromagnet material showing the real (left – higher value curve) and imaginary (left – lower curve) components of a Ferrite layer.

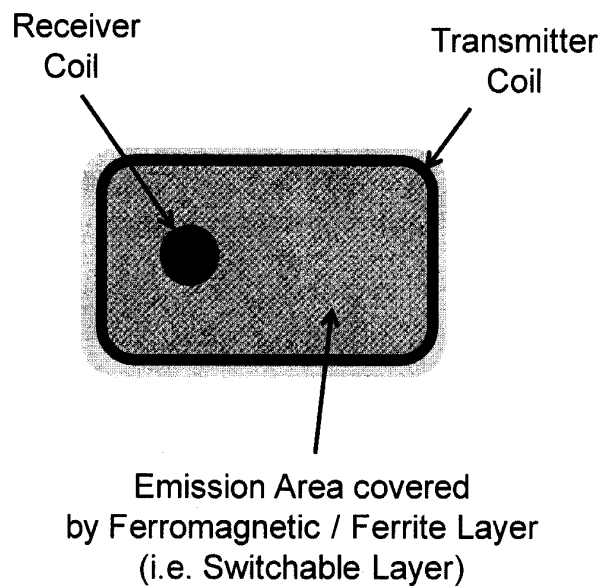


Figure 18 – Large area transmitter covered by Ferromagnetic / Ferrite layer

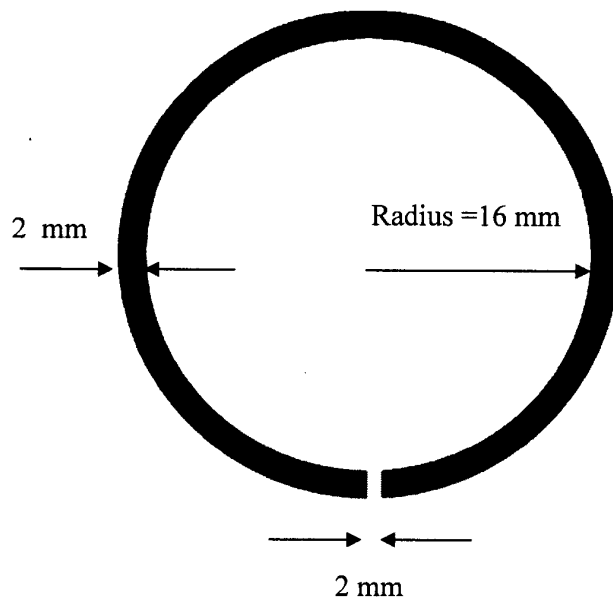


Figure 19 – Magnet used with receiver coil to saturate the switchable Ferrite layer.

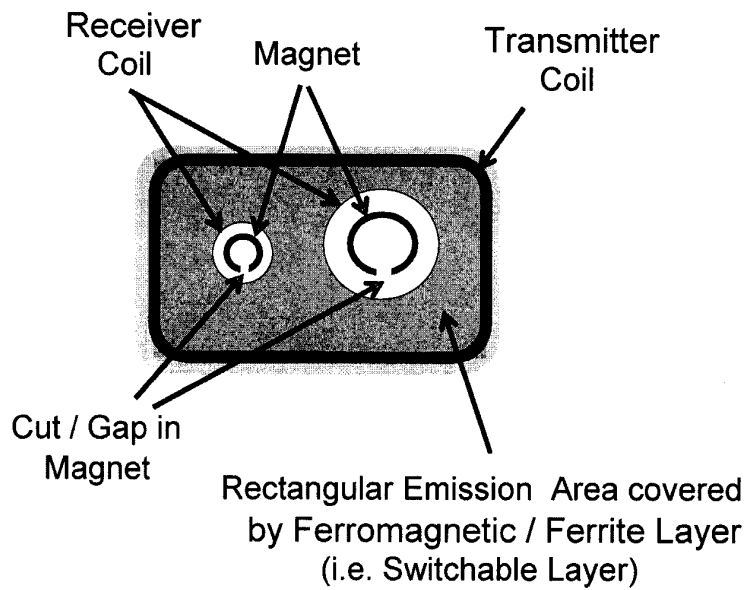


Figure 20 – Large area transmitter covered by Ferromagnetic / Ferrite layer with two receivers and ring magnets with optional cut / gap.

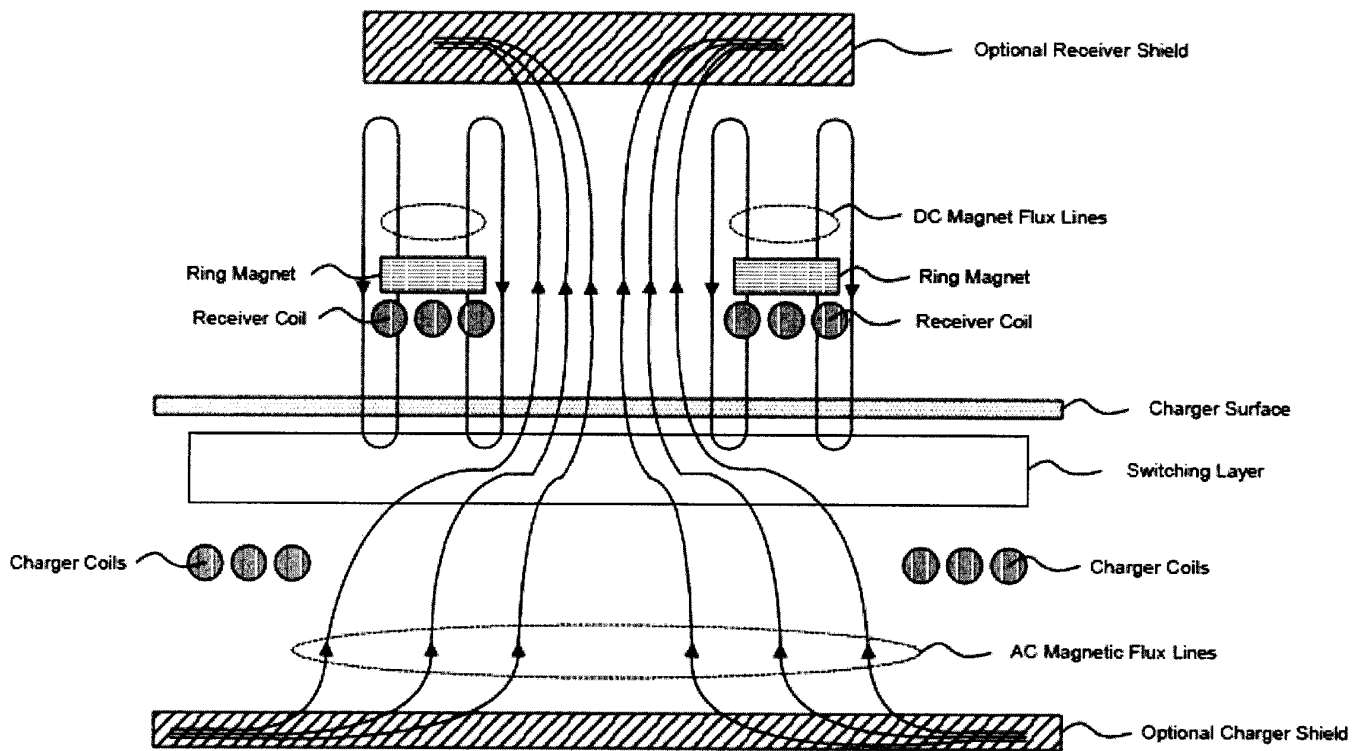


Figure 21 – Side view of the Wireless Power system showing the charger / receiver coils and the switching layer. Also the receiver magnet for switching is shown. Optional shielding layers above the receiver coil and below the charger coil are also shown

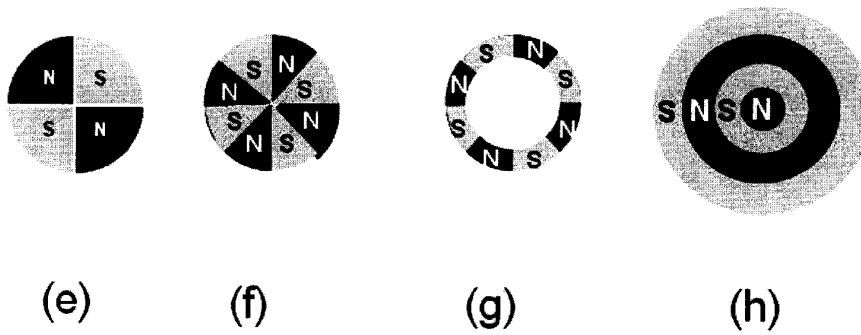
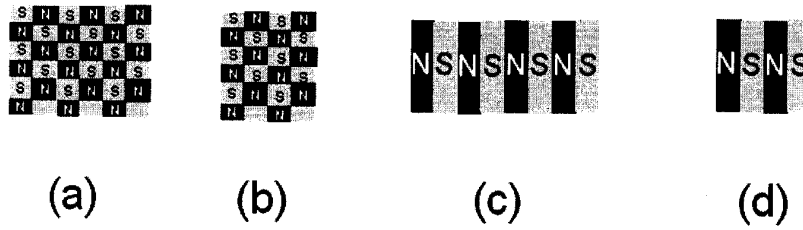


Figure 22- Showing some examples of multi-pole magnets

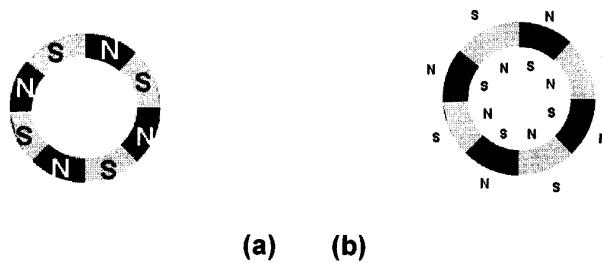


Figure 23 - Showing some examples of ring multi-pole magnets magnetized axially (a) and radially (b).

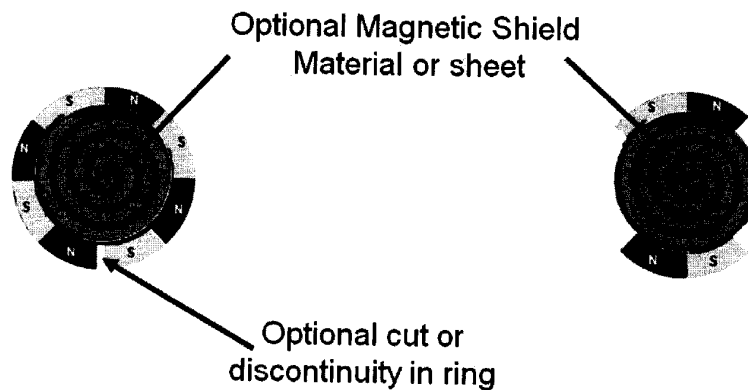


Figure 24 - Showing examples of transmitter or receiver coils and ring multi-pole magnets magnetized axially with an additional cut or gap in their circular pattern to reduce or eliminate eddy currents due to the alternating magnetic field.

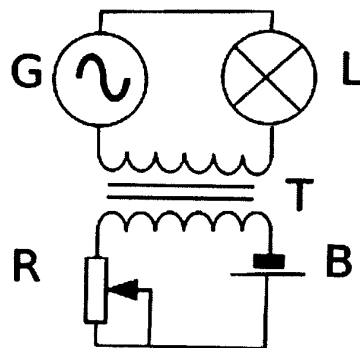


Figure 25 – In a Saturable Reactor or Magnetic Amplifier, the amount of an AC current flowing through a lamp (L) from an AC source (G) is controlled by the inductor T made of a ferrite core such as iron that is saturable. Another winding of the coil nearby is connected to a battery (B) or a DC power source and the current through the winding (creating the magnetic field and flux density on the core) are varied through a variable resistor (R) to change the permeability of the iron core or saturate it to modify the inductance value along the current path to the lamp.

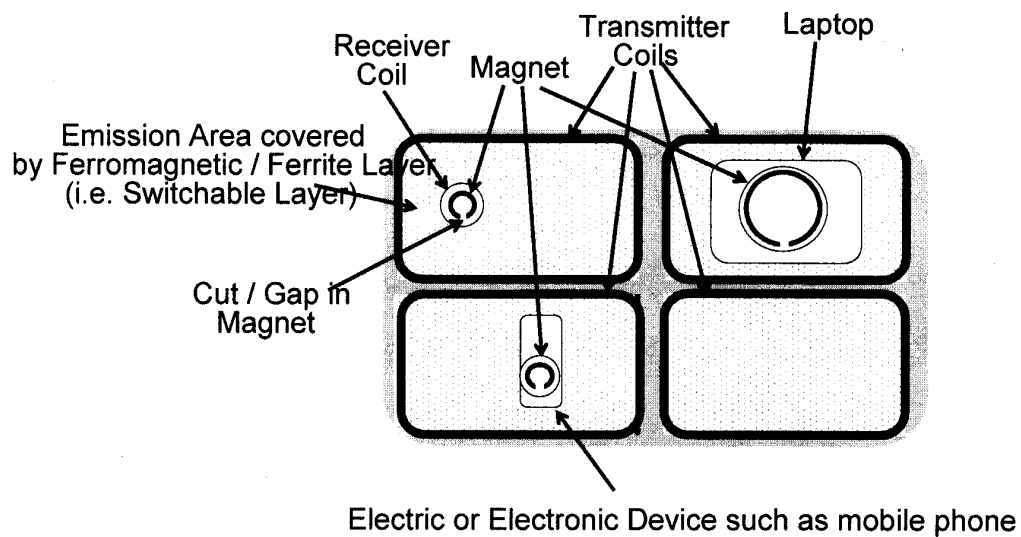


Figure 26 – A multi-charger or power supply surface where the area is sub-divided into sections powered by a coil and covered with Ferromagnetic switching layer. Each section is independent and driven by its own power driver and / or communication system to regulate and control power in that section.

Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

Application Data Sheet 37 CFR 1.76		Attorney Docket Number	AFPA-01029US0
		Application Number	
Title of Invention	SYSTEM AND METHOD FOR MODULATING THE PHASE AND AMPLITUDE OF AN ELECTROMAGNETIC WAVE IN MULTIPLE DIMENSIONS		
The application data sheet is part of the provisional or nonprovisional application for which it is being submitted. The following form contains the bibliographic data arranged in a format specified by the United States Patent and Trademark Office as outlined in 37 CFR 1.76. This document may be completed electronically and submitted to the Office in electronic format using the Electronic Filing System (EFS) or the document may be printed and included in a paper filed application.			

Secrecy Order 37 CFR 5.2

☐ Portions or all of the application associated with this Application Data Sheet may fall under a Secrecy Order pursuant to 37 CFR 5.2 (Paper filers only. Applications that fall under Secrecy Order may not be filed electronically.)

Applicant Information:

Applicant 1					Remove
Applicant Authority		☒ Inventor		☐ Legal Representative under 35 U.S.C. 117	
				☐ Party of Interest under 35 U.S.C. 118	
Prefix	Given Name	Middle Name	Family Name	Suffix	
	Afshin		Partovi		
Residence Information (Select One) ☒ US Residency ☐ Non US Residency ☐ Active US Military Service					
City	Sunnyvale	State/Province	CA	Country of Residence i	US
Citizenship under 37 CFR 1.41(b) i		US			
Mailing Address of Applicant:					
Address 1	1063 Morse Avenue				
Address 2	#5-100				
City	Sunnyvale	State/Province	CA		
Postal Code	94089	Country i	US		
All Inventors Must Be Listed - Additional Inventor Information blocks may be generated within this form by selecting the Add button.					
Add					

Correspondence Information:

Enter either Customer Number or complete the Correspondence Information section below. For further information see 37 CFR 1.33(a).			
☐ An Address is being provided for the correspondence Information of this application.			
Customer Number	23910		
Email Address	officeactions@fdml.com	Add Email	Remove Email

Application Information:

Title of the Invention	SYSTEM AND METHOD FOR MODULATING THE PHASE AND AMPLITUDE OF AN ELECTROMAGNETIC WAVE IN MULTIPLE DIMENSIONS		
Attorney Docket Number	AFPA-01029US0	Small Entity Status Claimed	☒
Application Type	Provisional		
Subject Matter	Utility		
Suggested Class (if any)		Sub Class (if any)	
Suggested Technology Center (if any)			
Total Number of Drawing Sheets (if any)	14	Suggested Figure for Publication (if any)	

Application Data Sheet 37 CFR 1.76		Attorney Docket Number	AFPA-01029US0
		Application Number	
Title of Invention	SYSTEM AND METHOD FOR MODULATING THE PHASE AND AMPLITUDE OF AN ELECTROMAGNETIC WAVE IN MULTIPLE DIMENSIONS		

Publication Information:

☐	Request Early Publication (Fee required at time of Request 37 CFR 1.219)
☐	Request Not to Publish. I hereby request that the attached application not be published under 35 U.S.C. 122(b) and certify that the invention disclosed in the attached application has not and will not be the subject of an application filed in another country, or under a multilateral international agreement, that requires publication at eighteen months after filing.

Representative Information:

Representative information should be provided for all practitioners having a power of attorney in the application. Providing this information in the Application Data Sheet does not constitute a power of attorney in the application (see 37 CFR 1.32). Enter either Customer Number or complete the Representative Name section below. If both sections are completed the Customer Number will be used for the Representative Information during processing.			
Please Select One:	☒ Customer Number	☐ US Patent Practitioner	☐ Limited Recognition (37 CFR 11.9)
Customer Number	23910		

Domestic Benefit/National Stage Information:

This section allows for the applicant to either claim benefit under 35 U.S.C. 119(e), 120, 121, or 365(c) or indicate National Stage entry from a PCT application. Providing this information in the application data sheet constitutes the specific reference required by 35 U.S.C. 119(e) or 120, and 37 CFR 1.78(a)(2) or CFR 1.78(a)(4), and need not otherwise be made part of the specification.			
Prior Application Status	Pending	Remove	
Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)
	non provisional of		
Additional Domestic Benefit/National Stage Data may be generated within this form by selecting the Add button.			Add

Foreign Priority Information:

This section allows for the applicant to claim benefit of foreign priority and to identify any prior foreign application for which priority is not claimed. Providing this information in the application data sheet constitutes the claim for priority as required by 35 U.S.C. 119(b) and 37 CFR 1.55(a).			
Remove			
Application Number	Country ⁱ	Parent Filing Date (YYYY-MM-DD)	Priority Claimed
			☐ Yes ☒ No
Additional Foreign Priority Data may be generated within this form by selecting the Add button.			Add

Assignee Information:

Providing this information in the application data sheet does not substitute for compliance with any requirement of part 3 of Title 37 of the CFR to have an assignment recorded in the Office.	
Assignee 1	Remove

Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

Application Data Sheet 37 CFR 1.76		Attorney Docket Number	AFPA-01029US0	
		Application Number		
Title of Invention	SYSTEM AND METHOD FOR MODULATING THE PHASE AND AMPLITUDE OF AN ELECTROMAGNETIC WAVE IN MULTIPLE DIMENSIONS			

If the Assignee is an Organization check here. ☐				
Prefix	Given Name	Middle Name	Family Name	Suffix
Mailing Address Information:				
Address 1				
Address 2				
City		State/Province		
Country ⁱ		Postal Code		
Phone Number		Fax Number		
Email Address				
Additional Assignee Data may be generated within this form by selecting the Add button.				Add

Signature:

A signature of the applicant or representative is required in accordance with 37 CFR 1.33 and 10.18. Please see 37 CFR 1.4(d) for the form of the signature.					
Signature	/Karl F. Kenna/			Date (YYYY-MM-DD)	2011-01-18
First Name	Karl F.	Last Name	Kenna	Registration Number	45445

This collection of information is required by 37 CFR 1.76. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 23 minutes to complete, including gathering, preparing, and submitting the completed application data sheet form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C. 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether the Freedom of Information Act requires disclosure of these records.
2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.
3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.
4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).
5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.
6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).
7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.
8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspections or an issued patent.
9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

Electronic Patent Application Fee Transmittal				
Application Number:				
Filing Date:				
Title of Invention:		SYSTEM AND METHOD FOR MODULATING THE PHASE AND AMPLITUDE OF AN ELECTROMAGNETIC WAVE IN MULTIPLE DIMENSIONS		
First Named Inventor/Applicant Name:		Afshin Partovi		
Filer:		Karl Kenna/narissa besada		
Attorney Docket Number:		AFPA-01029US0		
Filed as Small Entity				
Provisional Filing Fees				
Description	Fee Code	Quantity	Amount	Sub-Total in USD(\$)
Basic Filing:				
Provisional Application filing fee	2005	1	110	110
Pages:				
Claims:				
Miscellaneous-Filing:				
Petition:				
Patent-Appeals-and-Interference:				
Post-Allowance-and-Post-Issuance:				
Extension-of-Time:				

Description	Fee Code	Quantity	Amount	Sub-Total in USD(\$)
Miscellaneous:				
Total in USD (\$)				110

Electronic Acknowledgement Receipt	
EFS ID:	9255604
Application Number:	61433883
International Application Number:	
Confirmation Number:	9465
Title of Invention:	SYSTEM AND METHOD FOR MODULATING THE PHASE AND AMPLITUDE OF AN ELECTROMAGNETIC WAVE IN MULTIPLE DIMENSIONS
First Named Inventor/Applicant Name:	Afshin Partovi
Customer Number:	23910
Filer:	Karl Kenna/narissa besada
Filer Authorized By:	Karl Kenna
Attorney Docket Number:	AFPA-01029US0
Receipt Date:	18-JAN-2011
Filing Date:	
Time Stamp:	19:33:09
Application Type:	Provisional

Payment information:

Submitted with Payment	yes
Payment Type	Deposit Account
Payment was successfully received in RAM	\$ 110
RAM confirmation Number	6693
Deposit Account	061325
Authorized User	
The Director of the USPTO is hereby authorized to charge indicated fees and credit any overpayment as follows: Charge any Additional Fees required under 37 C.F.R. Section 1.21 (Miscellaneous fees and charges)	

File Listing:					
Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1		afpa_1029us0_application.pdf	216775	yes	47
			cb2bc2e32e93d00b0de642a83e71c27621a b4695		
	Multipart Description/PDF files in .zip description				
	Document Description		Start	End	
	Specification		1	42	
	Claims		43	46	
	Abstract		47	47	
Warnings:					
Information:					
2	Drawings-only black and white line drawings	afpa_1029us0_figures.pdf	3608789	no	14
			3bf3b2f9f71a928720a5f5b025e32a17a6dc 9b2e		
Warnings:					
Information:					
3	Application Data Sheet	afpa_1029us0_ADS.pdf	1359672	no	4
			fcf3f9301b3817ffb8e73662d3657a94732b b18		
Warnings:					
Information:					
4	Fee Worksheet (PTO-875)	fee-info.pdf	29629	no	2
			f03b7bff75f20c6843ef42c569883104e8481 9de		
Warnings:					
Information:					
Total Files Size (in bytes):			5214865		

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111

If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371

If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office

If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.