(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
25 August 2016 (25.08.2016)

(10) International Publication Number
WO 2016/133628 A1

(51) International Patent Classification:
G01V 3/10 (2006.01) *H02J 5/00* (2016.01) *B60L 11/18* (2006.01) *H02J 50/10* (2016.01) *H02J 7/02* (2006.01)

(21) International Application Number: PCT/US2016/013920

(22) International Filing Date: 19 January 2016 (19.01.2016)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/117,361 17 February 2015 (17.02.2015) US
14/817,904 4 August 2015 (04.08.2015) US

(71) Applicant: **QUALCOMM INCORPORATED** [US/US]; ATTN: International IP Administration, 5775 Morehouse Drive, San Diego, California 92121-1714 (US).

(72) Inventors: **WERNER, Michael**; 5775 Morehouse Drive, San Diego, California 92121-1714 (US). **PERCEBON, Leandro Alberto**; 5775 Morehouse Drive, San Diego, California 92121-1714 (US).

(74) Agent: **ABUMERI, Mark M.**; Knobbe Martens Olson & Bear LLP, 2040 Main Street, Fourteenth Floor, Irvine, California 92614 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:
— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*
— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

[Continued on next page]

(54) **Title**: CLOVER LEAF AND BUTTERFLY COIL STRUCTURES FOR FLAT WIRELESS COUPLING PROFILES IN WIRELESS POWER TRANSFER APPLICATIONS

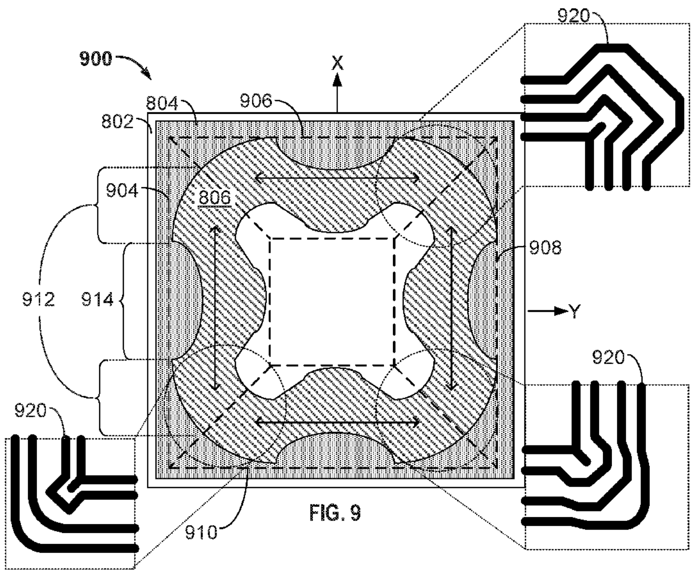

FIG. 9

(57) **Abstract**: In one aspect, an apparatus for wirelessly transferring charging power is provided. The apparatus comprises a coil comprising a conductor defining a plurality of sides of the coil. For each of the plurality of sides of the coil, the conductor bows toward a center of the coil as the conductor extends from an outer portion of the respective side of the coil toward a middle portion of the respective side of the coil. A magnetic coupling factor between the coil and a receive coil is within a predetermined percentage of a maximum or minimum magnetic coupling factor between the coil and the receive coil for all offsets of a center of the receive coil, with respect to the center of the coil, that are within a perimeter defined by the conductor of the coil.

WO 2016/133628 A1

Published:

— *with international search report (Art. 21(3))*

CLOVER LEAF AND BUTTERFLY COIL STRUCTURES FOR FLAT WIRELESS COUPLING PROFILES IN WIRELESS POWER TRANSFER APPLICATIONS

FIELD

[0001] The present disclosure relates generally to wireless power transfer, and more specifically to clover leaf and butterfly coil structures for flat wireless coupling profiles in wireless power transfer applications.

BACKGROUND

[0002] Inductive power transfer (IPT) systems provide one example of wireless transfer of energy. In IPT systems, a primary power device (e.g., “transmitter”) transmits power wirelessly to a secondary power device (e.g., “receiver”). Each of the transmitter and receiver includes an inductive coupler, typically a single or multi-coil arrangement of windings comprising electric current conveying materials, such as Litz wire. An alternating current passing through a transmit coupler produces an alternating electromagnetic field. When a receive coupler is placed in proximity to the transmit coupler, the alternating magnetic field induces an electromotive force (EMF) in the receive coupler according to Faraday’s law, thereby wirelessly transferring power to the receiver.

[0003] However, conventional circular or rectangular coils typically have a large variation in a magnetic coupling factor between the transmit coil and the receive coil over the desired range of lateral offsets for those coils, especially where their vertical separation (e.g., z-gap) is small. Such large coupling variations cause proportionally large variations in transmit and/or receive coil currents, which can require expensive power electronics or force undesirable limitations on the range of lateral offsets between coils for which the system functions within rated limitations. As such, clover leaf and butterfly coil structures for flat wireless coupling profiles in wireless power transfer applications are desirable.

SUMMARY

[0004] Some implementations provide an apparatus for wirelessly transferring charging power. The apparatus comprises a coil comprising a conductor defining a plurality of sides of the coil. For each of the plurality of sides of the coil, the conductor bows toward a center of the coil as the conductor extends from an outer portion of the respective side of the coil toward a middle portion of the respective side of the coil.

[0005] Some other implementations provide a method for wirelessly transferring charging power. The method comprises driving, with an alternating current, a coil comprising a conductor defining a plurality of sides of the coil. For each of the plurality of sides of the coil, the conductor bows toward a center of the coil as the conductor extends from an outer portion of the respective side of the coil toward a middle portion of the respective side of the coil. The method comprises wirelessly transferring charging power from the coil to a receive coil.

[0006] Yet other implementations provide a method for fabricating an apparatus for wirelessly transferring charging power. The method comprises providing a ferrimagnetic structure. The method comprises forming a coil by disposing a conductor defining a plurality of sides of the coil such that, for each of the plurality of sides, the conductor bows toward a center of the coil as the conductor extends from an outer portion of the respective side of the coil toward a middle portion of the respective side of the coil.

[0007] Yet other implementations provide an apparatus for wirelessly transferring charging power. The apparatus comprises means for wirelessly transmitting charging power comprising a conductor defining a plurality of sides of the means for wirelessly transmitting charging power, wherein for each of the plurality of sides, the conductor bows toward a center of the means for wirelessly transmitting charging power as the conductor extends from an outer portion of the respective side toward a middle portion of the respective side. The apparatus comprises means for driving the means for wirelessly transmitting charging power with an alternating current.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] FIG. 1 illustrates a wireless power transfer system for charging an electric vehicle, in accordance with some implementations.

[0009] FIG. 2 is a schematic diagram of core components of a wireless power transfer system similar to that previously discussed in connection with FIG. 1, in accordance with some implementations.

[0010] FIG. 3 is a functional block diagram showing core and ancillary components of the wireless power transfer system of FIG. 1.

[0011] FIG. 4 is an isometric view of a conventional coil system for wireless power transfer.

[0012] FIG. 5 is a top view of the conventional coil system of FIG. 4.

[0013] FIG. 6 is a diagram illustrating a magnetic coupling factor versus offset in each of an x-direction and a perpendicular y-direction between a receive coil and the conventional coil of FIGs. 4 and 5, in accordance with some implementations.

[0014] FIG. 7 is a 3-dimensional diagram illustrating a magnetic coupling factor versus offset in each of an x-direction and a perpendicular y-direction between a receive coil and the conventional coil of FIGs. 4 and 5.

[0015] FIG. 8 is an isometric view of a “butterfly” or “clover leaf” shaped coil for wireless power transfer, in accordance with some implementations.

[0016] FIG. 9 is a top view of the “butterfly” or “clover leaf” shaped coil in the system of FIG. 8.

[0017] FIG. 10 is a diagram illustrating a magnetic coupling factor versus offset in each of an x-direction and a perpendicular y-direction between a receive coil and the “butterfly” or “clover leaf” shaped coil in FIGs. 8 and 9, in accordance with some implementations.

[0018] FIG. 11 is a 3-dimensional diagram illustrating a magnetic coupling factor versus offset in each of an x-direction and a perpendicular y-direction between a receive coil and the “butterfly” or “clover leaf” shaped coil in FIGs. 8 and 9, in accordance with some implementations.

[0019] FIG. 12 is a diagram illustrating a coupling range in each of an x-direction and a perpendicular y-direction for the conventional coil system of FIGs. 4 and 5, in accordance with some implementations.

[0020] FIG. 13 is a diagram illustrating another coupling range in each of an x-direction and a perpendicular y-direction for the conventional coil system of FIGs. 4 and 5, in accordance with some implementations.

[0021] FIG. 14 is a diagram illustrating a coupling range in each of an x-direction and a perpendicular y-direction for the “butterfly” or “clover leaf” shaped coil of FIGs. 8 and 9, in accordance with some implementations.

[0022] FIG. 15 is a top view of an alternatively designed “butterfly” or “clover leaf” shaped coil, in accordance with some implementations.

[0023] FIG. 16 is a top view of another alternatively designed “butterfly” or “clover leaf” shaped coil, in accordance with some implementations.

[0024] FIG. 17 is a top view of yet another alternatively designed “butterfly” or “clover leaf” shaped coil, in accordance with some implementations.

[0025] FIG. 18 is a flowchart depicting a method for wirelessly transferring charging power, in accordance with some implementations.

[0026] FIG. 19 is a flowchart depicting a method for fabricating an apparatus for wirelessly transferring charging power, in accordance with some implementations.

DETAILED DESCRIPTION

[0027] The detailed description set forth below in connection with the appended drawings is intended as a description of implementations and is not intended to represent the only implementations in which the invention may be practiced. The term "exemplary" used throughout this description means "serving as an example, instance, or illustration," and should not necessarily be construed as preferred or advantageous over other implementations. The detailed description includes specific details for the purpose of providing a thorough understanding of the implementations. In some instances, some devices are shown in block diagram form.

[0028] Wirelessly transferring power may refer to transferring any form of energy associated with electric fields, magnetic fields, electromagnetic fields, or otherwise from a transmitter to a receiver without the use of physical electrical conductors (e.g., power may be transferred through free space). The power output into a wireless field (e.g., a magnetic field) may be received, captured by, or coupled by a "receiving coil" to achieve power transfer.

[0029] An electric vehicle is used herein to describe a remote system, an example of which is a vehicle that includes, as part of its locomotion capabilities, electrical power derived from a chargeable energy storage device (e.g., one or more rechargeable electrochemical cells or other type of battery). As non-limiting examples, some electric vehicles may be hybrid electric vehicles that include, besides electric motors, a traditional combustion engine for direct locomotion or to charge the vehicle's battery. Other electric vehicles may draw all locomotion ability from electrical power. An electric vehicle is not limited to an automobile and may include motorcycles, carts, scooters, and the like. By way of example and not limitation, a remote system is described herein in the form of an electric vehicle (EV). Furthermore, other remote systems that may be at least partially powered using a chargeable energy storage device are also contemplated (e.g., electronic devices such as personal computing devices and the like).

[0030] FIG. 1 is a diagram of a wireless power transfer system 100 for charging an electric vehicle, in accordance with some implementations. The wireless power transfer system 100 enables charging of an electric vehicle 112 while the electric vehicle 112 is parked so as to efficiently couple with a base wireless charging system 102a. Spaces for two electric vehicles are illustrated in a parking area to be parked over corresponding base wireless charging systems 102a and 102b. In some implementations, a local distribution center 130 may be connected to a power backbone 132 and configured to provide an alternating current (AC) or a direct current (DC) supply through a power link 110 to the base wireless charging systems 102a and 102b. Each of the base wireless charging systems 102a and 102b also includes a base coupler 104a and 104b, respectively, for wirelessly transferring power. In some other implementations (not shown in FIG. 1), base couplers 104a or 104b may be stand-alone physical units and are not part of the base wireless charging system 102a or 102b.

[0031] The electric vehicle 112 may include a battery unit 118, an electric vehicle coupler 116, and an electric vehicle wireless charging unit 114. The electric vehicle wireless charging unit 114 and the electric vehicle coupler 116 constitute the electric vehicle wireless charging system. In some diagrams shown herein, the electric vehicle wireless charging unit 114 is also referred to as the vehicle charging unit (VCU). The electric vehicle coupler 116 may interact with the base coupler 104a for example, via a region of the electromagnetic field generated by the base coupler 104a.

[0032] In some implementations, the electric vehicle coupler 116 may receive power when the electric vehicle coupler 116 is located in an electromagnetic field produced by the base coupler 104a. The field may correspond to a region where energy output by the base coupler 104a may be captured by the electric vehicle coupler 116. For example, the energy output by the base coupler 104a may be at a level sufficient to charge or power the electric vehicle 112. In some cases, the field may correspond to a "near-field" of the base coupler 104a. The near-field may correspond to a region in which there are strong reactive fields resulting from the currents and charges in the base coupler 104a that do not radiate power away from the base coupler 104a. In some cases the near-field may correspond to a region that is within about $1/2\pi$ of a wavelength of the a frequency of the electromagnetic field produced by the base coupler 104a distant from the base coupler 104a, as will be further described below.

[0033] Local distribution center 130 may be configured to communicate with external sources (e.g., a power grid) via a communication backhaul 134, and with the base wireless charging system 102a via a communication link 108.

[0034] In some implementations the electric vehicle coupler 116 may be aligned with the base coupler 104a and, therefore, disposed within a near-field region simply by the electric vehicle operator positioning the electric vehicle 112 such that the electric vehicle coupler 116 is sufficiently aligned relative to the base coupler 104a. Alignment may be considered sufficient when an alignment error has fallen below a tolerable value. In other implementations, the operator may be given visual and/or auditory feedback to determine when the electric vehicle 112 is properly placed within a tolerance area for wireless power transfer. In yet other implementations, the electric vehicle 112 may be positioned by an autopilot system, which may move the electric vehicle 112 until the sufficient alignment is achieved. This may be performed automatically and autonomously by the electric vehicle 112 with or without driver intervention. This may be possible for an electric vehicle 112 that is equipped with a servo steering, radar sensors (e.g., ultrasonic sensors), and intelligence for safely maneuvering and adjusting the electric vehicle. In still other implementations, the electric vehicle 112 and/or the base wireless charging system 102a may have functionality for mechanically displacing and moving the couplers 116 and 104a, respectively, relative to each other to more accurately orient or align them and develop sufficient and/or otherwise more efficient coupling there between.

[0035] The base wireless charging system 102a may be located in a variety of locations. As non-limiting examples, some suitable locations include a parking area at a home of the electric vehicle 112 owner, parking areas reserved for electric vehicle wireless charging modeled after conventional petroleum-based filling stations, and parking lots at other locations such as shopping centers and places of employment.

[0036] Charging electric vehicles wirelessly may provide numerous benefits. For example, charging may be performed automatically, virtually without driver intervention or manipulation thereby improving convenience to a user. There may also be no exposed electrical contacts and no mechanical wear out, thereby improving reliability of the wireless power transfer system 100. Safety may be improved since manipulations with cables and connectors may not be needed and there may be no cables, plugs, or sockets to be exposed to moisture in an outdoor environment. In addition, there may also be no visible or accessible sockets, cables, or plugs, thereby reducing potential vandalism of power charging devices. Further, since the electric vehicle 112 may be used as distributed storage devices to stabilize a power grid, a convenient docking-to-grid solution may help to increase availability of vehicles for vehicle-to-grid (V2G) operation.

[0037] The wireless power transfer system 100 as described with reference to FIG. 1 may also provide aesthetical and non-impedimental advantages. For example, there may be no charge columns and cables that may be impedimental for vehicles and/or pedestrians.

[0038] As a further explanation of the vehicle-to-grid capability, the wireless power transmit and receive capabilities may be configured to be reciprocal such that either the base wireless charging system 102a can transmit power to the electric vehicle 112 or the electric vehicle 112 can transmit power to the base wireless charging system 102a. This capability may be useful to stabilize the power distribution grid by allowing electric vehicles 112 to contribute power to the overall distribution system in times of energy shortfall caused by over demand or shortfall in renewable energy production (e.g., wind or solar).

[0039] FIG. 2 is a schematic diagram of core components of a wireless power transfer system 200 similar to that previously discussed in connection with FIG. 1, in accordance with some implementations. As shown in FIG. 2, the wireless power transfer system 200 may include a base resonant circuit 206 including a base coupler 204 having an inductance L_1. The wireless power transfer system 200 further includes an electric vehicle resonant circuit 222 including an electric vehicle coupler 216 having an inductance L_2. Implementations described herein may use capacitively loaded conductor loops (i.e., multi-winding coils) forming a resonant structure that is capable of efficiently coupling energy from a primary structure (transmitter) to a secondary structure (receiver) via a magnetic or electromagnetic near-field if both the transmitter and the receiver are tuned to a common resonant frequency. The coils may be used for the electric vehicle coupler 216 and the base coupler 204. Using resonant structures for coupling energy may be referred to as “magnetically coupled resonance,” “electromagnetically coupled resonance,” and/or “resonant induction.” The operation of the wireless power transfer system 200 will be described based on power transfer from a base coupler 204 to an electric vehicle 112 (not shown), but is not limited thereto. For example, as discussed above, energy may be also transferred in the reverse direction.

[0040] With reference to FIG. 2, a power supply 208 (e.g., AC or DC) supplies power P_{SDC} to the base power converter 236 as part of the base wireless power charging system 202 to transfer energy to an electric vehicle (e.g., electric vehicle 112 of FIG. 1). The base power converter 236 may include circuitry such as an AC-to-DC converter configured to convert power from standard mains AC to DC power at a suitable voltage level, and a DC-to-low frequency (LF) converter configured to convert DC power to power at an operating frequency suitable for wireless high power transfer. In some implementations, one or both of the power supply 208 and the base power converter 236 may be known as means for driving a transmit coil with an alternating current. The base power converter 236 supplies power P_1 to the base resonant circuit 206 including tuning capacitor C_1 in series with base coupler 204 to emit an electromagnetic field at the operating frequency. The series-tuned resonant circuit 206 should be construed as an example. In another implementation, the capacitor C_1 may be coupled with the base coupler 204 in parallel. In yet other implementations, tuning may be formed of several reactive elements in any combination of parallel or series topology. The capacitor C_1 may be provided to form a resonant circuit with the base coupler 204 that resonates substantially at the operating frequency. The base coupler 204 receives the power P_1 and wirelessly transmits power at a level sufficient to charge or power the electric vehicle. For example, the level of power provided wirelessly by the base coupler 204 may be on the order of kilowatts (kW) (e.g., anywhere from 1 kW to 110 kW, although actual levels may be or higher or lower).

[0041] The base resonant circuit 206 (including the base coupler 204 and tuning capacitor C_1) and the electric vehicle resonant circuit 222 (including the electric vehicle coupler 216 and tuning capacitor C_2) may be tuned to substantially the same frequency. The electric vehicle coupler 216 may be positioned within the near-field of the base coupler and vice versa, as further explained below. In this case, the base coupler 204 and the electric vehicle coupler 216 may become coupled to one another such that power may be transferred wirelessly from the base coupler 204 to the electric vehicle coupler 216. The series capacitor C_2 may be provided to form a resonant circuit with the electric vehicle coupler 216 that resonates substantially at the operating frequency. The series-tuned resonant circuit 222 should be construed as an example. In another implementation, the capacitor C_2 may be coupled with the electric vehicle coupler 216 in parallel. In yet other implementations, the electric vehicle resonant circuit 222 may be formed of several reactive elements in any combination of parallel or series topology. Element k(d) represents the mutual coupling coefficient resulting at coil separation d. Equivalent resistances $R_{eq,1}$ and $R_{eq,2}$ represent the losses that may be inherent to the base and electric vehicle couplers 204 and 216 and the tuning (anti-reactance) capacitors C_1 and C_2, respectively. The electric vehicle resonant circuit 222, including the electric vehicle coupler 216 and capacitor C_2, receives and provides the power P_2 to an electric vehicle power converter 238 of an electric vehicle charging system 214.

[0042] The electric vehicle power converter 238 may include, among other things, a LF-to-DC converter configured to convert power at an operating frequency back to DC power at a voltage level of the load 218 that may represent the electric vehicle battery unit. The electric vehicle power converter 238 may provide the converted power P_{LDC} to the load 218. The power supply 208, base power converter 236, and base coupler 204 may be stationary and located at a variety of locations as discussed above. The electric vehicle load 218 (e.g., the electric vehicle battery unit), electric vehicle power converter 238, and electric vehicle coupler 216 may be included in the electric vehicle charging system 214 that is part of the electric vehicle (e.g., electric vehicle 112) or part of its battery pack (not shown). The electric vehicle charging system 214 may also be configured to provide power wirelessly through the electric vehicle coupler 216 to the base wireless power charging system 202 to feed power back to the grid. Each of the electric vehicle coupler 216 and the base coupler 204 may act as transmit or receive couplers based on the mode of operation.

[0043] While not shown, the wireless power transfer system 200 may include a load disconnect unit (LDU) (not known) to safely disconnect the electric vehicle load 218 or the power supply 208 from the wireless power transfer system 200. For example, in case of an emergency or system failure, the LDU may be triggered to disconnect the load from the wireless power transfer system 200. The LDU may be provided in addition to a battery management system for managing charging to a battery, or it may be part of the battery management system.

[0044] Further, the electric vehicle charging system 214 may include switching circuitry (not shown) for selectively connecting and disconnecting the electric vehicle coupler 216 to the electric vehicle power converter 238. Disconnecting the electric vehicle coupler 216 may suspend charging and also may change the "load" as "seen" by the base wireless power charging system 202 (acting as a transmitter), which may be used to "cloak" the electric vehicle charging system 214 (acting as the receiver) from the base wireless charging system 202. The load changes may be detected if the transmitter includes a load sensing circuit. Accordingly, the transmitter, such as the base wireless charging system 202, may have a mechanism for determining when receivers, such as the electric vehicle charging system 214, are present in the near-field coupling mode region of the base coupler 204 as further explained below.

[0045] In operation, during energy transfer towards an electric vehicle (e.g., electric vehicle 112 of FIG. 1), input power is provided from the power supply 208 such that the base coupler 204 generates an electromagnetic field for providing the energy transfer. The electric vehicle coupler 216 couples to the electromagnetic field and generates output power for storage or consumption by the electric vehicle 112. As described above, in some implementations, the base resonant circuit 206 and the electric vehicle resonant circuit 222 are configured and tuned according to a mutual resonant relationship such that they are resonating nearly or substantially at the operating frequency. Transmission losses between the base wireless power charging system 202 and the electric vehicle charging system 214 are minimal when the electric vehicle coupler 216 is located in the near-field coupling mode region of the base coupler 204 as further explained below.

[0046] An efficient energy transfer occurs by transferring energy via an magnetic near-field rather than via electromagnetic waves in the far field, which may involve substantial losses due to radiation into the space. When in the near-field, a coupling mode may be established between the transmit coupler and the receive coupler. The space around the couplers where this near-field coupling may occur is referred to herein as a near-field coupling mode region.

[0047] While not shown, the base power converter 236 and the electric vehicle power converter 238, if bidirectional, may both include, for the transmit mode, an oscillator, a driver circuit such as a power amplifier, a filter and matching circuit, and for the receive mode a rectifier circuit. The oscillator may be configured to generate a desired operating frequency, which may be adjusted in response to an adjustment signal. The oscillator signal may be amplified by a power amplifier with an amplification amount responsive to control signals. The filter and matching circuit may be included to filter out harmonics or other unwanted frequencies and match the impedance as presented by the resonant circuits 206 and 222 to the base and electric vehicle power converters 236 and 238, respectively. For the receive mode, the base and electric vehicle power converters 236 and 238 may also include a rectifier and switching circuitry.

[0048] The electric vehicle coupler 216 and the base coupler 204 as described throughout the disclosed implementations may be referred to or configured as “conductor loops”, and more specifically, “multi-winding conductor loops” or coils. The base and electric vehicle couplers 204 and 216 may also be referred to herein or be configured as “magnetic” couplers. The term “coupler” is intended to refer to a component that may wirelessly output or receive energy for coupling to another “coupler.”

[0049] As discussed above, efficient transfer of energy between a transmitter and receiver occurs during matched or nearly matched resonance between a transmitter and a receiver.

However, even when resonance between a transmitter and receiver are not matched, energy may be transferred at a lower efficiency.

[0050] A resonant frequency may be based on the inductance and capacitance of a resonant circuit (e.g. the resonant circuit 206) including a coupler (e.g., the base coupler 204 and the capacitor C_2) as described above. As shown in FIG. 2, inductance may generally be the inductance of the coupler, whereas, capacitance may be added to the coupler to create a resonant structure at a desired resonant frequency. Accordingly, for larger size couplers using larger diameter coils exhibiting larger inductance, the value of capacitance needed to produce resonance may be lower. Inductance may also depend on a number of windings of a coil. Furthermore, as the size of the coupler increases, coupling efficiency may increase. This is mainly true if the size of both base and electric vehicle couplers increase. Furthermore a resonant circuit including a coupler and tuning capacitor may be designed to have a high quality (Q) factor to improve energy transfer efficiency. For example, the Q factor may be 300 or greater.

[0051] As described above, according to some implementations, coupling power between two couplers that are in the near-field of one another is disclosed. As described above, the near-field may correspond to a region around the coupler in which mainly reactive electromagnetic fields exist. If the physical size of the coupler is much smaller than the wavelength, inversely proportional to the frequency, there is no substantial loss of power due to waves propagating or radiating away from the coupler. Near-field coupling-mode regions may correspond to a volume that is near the physical volume of the coupler, typically within a small fraction of the wavelength. According to some implementations, magnetic couplers, such as single and multi-winding conductor loops, are preferably used for both transmitting and receiving since handling magnetic fields in practice is easier than electric fields because there is less interaction with foreign objects, e.g., dielectric objects and the human body. Nevertheless, “electric” couplers (e.g., dipoles and monopoles) or a combination of magnetic and electric couplers may be used.

[0052] FIG. 3 is a functional block diagram showing components of wireless power transfer system 300, which may be employed in wireless power transfer system 100 of FIG. 1 and/or that wireless power transfer system 200 of FIG. 2. The wireless power transfer system 300 illustrates a communication link 376, a guidance link 366, using, for example, a magnetic field signal for determining a position or direction, and an alignment mechanism 356 capable of mechanically moving one or both of the base coupler 304 and the electric vehicle coupler 316. Mechanical (kinematic) alignment of the base coupler

304 and the electric vehicle coupler 316 may be controlled by the base alignment system 352 and the electric vehicle charging alignment system 354, respectively. The guidance link 366 may be capable of bi-directional signaling, meaning that guidance signals may be emitted by the base guidance system or the electric vehicle guidance system or by both. As described above with reference to FIG. 1, when energy flows towards the electric vehicle 112, in FIG. 3 a base charging system power interface 348 may be configured to provide power to a base power converter 336 from a power source, such as an AC or DC power supply (not shown). The base power converter 336 may receive AC or DC power via the base charging system power interface 348 to drive the base coupler 304 at a frequency near or at the resonant frequency of the base resonant circuit 206 with reference to FIG. 2. The electric vehicle coupler 316, when in the near-field coupling-mode region, may receive energy from the electromagnetic field to oscillate at or near the resonant frequency of the electric vehicle resonant circuit 222 with reference to FIG. 2. The electric vehicle power converter 338 converts the oscillating signal from the electric vehicle coupler 316 to a power signal suitable for charging a battery via the electric vehicle power interface.

[0053] The base wireless charging system 302 includes a base controller 342 and the electric vehicle charging system 314 includes an electric vehicle controller 344. The base controller 342 may provide a base charging system communication interface to other systems (not shown) such as, for example, a computer, a base common communication (BCC), a communications entity of the power distribution center, or a communications entity of a smart power grid. The electric vehicle controller 344 may provide an electric vehicle communication interface to other systems (not shown) such as, for example, an on-board computer on the vehicle, a battery management system, other systems within the vehicles, and remote systems.

[0054] The base communication system 372 and the electric vehicle communication system 374 may include subsystems or modules for specific application with separate communication channels and also for wirelessly communicating with other communications entities not shown in the diagram of FIG. 3. These communications channels may be separate physical channels or separate logical channels. As non-limiting examples, a base alignment system 352 may communicate with an electric vehicle alignment system 354 through the communication link 376 to provide a feedback mechanism for more closely aligning the base coupler 304 and the electric vehicle coupler 316, for example via autonomous mechanical (kinematic) alignment, by either the electric vehicle alignment system 354 or the base alignment system 352, or by both, or with operator assistance as described herein. Similarly, a base guidance system 362 may communicate with an electric vehicle guidance system 364 through the communication link 376 and also using a guidance link 366 for determining a position or direction as needed to guide an operator to the charging spot and in aligning the base coupler 304 and the electric vehicle coupler 316. In some implementations, the communications link 376 may comprise a plurality of separate, general-purpose communication channels supported by the base communication system 372 and the electric vehicle communication system 374 for communicating other information between the base wireless charging system 302 and the electric vehicle charging system 314. This information may include information about electric vehicle characteristics, battery characteristics, charging status, and power capabilities of both the base wireless charging system 302 and the electric vehicle charging system 314, as well as maintenance and diagnostic data for the electric vehicle. These communication channels may be separate logical channels or separate physical communication channels such as, for example, WLAN, Bluetooth, zigbee, cellular, etc.

[0055] In some implementations, the electric vehicle controller 344 may also include a battery management system (BMS) (not shown) that manages charge and discharge of the electric vehicle principal and/or auxiliary battery. As discussed herein, the base guidance system 362 and the electric vehicle guidance system 364 include the functions and sensors as needed for determining a position or direction, e.g., based on microwave, ultrasonic radar, or magnetic vectoring principles. Further, the electric vehicle controller 344 may be configured to communicate with electric vehicle onboard systems. For example, the electric vehicle controller 344 may provide, via the electric vehicle communication interface, position data, e.g., for a brake system configured to perform a semi-automatic parking operation, or for a steering servo system configured to assist with a largely automated parking (“park by wire”) that may provide more convenience and/or higher parking accuracy as may be needed in certain applications to provide sufficient alignment between the base and electric vehicle couplers 304 and 316. Moreover, the electric vehicle controller 344 may be configured to communicate with visual output devices (e.g., a dashboard display), acoustic/audio output devices (e.g., buzzer, speakers), mechanical input devices (e.g., keyboard, touch screen, and pointing devices such as joystick, trackball, etc.), and audio input devices (e.g., microphone with electronic voice recognition).

[0056] The wireless power transfer system 300 may include other ancillary systems such as detection and sensor systems (not shown). For example, the wireless power transfer system 300 may include sensors for use with systems to determine a position as required by the guidance system 362, 364 to properly guide the driver or the vehicle to the charging spot, sensors to mutually align the couplers with the required separation/coupling, sensors to detect objects that may obstruct the electric vehicle coupler 316 from moving to a particular height and/or position to achieve coupling, and safety sensors for use with systems to perform a reliable, damage free, and safe operation of the system. For example, a safety sensor may include a sensor for detection of presence of animals or children approaching the base and electric vehicle couplers 304, 316 beyond a safety radius, detection of metal objects located near or in proximity of the base or electric vehicle coupler 304, 316 that may be heated up (induction heating), and for detection of hazardous events such as incandescent objects near the base or electric vehicle coupler 304, 316.

[0057] The wireless power transfer system 300 may also support plug-in charging via a wired connection, for example, by providing a wired charge port (not shown) at the electric vehicle charging system 314. The electric vehicle charging system 314 may integrate the outputs of the two different chargers prior to transferring power to or from the electric vehicle. Switching circuits may provide the functionality as needed to support both wireless charging and charging via a wired charge port.

[0058] To communicate between the base wireless charging system 302 and the electric vehicle charging system 314, the wireless power transfer system 300 may use in-band signaling via the base and electric vehicle couplers 304, 316 and/or out-of-band signaling via the communications systems 372, 374, e.g., via an RF data modem (e.g., Ethernet over radio in an unlicensed band). The out-of-band communication may provide sufficient bandwidth for the allocation of value-add services to the vehicle user/owner. A low depth amplitude or phase modulation of the wireless power carrier may serve as an in-band signaling system with minimal interference.

[0059] Some communications (e.g., in-band signaling) may be performed via the wireless power link without using specific communications antennas. For example, the base and electric vehicle couplers 304 and 316 may also be configured to act as wireless communication antennas. Thus, some implementations of the base wireless charging system 302 may include a controller (not shown) for enabling keying type protocol on the wireless power path. By keying the transmit power level (amplitude shift keying) at predefined intervals with a predefined protocol, the receiver may detect a serial communication from the transmitter. The base power converter 336 may include a load sensing circuit (not shown) for detecting the presence or absence of active electric vehicle power receivers in the near-field coupling mode region of the base coupler 304. By way of example, a load sensing circuit monitors the current flowing to a power amplifier of the base power converter 336, which is affected by the presence or absence of active power receivers in the near-field coupling mode region of the base coupler 304. Detection of changes to the loading on the power amplifier may be monitored by the base controller 342 for use in determining whether to enable the base wireless charging system 302 for transmitting energy, to communicate with a receiver, or a combination thereof.

[0060] FIG. 4 is an isometric view 400 of a conventional coil system for wireless power transfer. As shown in FIG. 4, a metallic back plate 402 may be disposed under a ferrimagnetic structure 404. A conventional transmit coil 406 may be disposed over the ferrimagnetic structure 404. The transmit coil 406 may have a substantially rectangular, circular, or oval shape and may be configured to wirelessly transmit power via an alternating electromagnetic field. A receive coil 408 may be disposed over the transmit coil 406, and may be configured to wirelessly receive the power from the transmit coil 406 via the alternating electromagnetic field. A ferrimagnetic structure 410 may overlay the receive coil 408 and a metallic backplate 412 may overlay the ferrimagnetic structure 410. When the receive coil 408 is ideally oriented for wireless power transfer, the receive coil 408 may be substantially centered over the transmit coil 406.

[0061] FIG. 5 is a top view 500 of the conventional coil system of FIG. 4. As shown in FIG. 5, the transmit coil 406 is disposed over the ferrimagnetic structure 404, which is disposed over the metallic back plate 402. The receive coil 408 is shown as substantially centered over the transmit coil 406 in both an x-direction, and a perpendicular y-direction. The ferrimagnetic structure 410 is disposed over the receive coil 408 and the metallic backplate 412 is disposed over the ferrimagnetic structure 410. Typically, the receive coil 408, the ferrimagnetic structure 410 and the metallic back plate 412 comprise a vehicle coupler, while the transmit coil 406, the ferrimagnetic structure 404 and the metallic backplate 402 comprise a base coupler. As shown in more detail, the transmit coil 406 may comprise a plurality of turns or windings of the conductor 420, which may be wound one on top of another and/or wound along a perimeter of an immediately adjacent winding.

[0062] The conventional rectangular-, circular- or oval-shaped coils 406 and 408 of FIGs. 4 and 5 typically have a relatively large variation in a magnetic coupling factor for small vertical separation distances (e.g., z-gaps) between them. This large variation is described in connection with FIGs. 6 and 7.

[0063] FIG. 6 is a diagram 600 illustrating a magnetic coupling factor versus offset in each of an x-direction and a perpendicular y-direction between a receive coil and the conventional coil 406 of FIGs. 4 and 5, in accordance with some implementations. The horizontal axis shows positive and negative offsets in millimeters (mm), while the vertical axis shows positive and negative offsets, also in millimeters. For diagram 600, the transmit coil 406 is separated from the receive coil 408 by an example distance of 32mm, with a distance from the vehicle holding the receive coil 408 being approximately 70mm from the ground. Magnetic coupling factors between the transmit coil 406 and the receive coil 408, which may theoretically fall within the range of 0.00 to 1.00, are shown to range from ~0.21 to ~0.28. As shown in FIG. 6, with substantially ideal centered alignment between the transmit coil 406 and the receive coil 408, a “valley” 602 in the magnetic coupling factor (e.g., having a coupling factor of ~0.21) may appear at the center of the ideally aligned coils 406 and 408. Such a valley tends to become larger and deeper as the dimensions of the transmit coil 406 increases. Unfortunately larger dimensioned transmit coils 406 are desirable for providing reasonable offset ranges within which adequate power may be wirelessly transferred. In such implementations, the coupling strength may increase in a radial direction away from the “valley” 602 and may reach “peaks” 604a, 604b, 604c and 604d (e.g., having a coupling factor of ~0.28), each substantially corresponding to the outside corners, edges, or perimeter of the receive coil 408. The “valley” 602 and the peaks 604a-604d may be more easily visualized with reference to FIG. 7.

[0064] FIG. 7 is a 3-dimensional diagram 700 illustrating a magnetic coupling factor versus offset in each of the x-direction and the perpendicular y-direction between the receive coil 408 and the conventional coil 406 of FIGs. 4 and 5. As shown in FIG. 7, the “valley” 602 in the magnetic coupling factor is shown as a dip at the center of the diagram 700, while the “peaks” 604a-604d are shown as the four high points near the edges of the diagram 700. This variation in the magnetic coupling factor between the transmit coil 406 and the receive coil 408 are proportional to a current range that is provided to the power electronics driving the transmit coil 406 and the power electronics receiving power from the receive coil 408 during wireless power transfer at all offset conditions. Thus, if this variation were to be reduced, a simpler, cheaper, more robust system may be designed for a given offset and distance range, or alternatively, the same system may support larger offset and distance ranges for a given cost.

[0065] FIG. 8 is an isometric view 800 of a “butterfly” or “clover leaf” shaped transmit coil 806 for wireless power transfer, in accordance with some implementations. As shown in FIG. 8, a metallic backplate 802 may be disposed under a ferrimagnetic structure 804. The “butterfly” or “clover leaf” shaped transmit coil 806 may be disposed over the ferrimagnetic structure 804. Although a vehicle pad comprising a receive coil may be utilized to receive the wireless power transmitted by the transmit coil 806, it is not shown in FIG. 8. The transmit coil 806 may comprise a conductor that is disposed or wound to form at least one winding (e.g., the conductor is disposed such that at least one loop is formed having the particular shape of the transmit coil 806 as shown). In some implementations, “means for wirelessly transmitting charging power” may comprise the transmit coil 806. The particular shape of the transmit coil 806 provides a smaller variation in a magnetic coupling factor between the transmit coil 806 and a receive coil (not shown) as compared to the conventional transmit coil 406 and the conventional receive coil 408, as previously described in connection with FIGs. 4-7. In addition, the self-inductance of the transmit coil 806 of FIGs. 8 and 9 is higher than the self-inductance of the transmit coil 406 of FIGs. 4 and 5 (e.g., 6.2μH for the coil 806 versus 5.87μH for the coil 406 in one implementation). The particular shape of the transmit coil 806 may be more easily understood as illustrated in FIG. 9.

[0066] FIG. 9 is a top view 900 of the “butterfly” or “clover leaf” shaped coil 806 in the system of FIG. 8. FIG. 9 illustrates the metallic backplate 802, the ferrimagnetic structure 804, and the “butterfly” or “clover leaf” shaped transmit coil 806, though no vehicle pad is shown. FIG. 9 shows the transmit coil 806 having a center 902, as well as a plurality of sides 904, 906, 908, 910. The transmit coil 806 is formed by disposing or winding a conductor into the shape of the coil 806. For example, the conductor may define each of the plurality of sides 904, 906, 908, and 910. As shown in FIG. 9, for each of the plurality of sides 904, 906, 908, and 910, the conductor bows toward the center 902 of the transmit coil 806 as the conductor extends from an outer portion 912 of the respective side of the transmit coil toward a middle portion 914 of the respective side of the transmit coil 806. The directions of extension of each of the sides 904, 906, 908 and 910 may be substantially in the directions of the white arrows. Accordingly, the middle portions 914 of two opposite sides of the transmit coil 806 may be closer to one another (as well as to the center 902 of the transmit coil 806) than are the outer portions 912 of the two opposite sides of the transmit coil 806. As shown in more detail at the upper right of view 900, the transmit coil 806 may comprise a plurality of turns or windings of the conductor 920, which may be wound one on top of another and/or wound along a perimeter of an immediately adjacent winding. Although only one corner of the transmit coil 806 is shown as such, in such implementations, each corner of the transmit coil 806 may have the same construction.

[0067] In other implementations, as shown in more detail at the lower right of view 900, rather than all turns or windings of the conductor 920 bowing toward the center 902 of the transmit coil 806 to a substantially equal degree, the successive turns or windings of the conductor 920 may bow toward the center 902 of the transmit coil 806 to an increasing extent from an outermost winding to an innermost winding of the transmit coil 806. Although only one corner of the transmit coil 806 is shown as such, in such implementations, each corner of the transmit coil 806 may have the same construction.

[0068] In yet other implementations, as shown in more detail at the lower left of view 900, rather than all turns or windings of the conductor 920 bowing toward the center 902 of the transmit coil 806, one or more windings may not bow toward the center 902, while one or more other windings may bow toward the center 902. Although only one corner of the transmit coil 806 is shown as such, in such implementations, each corner of the transmit coil 806 may have the same construction. Distributing turns or windings in the same coil between the cloverleaf winding pattern and the conventional winding pattern may further flatten the magnetic coupling factor range across all offsets of (or increase the acceptable offset range of) a receive coil with the transmit coil 806. Although 4 turns or windings are shown in each of the more detailed portions of view 900, any number of windings may be contemplated, for example, 5 to 20.

[0069] FIG. 10 is a diagram 1000 illustrating a magnetic coupling factor versus offset in each of an x-direction and a perpendicular y-direction between a receive coil and the "butterfly" or "clover leaf" shaped coil 806 of FIGs. 8 and 9, in accordance with some implementations. The horizontal axis corresponds to a positive or negative offset (in millimeters) of the receive coil with respect to the "Y" axis shown in FIG. 9, while the vertical axis corresponds to a positive or negative offset (in millimeters) of the receive coil with respect to the "X" axis, as shown in FIG. 9. For diagram 1000, the transmit coil 806 is separated from a receive coil (not shown) by an example distance of 32mm, with a distance from the vehicle holding (not shown) the receive coil being approximately 70mm from the ground. Magnetic coupling factors between the transmit coil 806 and the receive coil, which may theoretically fall within the range of 0.00 to 1.00, are shown to range from ~0.20 to ~0.28. As shown in FIG. 10, a large, substantially flat “clover leaf”-shaped area 1002 having a substantially uniform (e.g., stable) magnetic coupling factor of between ~0.26 and ~0.28 is located at a center of the diagram 1000. This area 1002 may exist due to the particular shape of the transmit coil 806 as show in FIGs. 8 and 9. Specifically, because the middle portions 914 of each of the plurality of sides 904, 906, 908 and 910 bow towards the center 902 of the transmit coil 806, the conductor on one side of the transmit coil 806 is closer to the conductor on an adjacent side of the transmit coil 806 as compared to a similarly sized conventional circular-, rectangular-, or oval-shaped coil 406 of FIGs. 4 and 5. This may concentrate more lines of magnetic flux, generated by an alternating current circulating through the transmit coil 806, in the smaller area defined by a perimeter of the transmit coil 806. Concentration of the lines of magnetic flux allow a nearby receive coil to capture more of lines of magnetic flux for a given receive coil size. This large, substantially flat area 1002 may be more easily visualized in FIG. 11.

[0070] FIG. 11 is a 3-dimensional diagram 1100 illustrating a magnetic coupling factor versus offset in each of an x-direction and a perpendicular y-direction between a receive coil and the “butterfly” or “clover leaf” shaped coil 806 in FIGs. 8 and 9, in accordance with some implementations. As shown in FIG. 11, the large, substantially flat “clover leaf”-shaped area 1002 in the magnetic coupling factor is shown in the diagram 1100. This flat area 1002 results in a proportionally flat range of currents that need to be provided by the power electronics driving the transmit coil 806 and/or need to be processed by the power electronics receiving power from a receive coil during wireless power transfer at all offset conditions for the same given amount of power transferred. This would result in less stress on the components of such power electronics. Thus, a simpler, cheaper, and more robust system may be designed for a given offset and distance range, or alternatively, the same system may support larger offset and distance ranges for a given cost, as compared to the implementations previously described in connection with FIGs. 4-7. Moreover, since the magnetic coupling factor has a flatter profile in the area 1002, a larger vertical separation (z-gap) between the transmit coil 806 and an associated receive coil may be utilized for a given amount of power transmission, driver current, or x/y-offset, as compared to the implementations previously described in connection with FIGs. 4-7.

[0071] In order to more clearly understand the effect that a substantially flat magnetic coupling factor between transmit and receive coils can have on the operation of a wireless charging power transmission system, reference will now be made to FIGs. 12-14. FIG. 12 is a diagram 1200 illustrating an area 1202 of offsets in each of an x-direction and a perpendicular y-direction providing magnetic coupling factors within a predetermined percentage of a maximum or minimum of a magnetic coupling factor range for the conventional coil system 400 of FIGs. 4 and 5, in accordance with some implementations. The offsets and magnetic coupling factors shown in FIG. 12 may correspond to those shown in FIG. 6, which range from ~0.21 to ~0.28. However, in some implementations, the power electronic circuitry that provides current, voltage or power to the transmit coil 406, or receives current, voltage or power from the receive coil 408 may only be designed to operate within a predetermined percentage of a maximum or minimum of a magnetic coupling factor range (e.g., generally between 1% and 55%, but shown as 12% in FIGs. 12-14), providing a proportional current, voltage or power, respectively. Thus, the individual boxes shown in FIG. 12 include a particular magnetic coupling factor value where that value is within 12% of a minimum magnetic coupling factor (e.g., 0.21-0.24) and a blank white box where that value is greater than 12% of the minimum magnetic coupling factor (>0.24). The area 1202 shows the only x-direction and y-direction offsets where the wireless power transfer system would operate correctly, given a limitation of coupling and current variations of 12% or less of the minimum coupling values in the diagram 1200. As shown, the area 1202 includes a small circular shaped region including only y-offsets of 10mm or less for an x-offset of ±40mm, 20mm or less for an x-offset of ±30mm, 30mm or less for an x-offset of ±20mm, and 40mm or less for x-offsets of 10mm or less. The remaining offsets where such a wireless power transfer system would operate properly are all at extreme x- or y-offsets of 90-100mm, leaving a great majority of the x- and y-offsets outside the desired operating range.

[0072] FIG. 13 is a diagram 1300 illustrating an area 1302 of offsets in each of an x-direction and a perpendicular y-direction providing magnetic coupling factors within a predetermined percentage of a maximum or minimum of a magnetic coupling factor range for the conventional coil system 400 of FIGs. 4 and 5, in accordance with some implementations. The offsets and magnetic coupling factors shown in FIG. 13 may correspond to those shown in FIG. 6, which range from ~0.21 to ~0.28. The individual boxes shown in FIG. 13 include a particular magnetic coupling factor value where that value is within 12% of a maximum magnetic coupling factor (e.g., 0.25-0.28) and a blank white box where that value is outside that 12% range from maximum magnetic coupling factor (<0.25). The area 1302 shows the only x-direction and y-direction offsets where the wireless power transfer system would operate correctly, given a limitation of coupling and current variations of 12% or less from the maximum coupling values. As shown, the area 1302 includes nearly all offsets not included in the area 1202 of FIG. 12, but would not operate correctly within the area 1202 illustrated in FIG. 12. Accordingly, based on the above discussion for FIGs. 12 and 13, the large "valley" in the magnetic coupling factor necessarily and undesirably limits the offsets at which the receive coil 408 may be positioned with respect to the transmit coil 406 given a particular limitation on the range of coupling factors and currents the associated power electronics are configured to support.

[0073] FIG. 14 is a diagram 1400 illustrating an area 1402 of offsets in each of an x-direction and a perpendicular y-direction providing magnetic coupling factors within a predetermined percentage of a maximum or minimum of a magnetic coupling factor range for the coil system shown in FIGs. 8 and 9, in accordance with some implementations. The offsets and magnetic coupling factors shown in FIG. 14 may correspond to those shown in FIG. 10, which range from ~0.20 to ~0.28. The individual boxes shown in FIG. 14 include a particular magnetic coupling factor where that value is within 12% of a maximum magnetic coupling factor (e.g., 0.25-0.28) and a blank white box where that value is outside that 12% range from the maximum magnetic coupling factor (<0.25). The area 1402 shows the x-direction and y-direction offsets where the wireless power transfer system would operate correctly, given a limitation of coupling and current variations of 12% or less from the maximum coupling values. As shown, the area 1402 includes all x- and y-offsets of ±70mm or less, and most of the x- and y-offsets between 70mm and 90mm in either the positive or negative directions. The area 1402 resembles the particular shape of the transmit coil 806. Accordingly, the substantially flat, uniform magnetic coupling factor range across the area 1002 in each of FIGs. 10 and 11, which corresponds to the area 1402, reduces the limitations on (e.g., increases the size of) the areas in which a receive coil may be positioned with respect to the transmit coil 806, given a particular limitation on the range of coupling factors and currents the associated power electronics are configured to support. In addition, the diagrams 1200, 1300, 1400 of FIGs. 12-14 are shown for a single z-gap, or vertical displacement, between the respective transmit and receive coils. However, the present application contemplates offset ranges in each of the x-, y- and z-directions within which the transmit and receive coils will have an acceptably flat magnetic coupling factor range, as previously described. Thus, when driven with an alternating current, a magnetic coupling factor between the transmit coil 806 and another coil (e.g., a receive coil) is within a predetermined percentage of a maximum or minimum magnetic coupling factor between the transmit coil 806 and the another coil for all offsets (e.g., x-, y- or z-offsets) of a center of the receive coil, with respect to the center 902 of the transmit coil 806, that are within a perimeter defined by the conductor of the transit coil 806.

[0074] Although a particular coil shape is shown in FIGs. 8 and 9, the present application is not so limited. FIGs. 15-17 show additional, non-limiting coil shapes that are contemplated. FIG. 15 is a top view 1500 of an alternatively designed "butterfly" or "clover leaf" shaped coil 1506, in accordance with some implementations. The coil 1506 may be substantially the same shape as the transmit coil 806, except that all changes in a direction of extension of a conductor that forms the coil 1506 are made at a particular bend point, rather than gently sloping in a particular direction, as for the transmit coil 806. For example, at each corner (e.g., corner 1508) of corresponding sides (e.g., the sides 1504 and 1502), the conductor is bent at an acute angle (e.g., a substantially 45° angle) with respect to a direction of extension of each of the corresponding sides 1502, 1504 to form substantially rounded corners 1508. Such directions of extension are shown by the double headed arrows. In addition, at a middle portion 1514 of each of the sides, the conductor is bent at an acute angle (e.g., a substantially 45° angle) with respect to the direction of extension of the side at each end of the middle portion 1514. Though 45° is expressly labeled, any acute angle may be utilized (e.g., $0° < \text{acute angle} < 90°$) that results in the rounded corner 1508, and/or the middle portion 1514 that bows toward the center 1510 of the coil 1506. Moreover, although the transmit coil 1506 is shown to have substantially the same width and length, either one of the width or the length may be longer than the other.

[0075] FIG. 16 is a top view 1600 of another alternatively designed "butterfly" or "clover leaf" shaped coil 1606, in accordance with some implementations. The coil 1606 may be substantially the same as the coil 1506 with the exception that at each corner (e.g., corner 1608) of corresponding sides (e.g., the sides 1604 and 1602), the conductor is bent at a right angle (e.g., a substantially 90° angle) with respect to the direction of extension of each of the corresponding sides 1604, 1602 to form substantially square corners. Such directions of extension are shown by the double headed arrows. Like the coil 1506 of FIG. 15, at a middle portion 1614 of each of the sides, the conductor is bent at an acute angle (e.g., a substantially 45° angle) with respect to the direction of extension of the side at each end of the middle portion 1614. As previously stated, though 45° is expressly labeled, any acute angle may be utilized that results in the middle portion 1614 bowing toward the center 1610 of the coil 1606. Moreover, although the transmit coil 1606 is shown to have substantially the same width and length, either one of the width or the length may be longer than the other.

[0076] In some implementations, less than all of the sides of the coil may bow toward a center of the coil. This may be useful where substantially uniform magnetic coupling factors and profiles are desired in only one dimension. FIG. 17 is a top view 1700 of yet another alternatively designed “butterfly” or “clover leaf” shaped coil 1706, in accordance with some implementations. The coil 1706 may be substantially the same as the coil 1606 with the exception that the conductor on less than all of the sides of the coil bows toward a center 1710 of the coil 1706. Like the coil 1606 of FIG. 16, at each corner (e.g., corner 1708) of corresponding sides (e.g., the sides 1704 and 1702), the conductor is bent at a right angle (e.g., a substantially 90° angle) with respect to the direction of extension of each of the corresponding sides 1704, 1702 to form substantially square corners. Such directions of extension are shown by the double headed arrows. At a middle portion 1714 of some of the sides, the conductor is bent at an acute angle (e.g., a substantially 45° angle) with respect to the direction of extension of the side at each end of the middle portion 1714. Though 45° is expressly labeled, any acute angle may be utilized that results in the middle portion 1714 bowing toward the center 1710 of the coil 1706. Since less than all of the sides 1702, 1704 of the coil 1700 bow toward the center 1710 of the coil 1700, for at least one side 1702 of the plurality of sides of the coil 1700, the conductor extends in a substantially straight line along the entire side 1702. Moreover, although the transmit coil 1706 is shown to have substantially the same width and length, either one of the width or the length may be longer than the other. Although one or more bends of the varied implementations of coil arrangements are shown having an immediate change of direction at the bend (e.g., having sharp edges or corners), it should be noted that in practice, the conductor will have a minimum practical bending radius for any bend. For example, where 5mm x 5mm square cross-section Litz wire is utilized, such a minimum bend radius may be 30mm, for example. Thus, implementations shown should not be limited to those where bends in the conductor are implemented with a zero minimum bend radius. But instead, the general scope may be understood such that, subject to such minimum bend radiuses, the changes in the immediate directions of extension of the conductor of the coils may be described by the acute and/or right angles previously described.

[0077] FIG. 18 is a flowchart 1800 depicting a method for wirelessly transferring charging power, in accordance with some implementations. The method of flowchart 1800 is described herein with reference to the descriptions in connection with FIGs. 1-3, 8-11 and 14-17. Although the method of flowchart 1800 is described herein with reference to a particular order, in various implementations, blocks herein may be performed in a different order, or omitted, and additional blocks may be added.

[0078] The flowchart 1800 may start with block 1802, which includes driving, with an alternating current, a coil comprising a conductor defining a plurality of sides of the coil, wherein for each of the plurality of sides of the coil, the conductor bows toward a center of the coil as the conductor extends from an outer portion of the respective side of the coil toward a middle portion of the respective side of the coil. For example, as previously described in connection with FIG. 2, the power supply 208 and/or the base power converter 236 may drive, with an alternating current, any of the coils 806, 1506, 1606, 1706. For example the coil 806 comprises a conductor defining each of a plurality of sides 904, 906, 908, 910 of the coil 806, wherein for each of the plurality of sides 904, 906, 908, 910 of the coil 806, the conductor bows toward a center 902 of the coil 806 as the conductor extends from an outer portion 912 of the respective side of the coil toward a middle portion 914 of the respective side of the coil.

[0079] The flowchart 1800 may then advance to block 1804, which includes wirelessly transferring charging power from the coil to a receive coil. For example, as previously described in connection with FIGs. 8-11 and 14-17, the coil 806 may wirelessly transmit charging power to a receive coil (e.g., the receive coil 408 of FIG. 4).

[0080] FIG. 19 is a flowchart 1900 depicting a method for fabricating an apparatus for wirelessly transferring charging power, in accordance with some implementations. The method of flowchart 1900 is described herein with reference to the descriptions in connection with FIGs. 8, 9 and 15-17. Although the method of flowchart 1900 is described herein with reference to a particular order, in various implementations, blocks herein may be performed in a different order, or omitted, and additional blocks may be added.

[0081] The flowchart 1900 may start with block 1902, which includes providing a ferrimagnetic structure. For example, as previously described in connection with FIGs. 8 and 9, the ferrimagnetic structure 804 may be provided.

[0082] The flowchart 1900 may then advance to block 1904, which includes forming a coil by disposing a conductor defining a plurality of sides of the coil such that, for each of the plurality of sides, the conductor bows toward a center of the coil as the conductor extends from an outer portion of the respective side of the coil toward a middle portion of the respective side of the coil. For example, as previously described in connection with FIGs. 8, 9 and 15-16, the coil 806 has a plurality of sides 904, 906, 908, 910 which may be defined by a conductor such that, for each of the plurality of sides, the conductor bows toward a center 902 of the coil 806 as the conductor extends from an outer portion 912 of the respective side of the coil toward a middle portion 914 of the respective side of the coil 806.

[0083] The various operations of methods described above may be performed by any suitable means capable of performing the operations, such as various hardware and/or software component(s), circuits, and/or module(s). Generally, any operations illustrated in the Figures may be performed by corresponding functional means capable of performing the operations.

[0084] Information and signals may be represented using any of a variety of different technologies and techniques. For example, data, instructions, commands, information, signals, bits, symbols, and chips that may be referenced throughout the above description may be represented by voltages, currents, electromagnetic waves, magnetic fields or particles, optical fields or particles, or any combination thereof.

[0085] The various illustrative logical blocks, modules, circuits, and algorithm steps described in connection with the implementations disclosed herein may be implemented as electronic hardware, computer software, or combinations of both. To clearly illustrate this interchangeability of hardware and software, various illustrative components, blocks, modules, circuits, and steps have been described above generally in terms of their functionality. Whether such functionality is implemented as hardware or software depends upon the particular application and design constraints imposed on the overall system. The described functionality may be implemented in varying ways for each particular application, but such implementation decisions should not be interpreted as causing a departure from the scope of the implementations of the invention.

[0086] The various illustrative blocks, modules, and circuits described in connection with the implementations disclosed herein may be implemented or performed with a general purpose processor, a Digital Signal Processor (DSP), an Application Specific Integrated Circuit (ASIC), a Field Programmable Gate Array (FPGA) or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A general purpose processor may be a microprocessor, but in the alternative, the processor may be any conventional processor, controller, microcontroller, or state machine. A processor may also be implemented as a combination of computing devices, e.g., a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration.

[0087] The steps of a method or algorithm and functions described in connection with the implementations disclosed herein may be embodied directly in hardware, in a software module executed by a processor, or in a combination of the two. If implemented in software, the functions may be stored on or transmitted over as one or more instructions or code on a tangible, non-transitory computer-readable medium. A software module may reside in Random Access Memory (RAM), flash memory, Read Only Memory (ROM), Electrically Programmable ROM (EPROM), Electrically Erasable Programmable ROM (EEPROM), registers, hard disk, a removable disk, a CD ROM, or any other form of storage medium known in the art. A storage medium is coupled to the processor such that the processor can read information from, and write information to, the storage medium. In the alternative, the storage medium may be integral to the processor. Disk and disc, as used herein, includes compact disc (CD), laser disc, optical disc, digital versatile disc (DVD), floppy disk and blu ray disc where disks usually reproduce data magnetically, while discs reproduce data optically with lasers. Combinations of the above should also be included within the scope of computer readable media.

[0088] For purposes of summarizing the disclosure, certain aspects, advantages and novel features of the inventions have been described herein. It is to be understood that not necessarily all such advantages may be achieved in accordance with any particular implementation of the invention. Thus, the invention may be embodied or carried out in a manner that achieves or optimizes one advantage or group of advantages as taught herein without necessarily achieving other advantages as may be taught or suggested herein.

[0089] Various modifications of the above described implementations will be readily apparent, and the generic principles defined herein may be applied to other implementations without departing from the spirit or scope of the invention. Thus, the present invention is not intended to be limited to the implementations shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

WHAT IS CLAIMED IS:

1. An apparatus for wirelessly transferring charging power, the apparatus comprising:

a coil comprising a conductor defining a plurality of sides of the coil, wherein for each of the plurality of sides of the coil, the conductor bows toward a center of the coil as the conductor extends from an outer portion of the respective side of the coil toward a middle portion of the respective side of the coil.

2. The apparatus of claim 1, wherein at each corner of corresponding sides of the coil, the conductor is bent at an acute angle with respect to a direction of extension of each of the corresponding sides to form substantially rounded corners.

3. The apparatus of claim 1, wherein at each corner of corresponding sides of the coil, the conductor is bent at a substantially 90 degree angle with respect to a direction of extension of each of the corresponding sides.

4. The apparatus of claim 1, wherein the conductor of the coil forms a plurality of windings and for at least one winding on one side of the plurality of sides of the coil, the conductor extends in a substantially straight line along the entire side.

5. The apparatus of claim 1, wherein a magnetic coupling factor between the coil and another coil is within a predetermined percentage of a maximum or minimum magnetic coupling factor between the coil and the another coil for all offsets of a center of the another coil, with respect to the center of the coil, that are within a perimeter defined by the conductor of the coil.

6. The apparatus of claim 1, wherein for a given voltage applied across the coil, an amount of current circulating in the coil is within a predetermined percentage of a maximum or minimum amount of current circulating in the coil for all offsets of a center of another coil, with respect to the center of the coil, that are within a perimeter defined by the conductor of the coil.

7. The apparatus of claim 1, wherein the conductor of the coil forms a plurality of windings and wherein successive windings of the plurality of windings bow

toward a center of the coil to an increasing extent from an outermost winding to an innermost winding.

8. The apparatus of claim 1, wherein the conductor of the coil forms a plurality of windings and wherein the conductor extends in a substantially straight line along an entirety of each of the plurality of sides for at least one of the plurality of windings.

9. A method for wirelessly transferring charging power, the method comprising:

driving, with an alternating current, a coil comprising a conductor defining a plurality of sides of the coil, wherein for each of the plurality of sides of the coil, the conductor bows toward a center of the coil as the conductor extends from an outer portion of the respective side of the coil toward a middle portion of the respective side of the coil, and

wirelessly transferring charging power from the coil to another coil.

10. The method of claim 9, wherein the coil comprises a plurality of windings and for at least one winding on one side of the plurality of sides of the coil, the conductor extends in a substantially straight line along the entire side.

11. The method of claim 9, wherein a magnetic coupling factor between the coil and the another coil is within a predetermined percentage of a maximum or minimum magnetic coupling factor between the coil and the another coil for all offsets of a center of the another coil, with respect to the center of the coil, that are within a perimeter defined by the conductor of the coil.

12. The method of claim 9, wherein for a given voltage applied across the coil, an amount of current circulating in the coil is within a predetermined percentage of a maximum or minimum amount of current circulating in the coil for all offsets of a center of the another coil, with respect to the center of the coil, that are within a perimeter defined by the conductor of the coil.

13. The method of claim 9, wherein the conductor of the coil forms a plurality of windings and wherein successive windings of the plurality of windings bow toward a

center of the coil to an increasing extent from an outermost winding to an innermost winding.

14. The method of claim 9, wherein the conductor of the coil forms a plurality of windings and wherein the conductor extends in a substantially straight line along an entirety of each of the plurality of sides for at least one of the plurality of windings.

15. A method for fabricating an apparatus for wirelessly transferring charging power, the method comprising:

providing a ferrimagnetic structure, and

forming a coil by disposing a conductor defining a plurality of sides of the coil such that, for each of the plurality of sides, the conductor bows toward a center of the coil as the conductor extends from an outer portion of the respective side of the coil toward a middle portion of the respective side of the coil.

16. The method of claim 15, wherein the conductor is disposed such that, at each corner of corresponding sides, the conductor is bent at an acute angle with respect to a direction of extension of each of the corresponding sides to form substantially rounded corners.

17. The method of claim 15, wherein the conductor is disposed such that, at each corner of corresponding sides, the conductor is bent at a substantially 90 degree angle with respect to a direction of extension of each of the corresponding sides.

18. The method of claim 15, wherein for at least one side of the plurality of sides, the conductor is disposed to extend in a substantially straight line along the entire side.

19. The method of claim 15, wherein the coil is formed such that when driven with an alternating current, a magnetic coupling factor between the coil and another coil is within a predetermined percentage of a maximum or minimum magnetic coupling factor between the coil and the another coil for all offsets of a center of the another coil, with respect to the center of the coil, that are within a perimeter defined by the conductor of the coil.

20. The method of claim 15, wherein the coil is formed such that for a given voltage applied across the coil, an amount of current circulating in the coil is within a predetermined percentage of a maximum or minimum amount of current circulating in the coil for all offsets of a center of another coil, with respect to the center of the coil, that are within a perimeter defined by the conductor of the coil.

21. The method of claim 15, further comprising disposing the conductor such that the coil comprises a plurality of windings, wherein successive windings of the plurality of windings bow toward a center of the coil to an increasing extent from an outermost winding to an innermost winding.

22. The method of claim 15, further comprising disposing the conductor to form a plurality of windings, wherein the conductor extends in a substantially straight line along an entirety of each of the plurality of sides for at least one of the plurality of windings.

23. An apparatus for wirelessly transferring charging power, the apparatus comprising:

means for wirelessly transmitting charging power comprising a conductor defining a plurality of sides of the means for wirelessly transmitting charging power, wherein for each of the plurality of sides, the conductor bows toward a center of the means for wirelessly transmitting charging power as the conductor extends from an outer portion of the respective side toward a middle portion of the respective side; and

means for driving the means for wirelessly transmitting charging power with an alternating current.

24. The apparatus of claim 23, wherein at each corner of corresponding sides, the conductor is bent at an acute angle with respect to a direction of extension of each of the corresponding sides to form substantially rounded corners.

25. The apparatus of claim 23, wherein at each corner of corresponding sides, the conductor is bent at a substantially 90 degree angle with respect to a direction of extension of each of the corresponding sides.

26. The apparatus of claim 23, wherein the conductor forms a plurality of windings and wherein for at least one side of the plurality of sides, the conductor extends in a substantially straight line along the entire side.

27. The apparatus of claim 23, wherein a magnetic coupling factor between the means for wirelessly transmitting charging power and another coil is within a predetermined percentage of a maximum or minimum magnetic coupling factor between the means for wirelessly transmitting charging power and the another coil for all offsets of a center of the another coil, with respect to the center of the means for wirelessly transmitting charging power, that are within a perimeter defined by the conductor.

28. The apparatus of claim 23, wherein for a given voltage applied across the means for wirelessly transmitting charging power, an amount of current circulating in the means for wirelessly transmitting charging power is within a predetermined percentage of a maximum amount or minimum of current circulating in the means for wirelessly transmitting charging power for all offsets of a center of another coil, with respect to the center of the means for wirelessly transmitting charging power, that are within a perimeter defined by the conductor.

29. The apparatus of claim 23, wherein the conductor forms a plurality of windings and wherein successive windings of the plurality of windings bow toward a center of the means for wirelessly transmitting charging power to an increasing extent from an outermost winding to an innermost winding.

30. The apparatus of claim 23, wherein the conductor forms a plurality of windings and wherein the conductor extends in a substantially straight line along an entirety of each of the plurality of sides for at least one of the plurality of windings.

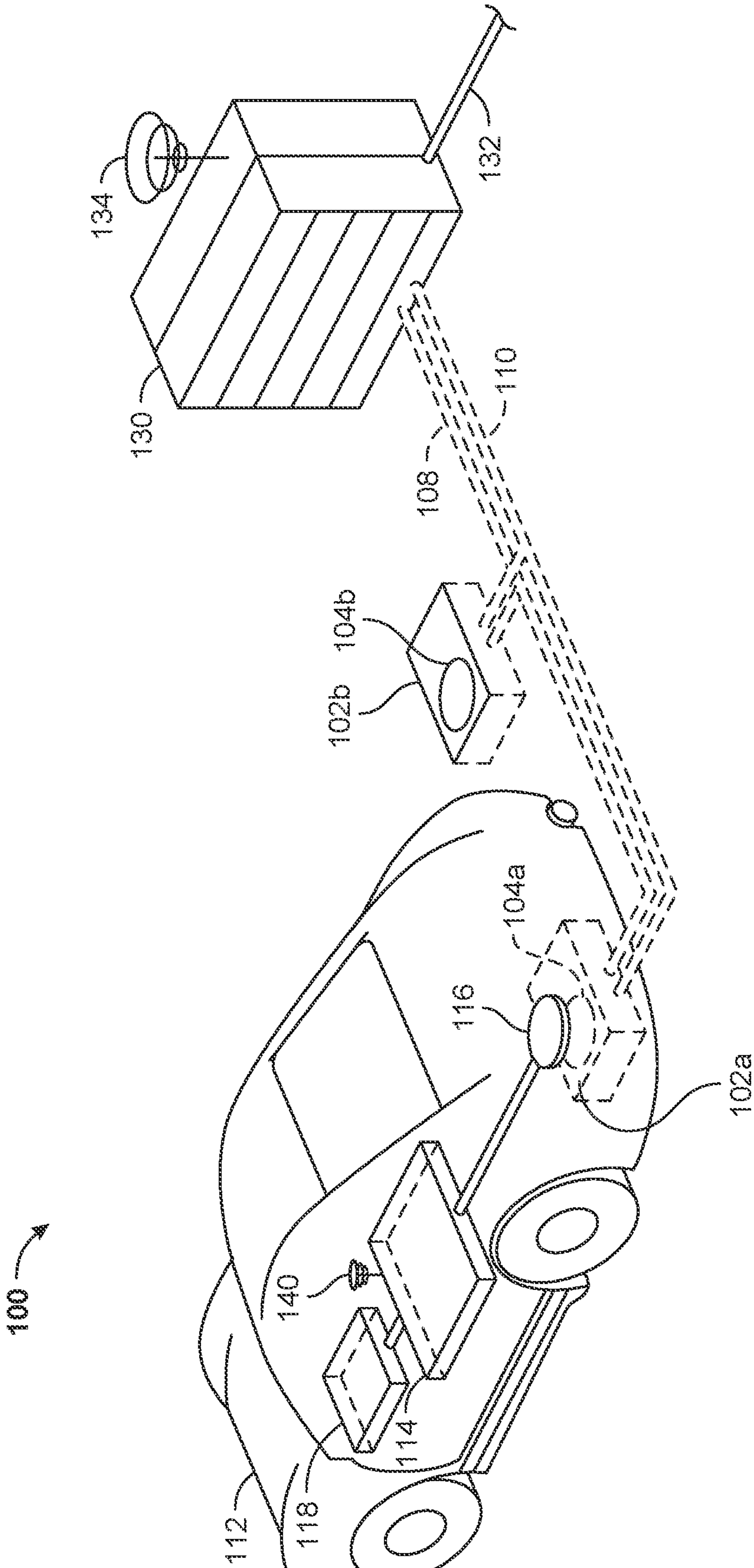

FIG. 1

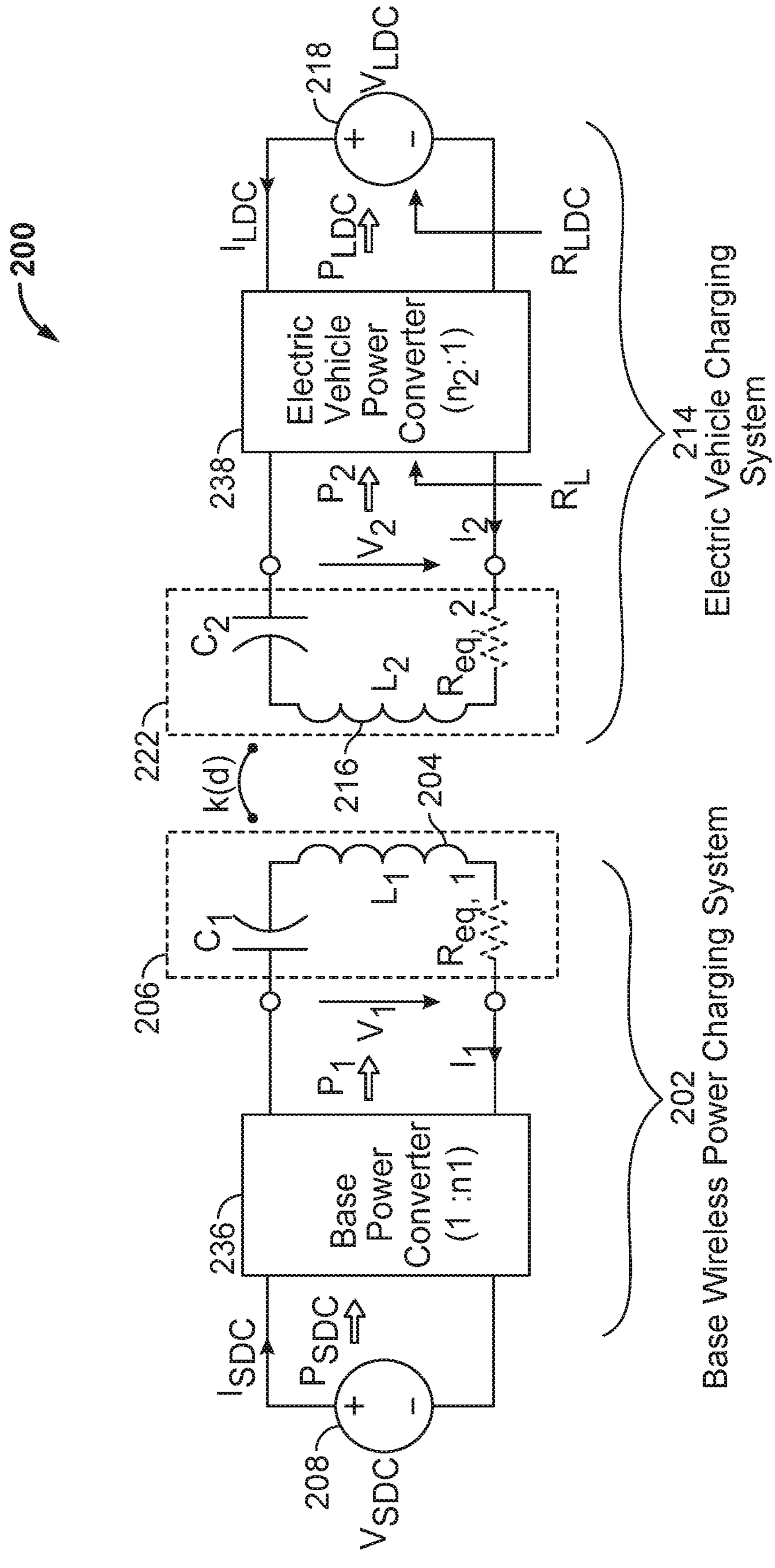
200
V_{LDC}
218
I_{LDC}
P_{LDC}
R_{LDC}
Electric Vehicle Power Converter (n_2:1)
238
P_2
V_2
I_2
R_L
214
Electric Vehicle Charging System
C_2
L_2
$R_{eq, 2}$
222
216
k(d)
204
C_1
L_1
$R_{eq, 1}$
206
P_1
V_1
I_1
202
Base Wireless Power Charging System
Base Power Converter (1 :n1)
236
I_{SDC}
P_{SDC}
208
V_{SDC}

FIG. 2

3/11

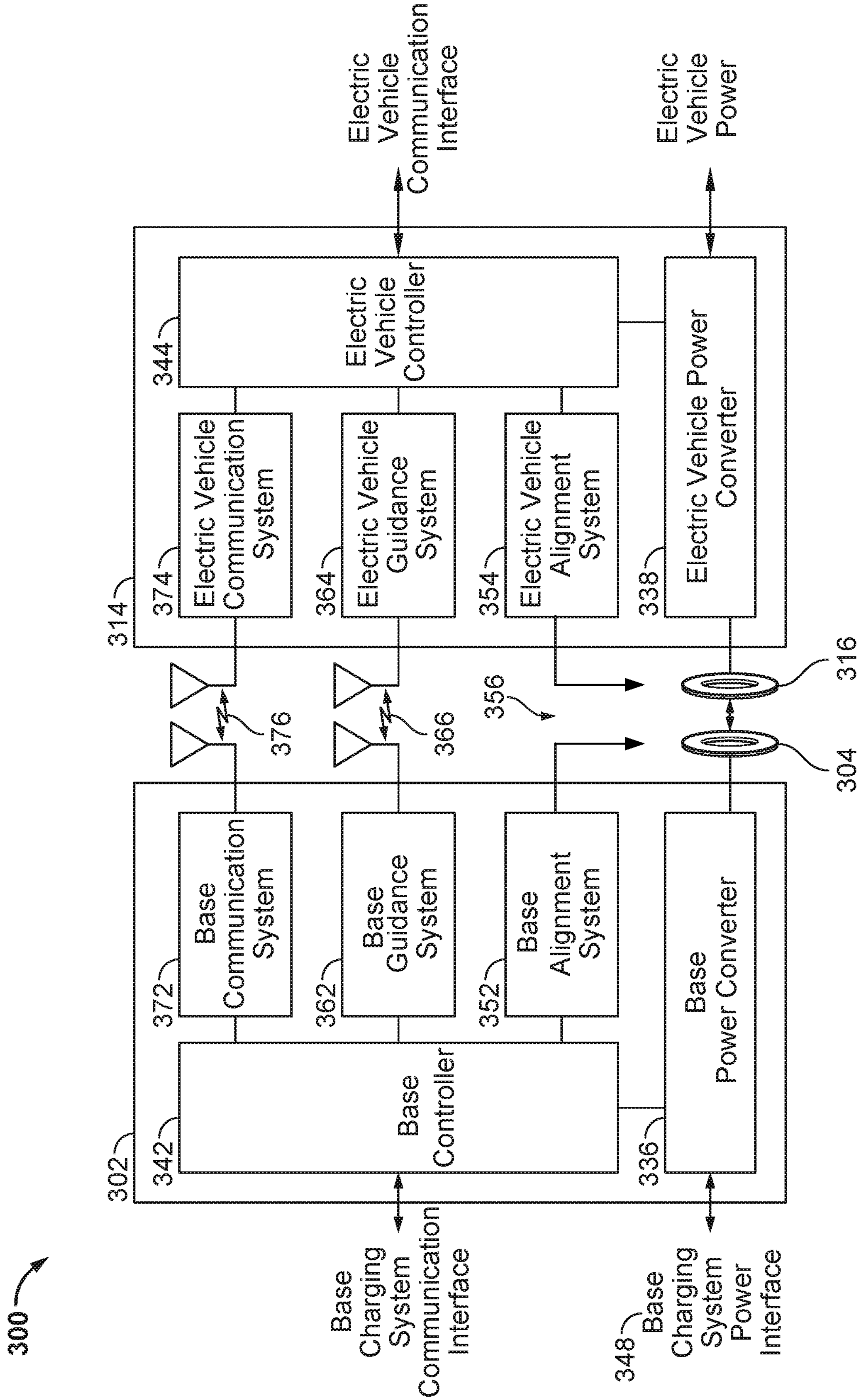
300
Electric Vehicle Communication Interface
Electric Vehicle Power
314
344
Electric Vehicle Controller
374
Electric Vehicle Communication System
364
Electric Vehicle Guidance System
354
Electric Vehicle Alignment System
338
Electric Vehicle Power Converter
376
366
356
316
304
302
342
Base Controller
372
Base Communication System
362
Base Guidance System
352
Base Alignment System
336
Base Power Converter
Base Charging System Communication Interface
348
Base Charging System Power Interface

FIG. 3

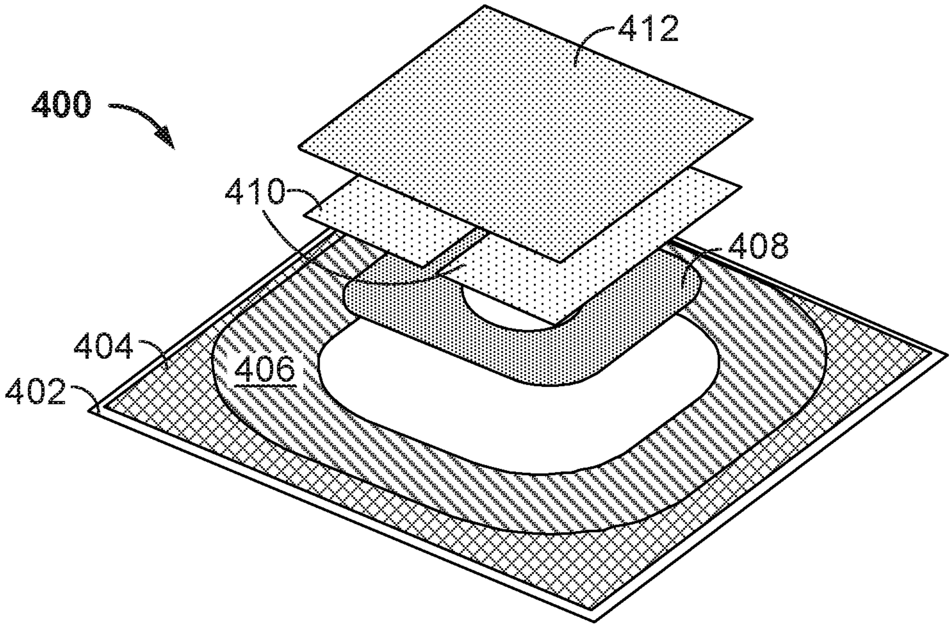

FIG. 4

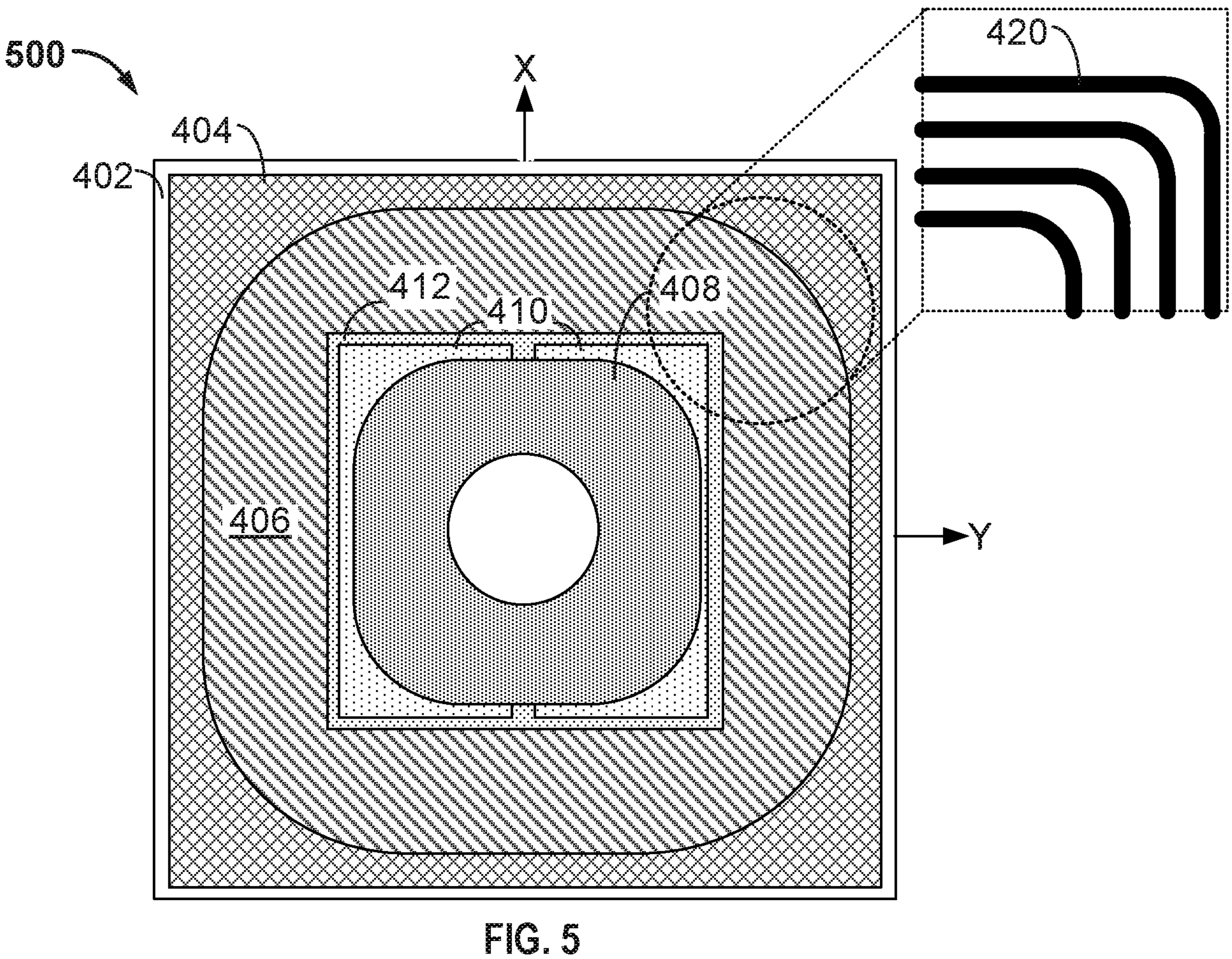

FIG. 5

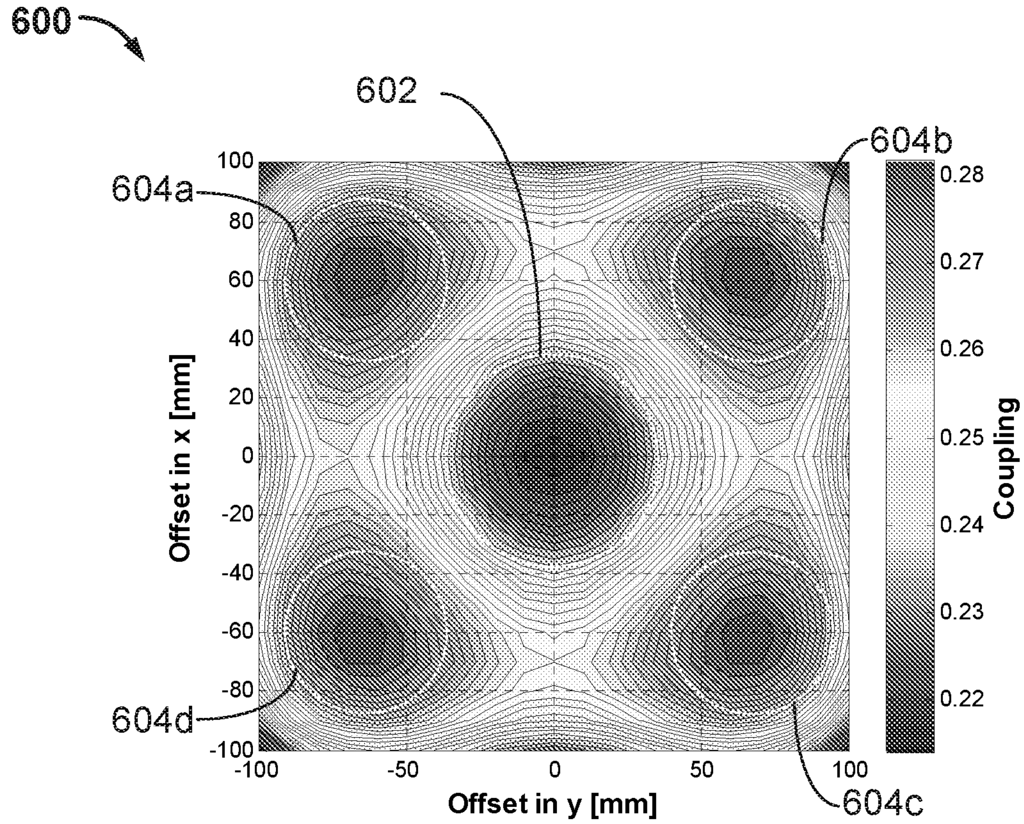
600
602
604a
604b
604c
604d
Offset in x [mm]
Offset in y [mm]
Coupling
100
80
60
40
20
0
-20
-40
-60
-80
-100
-50
50
0.28
0.27
0.26
0.25
0.24
0.23
0.22

FIG. 6

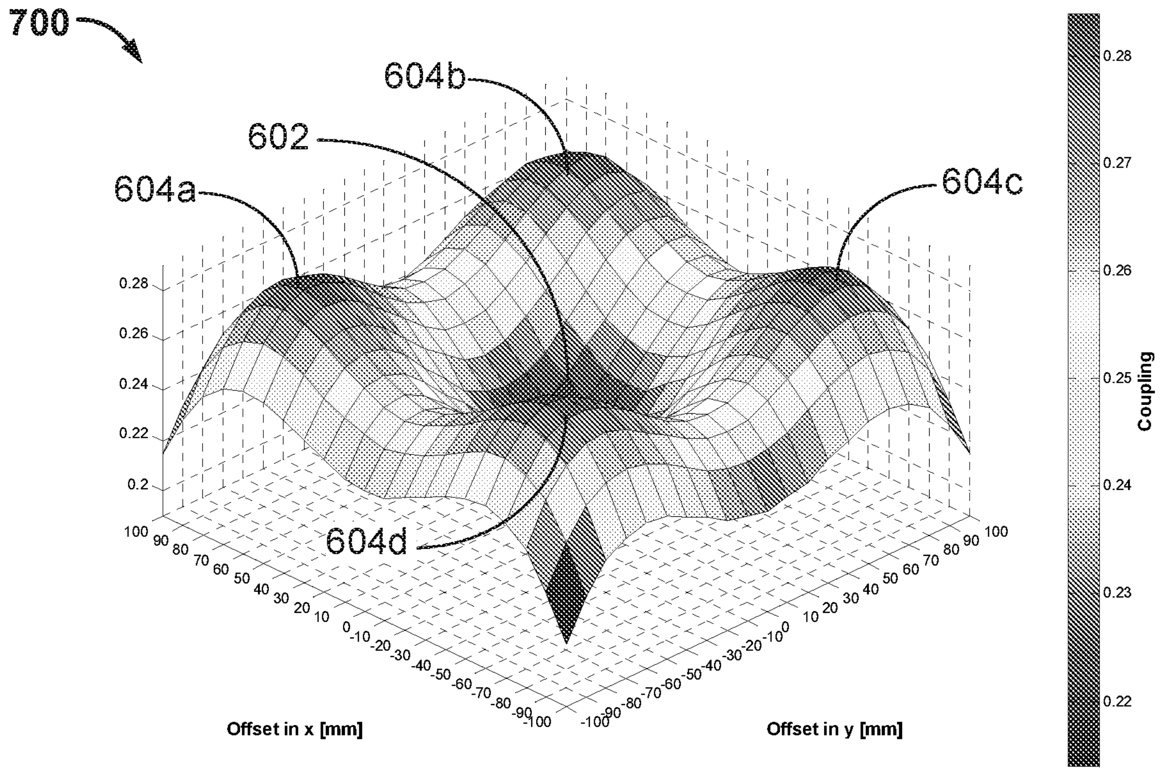
700
604b
602
604a
604c
604d
Offset in x [mm]
Offset in y [mm]
Coupling
0.28
0.26
0.24
0.22
0.2
0.27
0.25
0.23

FIG. 7

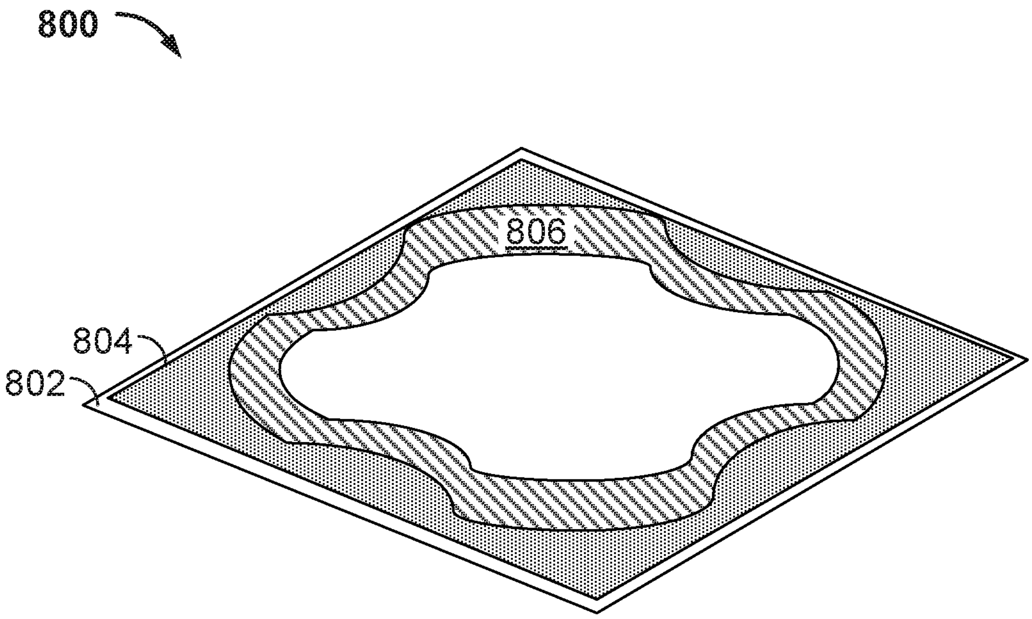
800
806
804
802

FIG. 8

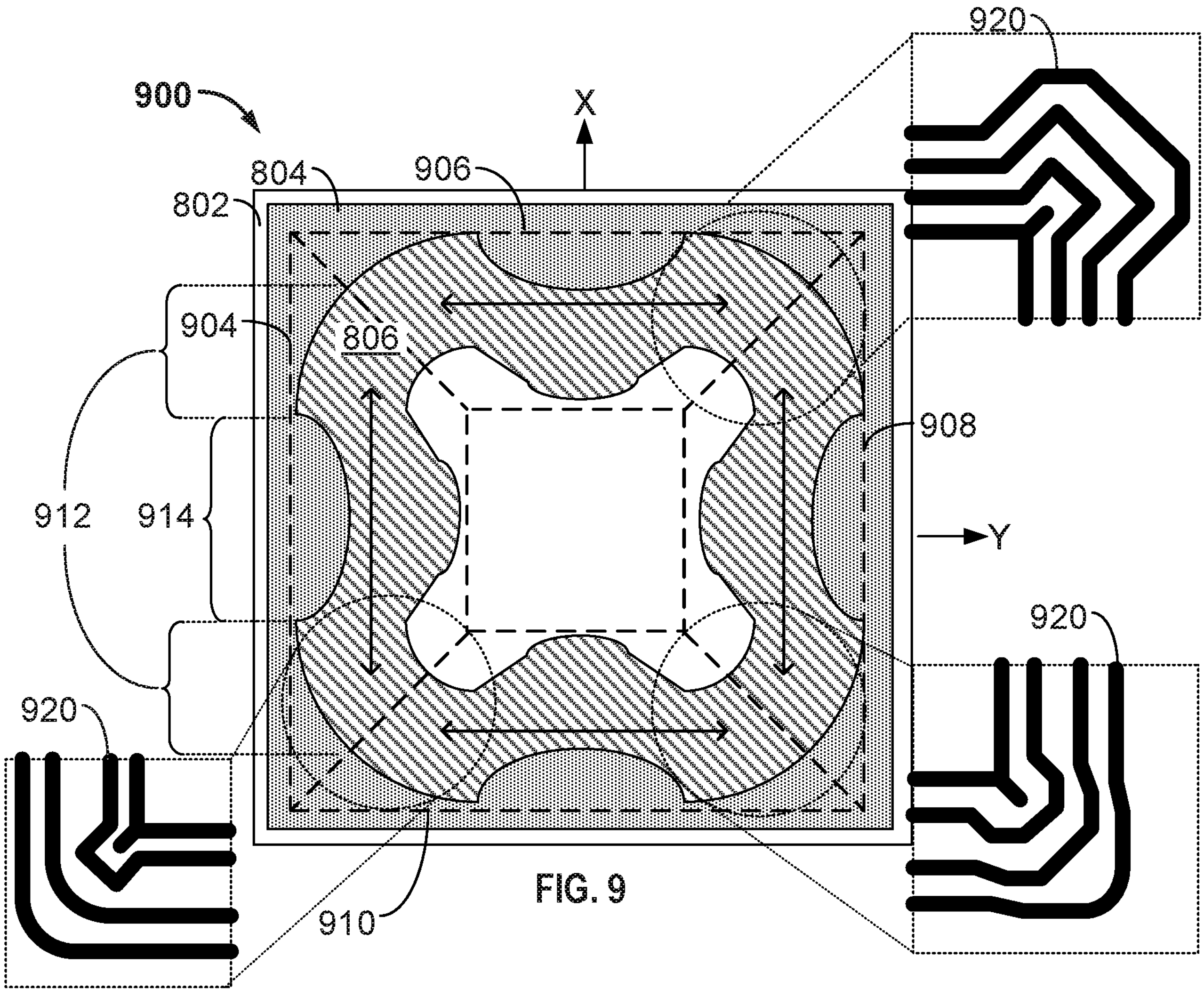
920
900
X
804
906
802
904
806
908
912
914
Y
920
920
910

FIG. 9

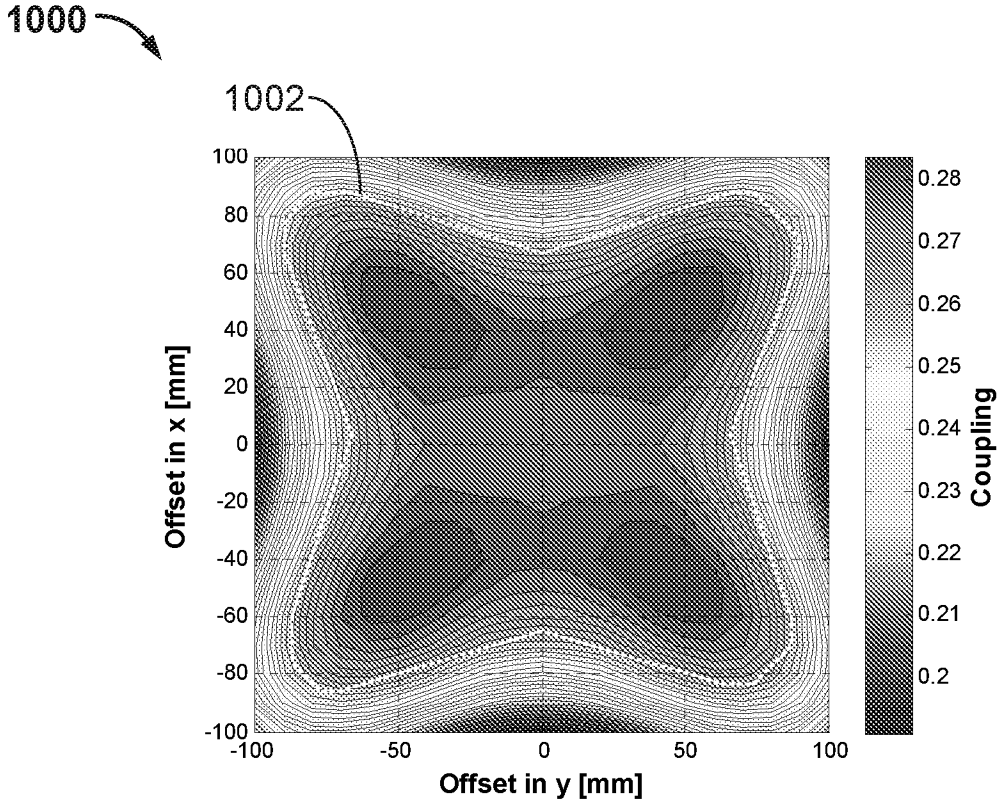
1000
1002
100
80
60
40
20
0
-20
-40
-60
-80
-100
Offset in x [mm]
-100
-50
0
50
100
Offset in y [mm]
0.28
0.27
0.26
0.25
0.24
0.23
0.22
0.21
0.2
Coupling

FIG. 10

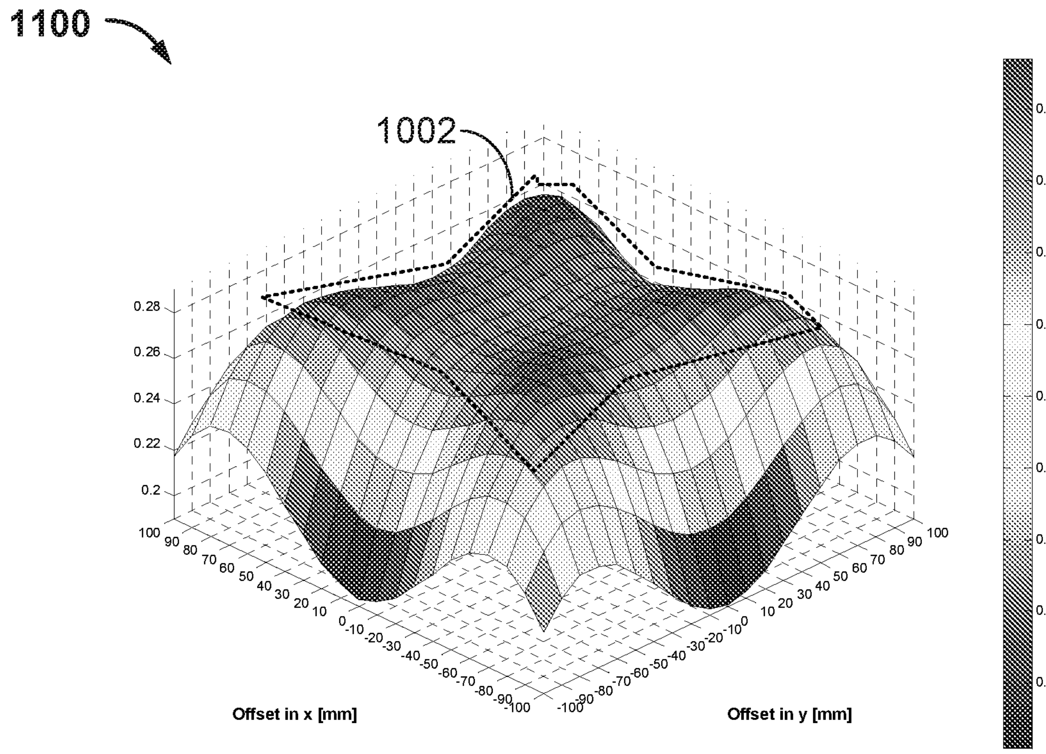
1100
1002
0.28
0.26
0.24
0.22
0.2
Offset in x [mm]
Offset in y [mm]
Coupling

FIG. 11

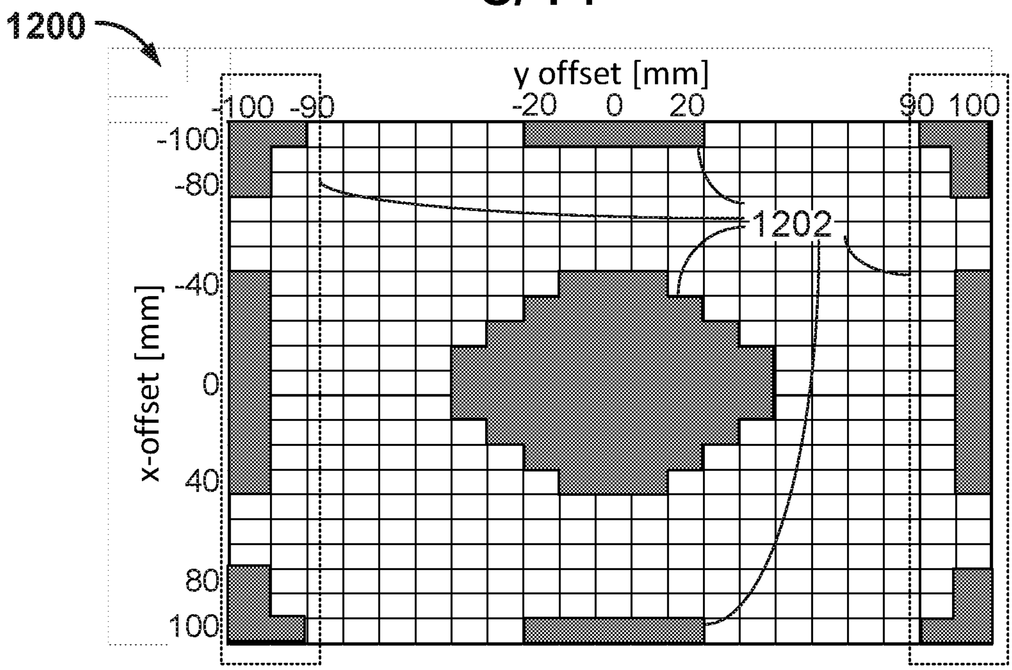
1200
y offset [mm]
-100 -90 -20 0 20 90 100
-100
-80
-40
0
40
80
100
x-offset [mm]
1202

FIG. 12

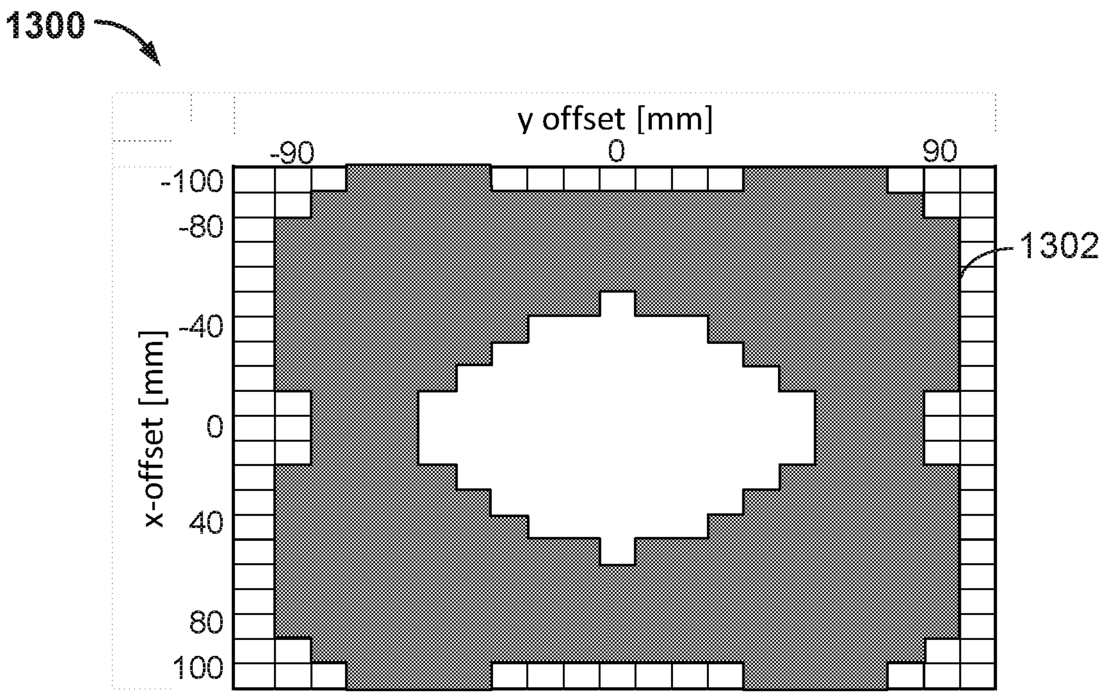
1300
y offset [mm]
-90 0 90
-100
-80
-40
0
40
80
100
x-offset [mm]
1302

FIG. 13

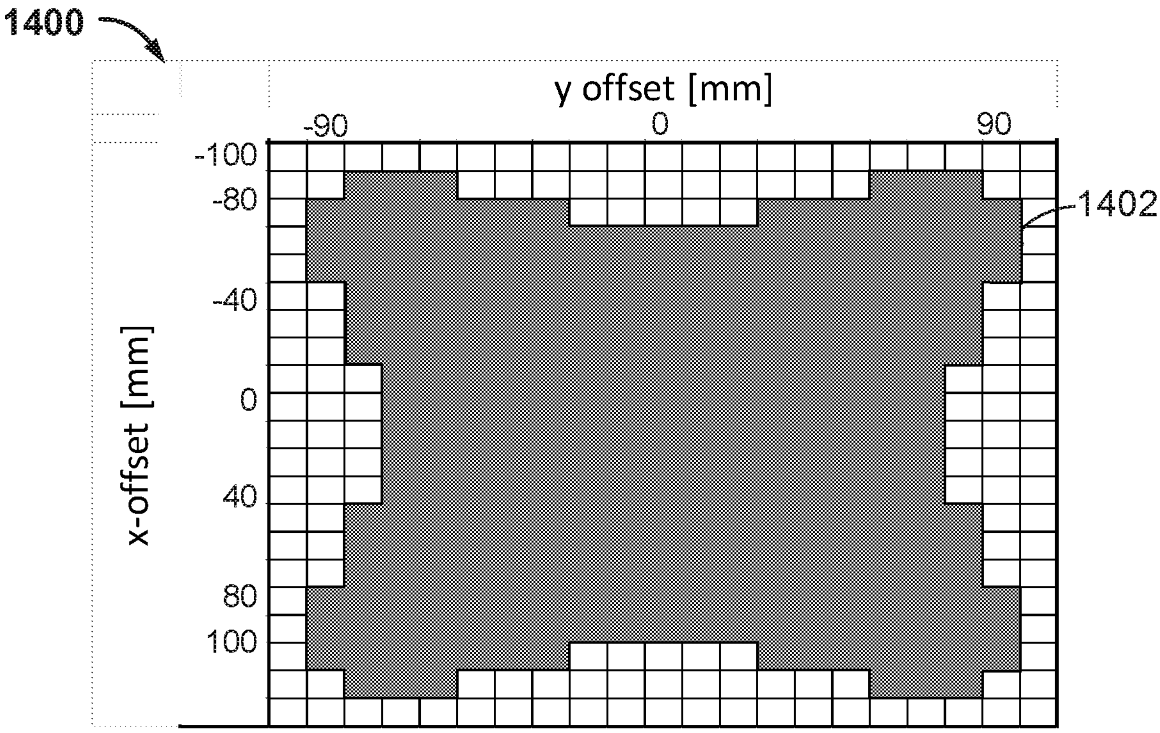
1400
y offset [mm]
-90
0
90
-100
-80
-40
0
40
80
100
x-offset [mm]
1402

FIG. 14

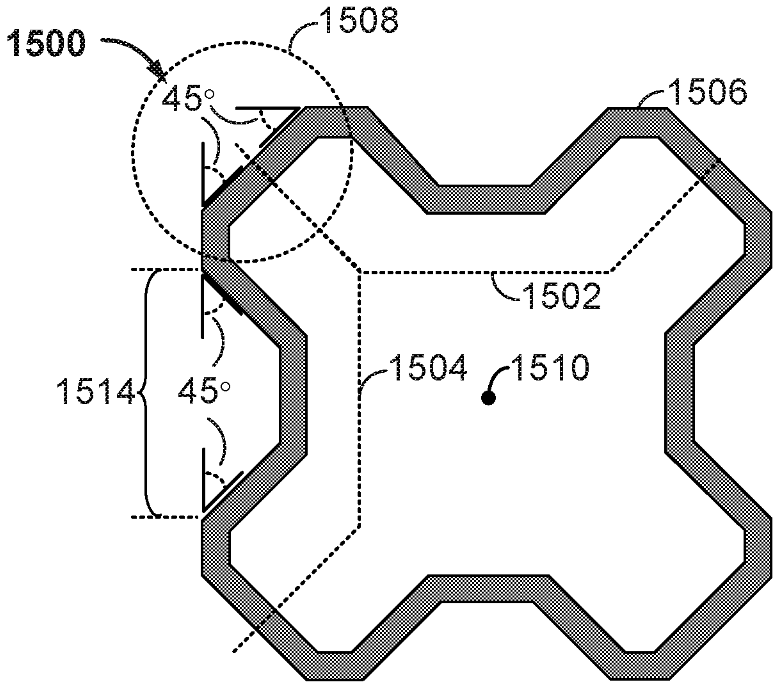
1500
1508
1506
45°
1502
1504
1510
1514
45°

FIG. 15

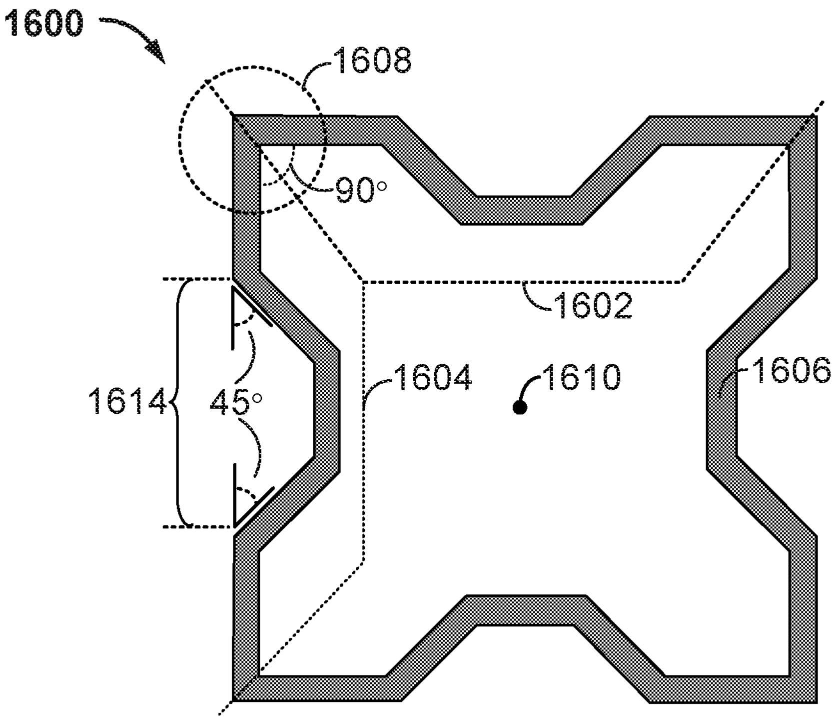
1600
1608
90°
1602
1614
45°
1604
1610
1606

FIG. 16

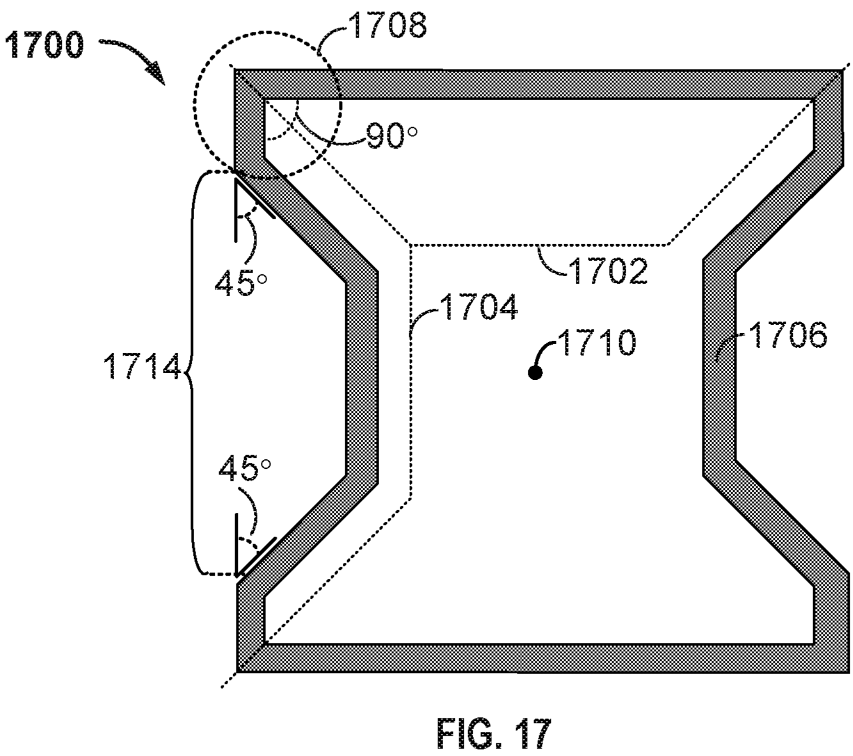
1700
1708
90°
1702
45°
1704
1710
1706
1714
45°

FIG. 17

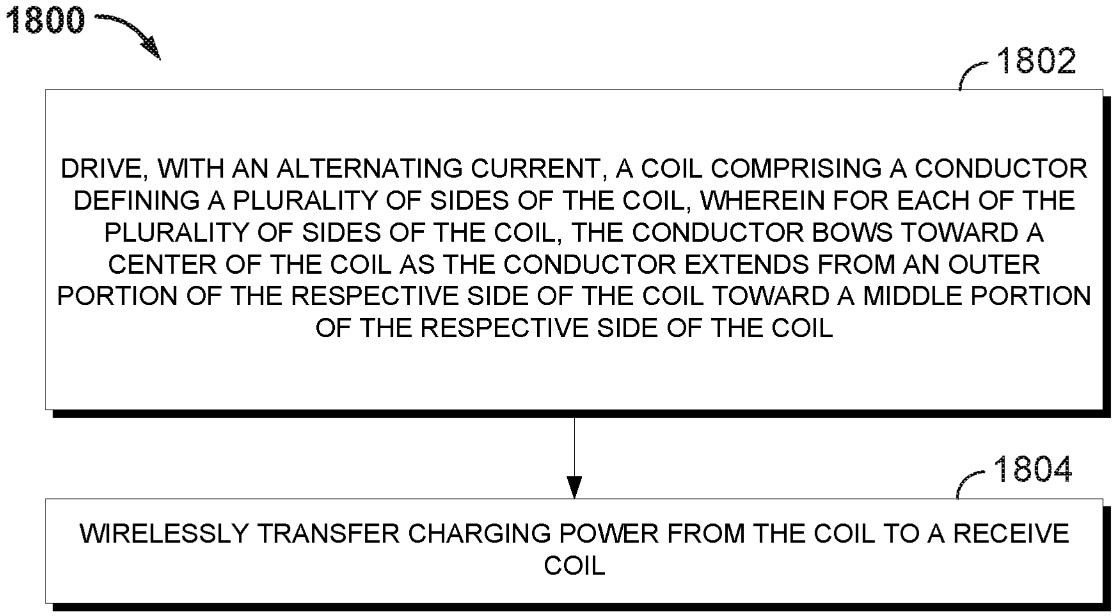
1800
1802
DRIVE, WITH AN ALTERNATING CURRENT, A COIL COMPRISING A CONDUCTOR DEFINING A PLURALITY OF SIDES OF THE COIL, WHEREIN FOR EACH OF THE PLURALITY OF SIDES OF THE COIL, THE CONDUCTOR BOWS TOWARD A CENTER OF THE COIL AS THE CONDUCTOR EXTENDS FROM AN OUTER PORTION OF THE RESPECTIVE SIDE OF THE COIL TOWARD A MIDDLE PORTION OF THE RESPECTIVE SIDE OF THE COIL
1804
WIRELESSLY TRANSFER CHARGING POWER FROM THE COIL TO A RECEIVE COIL

FIG. 18

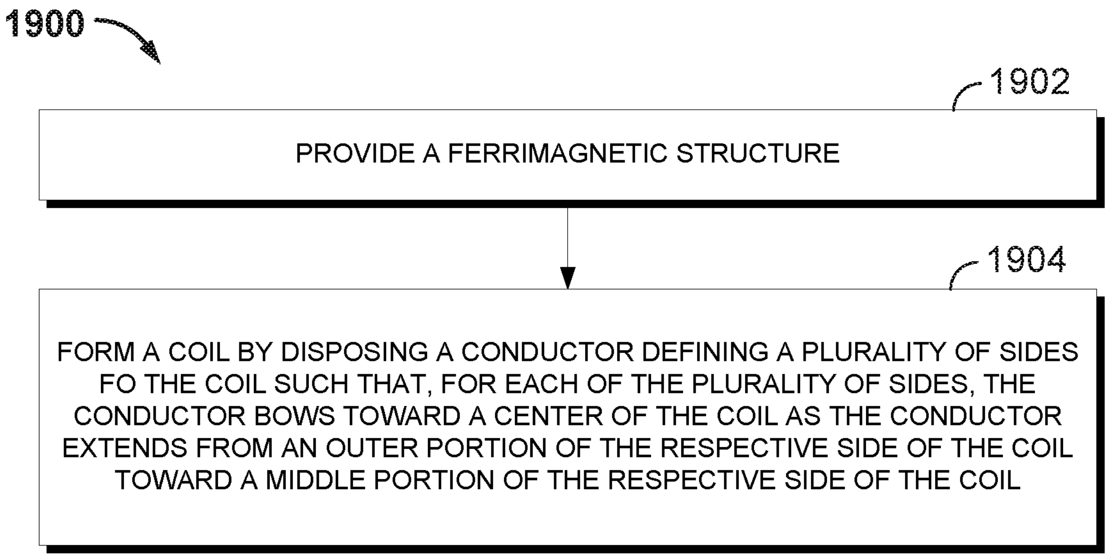
1900
1902
PROVIDE A FERRIMAGNETIC STRUCTURE
1904
FORM A COIL BY DISPOSING A CONDUCTOR DEFINING A PLURALITY OF SIDES FO THE COIL SUCH THAT, FOR EACH OF THE PLURALITY OF SIDES, THE CONDUCTOR BOWS TOWARD A CENTER OF THE COIL AS THE CONDUCTOR EXTENDS FROM AN OUTER PORTION OF THE RESPECTIVE SIDE OF THE COIL TOWARD A MIDDLE PORTION OF THE RESPECTIVE SIDE OF THE COIL

FIG. 19

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2016/013920

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01V3/10 B60L11/18 H02J7/02 H02J5/00 H02J50/10
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01V H02J B60L G06K

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2014/091640 A1 (SCHOLZ PETER-DOMINIK [DE] ET AL) 3 April 2014 (2014-04-03) paragraphs [0056], [0064]; figures 4A-4C,5A-5E -----	1-30
X	US 6 631 847 B1 (KASAHARA TETSUICHIRO [JP] ET AL) 14 October 2003 (2003-10-14) figure 1 -----	1-30
X	US 2002/023964 A1 (OKAMURA SHIGERU [JP] ET AL) 28 February 2002 (2002-02-28) figure 1 -----	1-30

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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

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

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

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
25 April 2016	03/05/2016

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Ramcke, Ties

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2016/013920

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2014091640 A1	03-04-2014	CN 103890875 A	25-06-2014
		EP 2705521 A1	12-03-2014
		JP 2014515888 A	03-07-2014
		US 2014091640 A1	03-04-2014
		WO 2012150293 A1	08-11-2012
US 6631847 B1	14-10-2003	AU 4395699 A	17-04-2000
		DE 69923427 D1	03-03-2005
		DE 69923427 T2	30-06-2005
		DE 69927623 T2	06-07-2006
		EP 1039411 A1	27-09-2000
		EP 1450298 A1	25-08-2004
		JP 3484356 B2	06-01-2004
		JP 2000105810 A	11-04-2000
		TW 436740 B	28-05-2001
		US 6631847 B1	14-10-2003
		WO 0019362 A1	06-04-2000
US 2002023964 A1	28-02-2002	EP 1184807 A1	06-03-2002
		JP 2002074300 A	15-03-2002
		US 2002023964 A1	28-02-2002