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(54) **HIGH EFFICIENCY AND POWER TRANSFER IN WIRELESS POWER MAGNETIC RESONATORS**

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(Continued)

(51) **Int. Cl.**
H01F 27/42 (2006.01)
H01F 37/00 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***H02J 50/40*** (2016.02); ***H01Q 1/2225*** (2013.01); ***H01Q 7/00*** (2013.01); ***H02J 5/005*** (2013.01); ***H02J 50/23*** (2016.02); ***H02J 50/27*** (2016.02)

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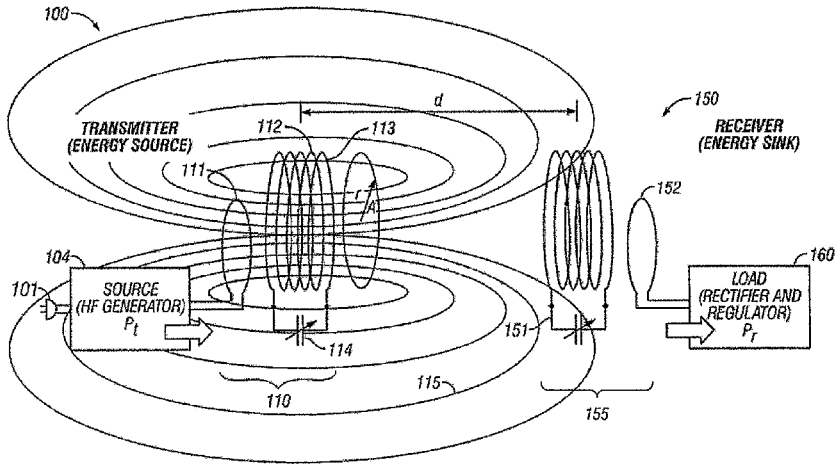
(57) **ABSTRACT**

A wireless power transmission system is disclosed. In one aspect, the system includes a transmitting antenna configured to transmit power, via a magnetic field, to a receiving antenna to power a load. The system also includes a tuning loop electrically isolated from the transmitting antenna and being movable relative to the transmitting antenna to adjust a coupling between the transmitting antenna and the tuning loop.

21 Claims, 5 Drawing Sheets



InductEV, Inc.
Exhibit 1036
InductEV v. WiTricity
IPR2024-00140
Ex. 1036-001

Related U.S. Application Data

(60) Provisional application No. 60/973,166, filed on Sep. 17, 2007.

(51) **Int. Cl.**

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H02J 50/23	(2016.01)

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USPC 307/104
See application file for complete search history.

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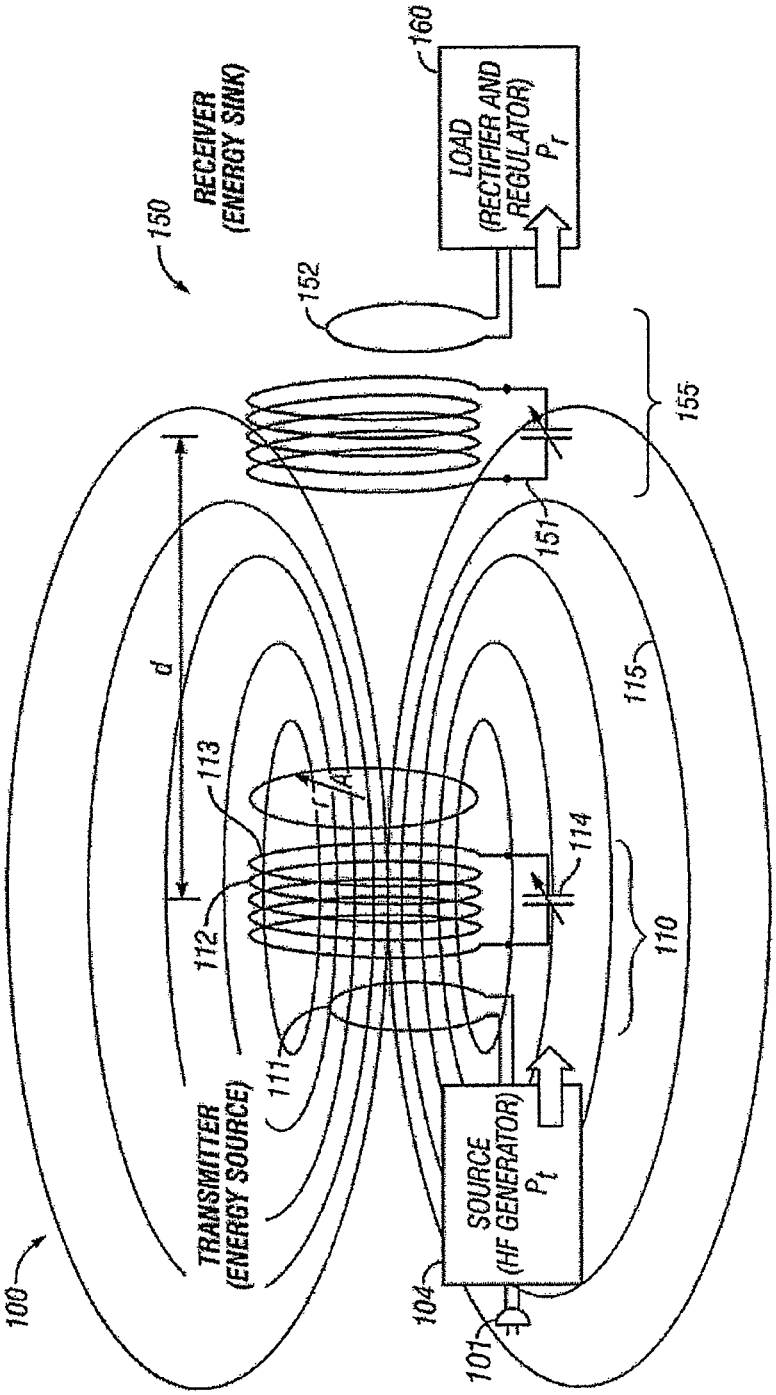
RECEIVER
(ENERGY SINK)
150
160
LOAD
(RECTIFIER AND
REGULATOR)
P_r
152
155
151
115
d
113
r
A
114
112
110
111
TRANSMITTER
(ENERGY SOURCE)
SOURCE
(HF GENERATOR)
P_t
100
104
101

FIG. 1

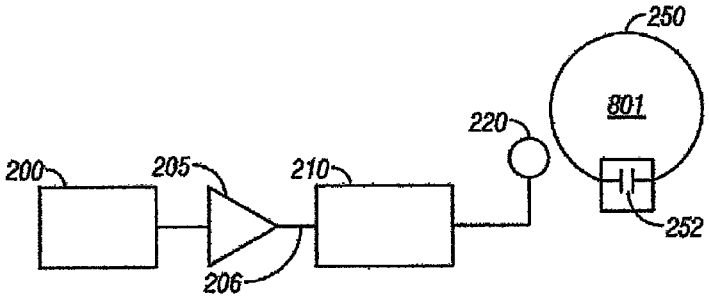

FIG. 2

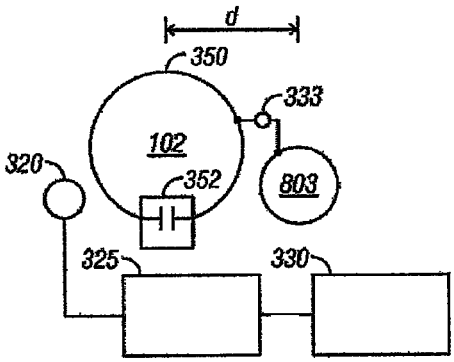

FIG. 3

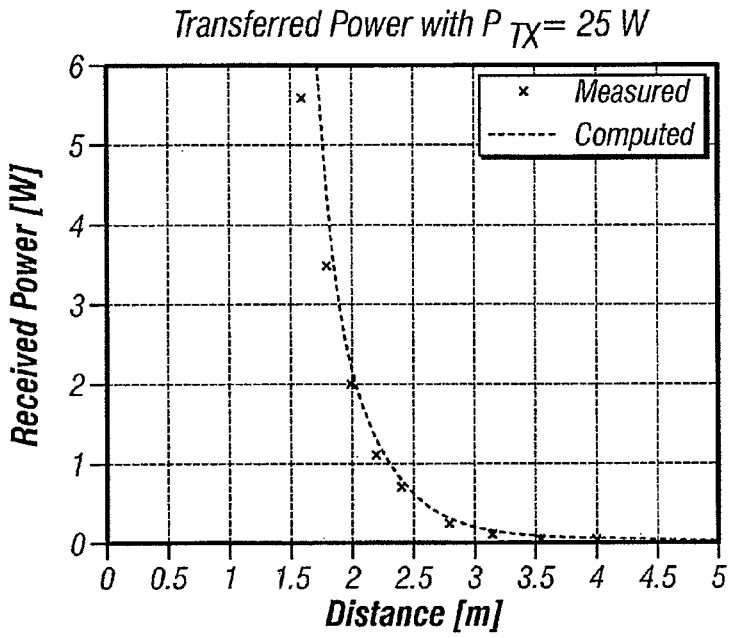
Transferred Power with P TX= 25 W
Measured
Computed
Received Power [W]
Distance [m]
0
1
2
3
4
5
6
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

FIG. 4

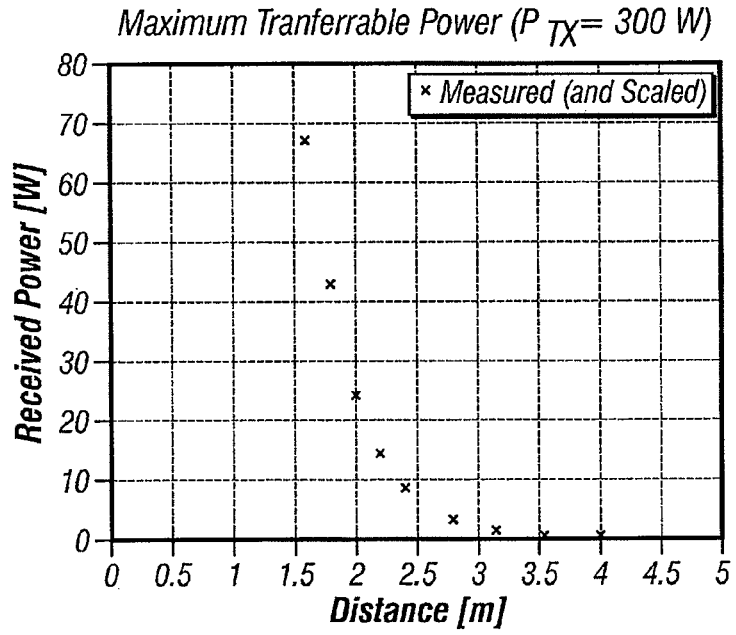
Maximum Tranferrable Power (P TX= 300 W)
Measured (and Scaled)
Received Power [W]
Distance [m]
0
10
20
30
40
50
60
70
80
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

FIG. 5

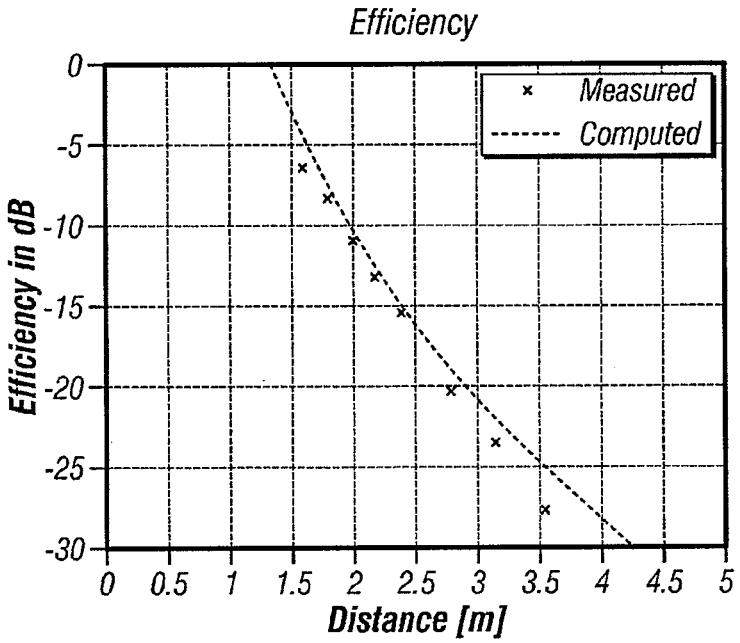
Efficiency
Measured
Computed
Efficiency in dB
0
-5
-10
-15
-20
-25
-30
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Distance [m]

FIG. 6

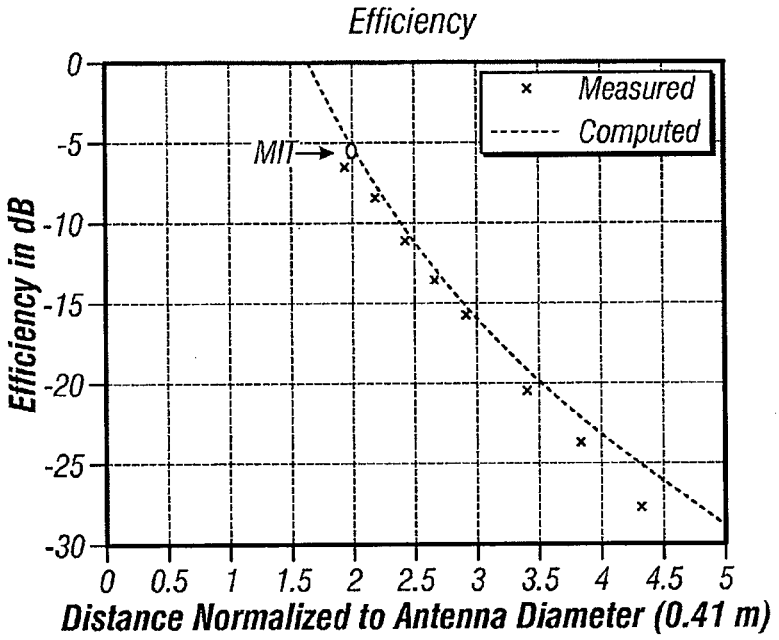
Efficiency
Measured
Computed
MIT
Efficiency in dB
0
-5
-10
-15
-20
-25
-30
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Distance Normalized to Antenna Diameter (0.41 m)

FIG. 7

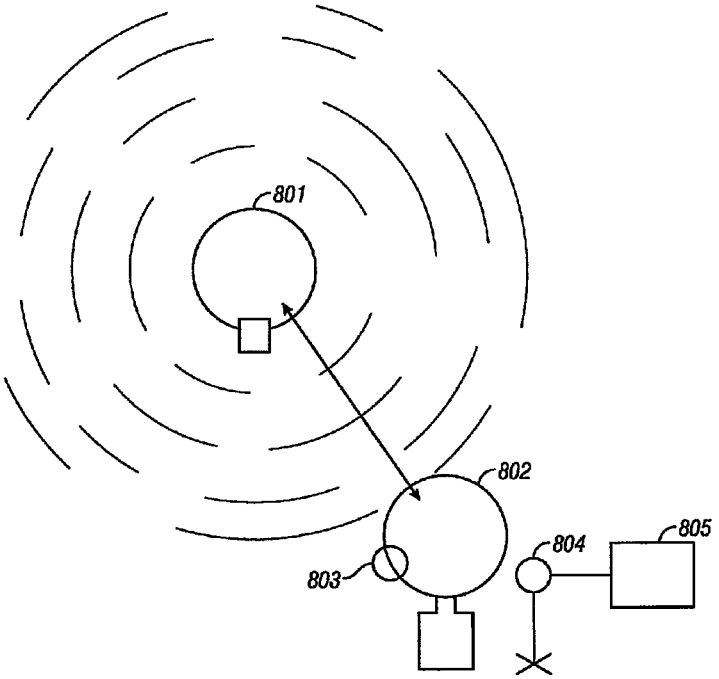

FIG. 8

HIGH EFFICIENCY AND POWER TRANSFER IN WIRELESS POWER MAGNETIC RESONATORS

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 12/211,750 entitled "High Efficiency and Power Transfer in Wireless Power Magnetic Resonators" filed Sep. 16, 2008, which claims benefit under 35 U.S.C. §119(e) to U.S. Provisional Patent Application 60/973,166 filed on Sep. 17, 2007. The disclosure of all of the priority applications are hereby incorporated by reference in their entirety.

BACKGROUND

It is desirable to transfer electrical energy from a source to a destination without the use of wires to guide the electromagnetic fields. A difficulty of previous attempts has been low efficiency together with an inadequate amount of delivered power.

Our previous applications and provisional applications, including, but not limited to, U.S. patent application Ser. No. 12/018,069, filed Jan. 22, 2008, entitled "Wireless Apparatus and Methods", the entire contents of the disclosure of which is herewith incorporated by reference, describe wireless transfer of power.

The system can use transmit and receiving antennas that are preferably resonant antennas, which are substantially resonant, e.g., within 5-10% of resonance, 15% of resonance, or 20% of resonance. The antenna(s) are preferably of a small size to allow it to fit into a mobile, handheld device where the available space for the antenna may be limited. An efficient power transfer may be carried out between two antennas by storing energy in the near field of the transmitting antenna, rather than sending the energy into free space in the form of a travelling electromagnetic wave. Antennas with high quality factors can be used. Two high-Q antennas are placed such that they react similarly to a loosely coupled transformer, with one antenna inducing power into the other. The antennas preferably have Qs that are greater than 1000.

SUMMARY

The present application describes transfer of energy from a power source to a power destination via electromagnetic field coupling with high efficiency and/or high power. Embodiments describe operations and actual efficiencies.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other aspects will now be described in detail with reference to the accompanying drawings, wherein:

FIG. **1** shows a block diagram of a magnetic wave based wireless power transmission system.

FIG. **2** illustrates a transmitter block diagram including amplifier coupling loop and antennas.

FIG. **3** illustrates a receiver block diagram including coupling loop, receiver and trends at tuning element.

FIG. **4** illustrates the received power over distance.

FIG. **5** illustrates the maximum transferable power over distance.

FIG. **6** illustrates the transfer efficiency over distance.

FIG. **7** illustrates the efficiency normalized to antenna diameter.

FIG. **8** illustrates an antenna measurement setup.

DETAILED DESCRIPTION

A basic embodiment is shown in FIG. **1**. A power transmitter assembly **100** receives power from a source, for example, an AC plug **101**. A frequency generator **104** is used to couple the energy to an antenna **110**, here a resonant antenna. The antenna **110** includes an inductive loop **111**, which is inductively coupled to a high Q resonant antenna part **112**. The resonant antenna includes a number N of coil loops **113** each loop having a radius R_A. A capacitor **114**, here shown as a variable capacitor, is in series with the coil **113**, forming a resonant loop. In the embodiment, the capacitor is a totally separate structure from the coil, but in certain embodiments, the self capacitance of the wire forming the coil can form the capacitance **114**.

The frequency generator **104** can be preferably tuned to the antenna **110**, and also selected for FCC compliance.

This embodiment uses a multidirectional antenna. **115** shows the energy as output in all directions. The antenna **100** is non-radiative, in the sense that much of the output of the antenna is not electromagnetic radiating energy, but is rather a magnetic field which is more stationary. Of course, part of the output from the antenna will in fact radiate.

Another embodiment may use a radiative antenna.

A receiver **150** includes a receiving antenna **155** placed a distance D away from the transmitting antenna **110**. The receiving antenna is similarly a high Q resonant coil antenna **151** having a coil part and capacitor, coupled to an inductive coupling loop **152**. The output of the coupling loop **152** is rectified in a rectifier **160**, and applied to a load. That load can be any type of load, for example a resistive load such as a light bulb, or an electronic device load such as an electrical appliance, a computer, a rechargeable battery, a music player or an automobile.

The energy can be transferred through either electrical field coupling or magnetic field coupling, although magnetic field coupling is predominantly described herein as an embodiment.

Electrical field coupling provides an inductively loaded electrical dipole that is an open capacitor or dielectric disk. Extraneous objects may provide a relatively strong influence on electric field coupling. Magnetic field coupling may be preferred, since extraneous objects in a magnetic field have the same magnetic properties as "empty" space.

The embodiment describes a magnetic field coupling using a capacitively loaded magnetic dipole. Such a dipole is formed of a wire loop forming at least one loop or turn of a coil, in series with a capacitor that electrically loads the antenna into a resonant state.

Our previous applications have described the advantages of single turn loops being used as the resonators. The present application describes how two different single turn loops can be used to produce significantly increased range in a wireless power transmission system.

In the embodiment, a test was carried out using the test setup shown in FIG. **8**. The transmitter **801** is a 45 cm diameter, 6 mm wire loop. The receiver is formed of a 40 cm×30 mm copper loop. It is noted that usually the receiver antenna should be smaller for purposes of packaging. As explained further herein, the test results are wholly reciprocal, thereby obviating any difference in received power.

The antenna **802** has a resonance frequency about 20 kHz lower than the antenna **801**. A tuning loop **803** is used to shift

the antenna of the tuning loop **802** to match the resonance of the transmitting receiver antenna **801**. The signal is coupled to coupling loop **804** and to load **805**.

FIG. **2** illustrates a transmitter block diagram including amplifier coupling loop and antennas. In operation, an RF generator is used to create a 13.56 MHz continuous wave signal. An amplifier **205** provides a 50 dB amplification to produce the maximum power output of 25 W at **206**. For purposes of the test, an analog power meter is used. The power is provided to a coupling loop **220** which is adjacent to and wirelessly coupled to the antenna **801** which is formed of a loop **250**; and a capacitor **252** that brings the loop to resonance at 13.56 MHz.

FIG. **3** shows the receiver, including the receive loop **102** formed of an inductive loop **350** and capacitor **352**, the tuning loop **803**, and the coupling loop **320** which receives the power. A digital power meter **330** tests the amount of power that is received after attenuation by a 20 dB attenuator.

The receive side resonator loop combined with tuning loop acts like a 1:1 transformer with a low but adjustable coupling factor. The coupling factor is the distance between the main loop and tuning loop. A tuning loop may be considered as a secondary that produces a short circuit. The short circuit reduces the overall inductance of the resonator by a small fraction depending on the coupling factor thus increasing its resonance frequency without substantially decreasing the quality factor. The receive loop **102** and the tuning loop **803** may be connected to a carriage **333**, which can move the two loops relative to one another. If a resonator which has a low inductance to capacitance ratio is used, it can be extremely effective.

FIG. **4** illustrates the received power over specified distances. According to this test, the distance was varied from 1.6 m to 4 m. Distances closer than 1.6 m were not measured, since the closer distances can cause detuning of the system. Hence, these values are interpolated, to avoid the detuning effects. Transition from near field into the far field occurs at about 3½ m at 13.56 MHz. This distance changes the preferred orientation from coaxial to coplanar, thereby affecting significantly the amount of power that can be received. FIG. **4** shows that at 3.5 m, the received power approaches 0 W because of this orientation variance.

At distances greater than 1.7 m, the calculated distance is closely related to the computed distance.

FIG. **5** illustrates the maximum transferable power. These antennas are highly linear, meaning that if the transmitter power is doubled, the receive power will also be doubled. The transmit loop is limited only by the voltage and current ratings of the capacitors; provided that there is sufficient cooling. The 30 mm copper loop uses a 200 pF capacitor with a limit of 9 kV peak and 100 amps carrying. That provides a transmit power of about 300 W.

Because the system is linear, FIG. **5** shows data point scale to a transmit power of 300 W. This shows that the existing system can transfer 67 W at a distance of 1.6 m. The maximum radiation exposure limits recommended by ICNIRP would be exceeded by these levels. The transfer efficiency, however, is shown in FIG. **6**, illustrating that the transfer efficiency is −15 dB for all distances less than 2½ m. FIG. **7** normalizes this distance to the antenna diameter. The tests performed by MIT are also shown in FIG. **7**.

Conclusions are as follows. Except for the region closest to the near field border and at close distances, the antennas are highly linear, and power can simply be doubled to double the received power.

The system can operate with a transmit power of 25 W and a transfer efficiency of 25% over a distance of 1.5 m. The system is extremely stable with respect to resonance frequency and Q factor. The system can also power up to 70 W at a distance of 1.5 m. Extrapolation to smaller distances can also be possible.

Although only a few embodiments have been disclosed in detail above, other embodiments are possible and the inventors intend these to be encompassed within this specification. The specification describes specific examples to accomplish~more general goal that may be accomplished in another way. This disclosure is intended to be exemplary, and the claims are intended to cover any modification or alternative which might be predictable to a person having ordinary skill in the art. For example, other sizes, materials and connections can be used. Although the coupling part of the antenna is shown as a single loop of wire, it should be understood that this coupling part can have multiple wire loops. Other embodiments may use similar principles of the embodiments and are equally applicable to primarily electrostatic and/or electrodynamic field coupling as well. In general, an electric field can be used in place of the magnetic field, as the primary coupling mechanism.

Also, the inventors intend that only those claims which use the-words "means for" are intended to be interpreted under 35 USC 112, sixth paragraph. Moreover, no limitations from the specification are intended to be read into any claims, unless those limitations are expressly included in the claims.

Where a specific numerical value is mentioned herein, it should be considered that the value may be increased or decreased by 20%, while still staying within the teachings of the present application, unless some different range is specifically mentioned. Where a specified logical sense is used, the opposite logical sense is also intended to be encompassed.

What is claimed is:

1. A wireless power transmission system, comprising:

a transmitting antenna configured to transmit power, via a magnetic field, to a receiving antenna to power a load; and

a tuning loop electrically isolated from the transmitting antenna and being movable to adjust a coupling between the transmitting antenna and the tuning loop.

2. The system of claim **1**, wherein the tuning loop is movable relative to the receiving antenna.

3. The system of claim **1**, wherein the tuning loop is configured to adjust the coupling based on its movement.

4. The system of claim **1**, wherein the receiving antenna is movable.

5. The system of claim **4**, wherein the transmitting antenna is configured to further adjust the coupling based on the movement of the receiving antenna.

6. The system of claim **1**, wherein the tuning loop is configured to substantially match a resonant frequency of the receiving antenna and a resonant frequency of the transmitting antenna.

7. The system of claim **6**, wherein the resonant frequency of the receiving antenna is lower than the resonant frequency of the transmitting antenna, and wherein the tuning loop is further configured to increase the resonant frequency of the receiving antenna to be substantially the same as the resonant frequency of the transmitting antenna.

8. The system of claim **1**, wherein the size of the tuning loop is less than that of the transmitting antenna.

9. A method of transmitting power, comprising:

transmitting power, via a magnetic field, from a transmitting antenna to a receiving antenna to power a load, the transmitting antenna electrically isolated from a tuning loop; and

moving the tuning loop to adjust a coupling between the transmitting antenna and the tuning loop.

10. The method of claim **9**, further comprising moving the receiving antenna to further adjust the coupling.

11. The method of claim **9**, further comprising moving the tuning loop relative to the receiving antenna.

12. The method of claim **9**, wherein the moving comprises substantially matching a resonant frequency of the receiving antenna and a resonant frequency of the transmitting antenna.

13. The method of claim **12**, wherein the resonant frequency of the receiving antenna is lower than the resonant frequency of the transmitting antenna, and wherein the moving further comprises increasing the resonant frequency of the receiving antenna to be substantially the same as the resonant frequency of the transmitting antenna.

14. A wireless power receiver, comprising:

a receiving antenna configured to receive power, via a magnetic field, from a transmitting antenna to power a load; and

a tuning loop being electrically isolated from the receiving antenna and being movable relative to the receiving antenna to adjust a coupling between the receiving antenna and the tuning loop.

15. The receiver of claim **14**, wherein the tuning loop is electrically isolated from the load.

16. The receiver of claim **14**, wherein the tuning loop is further configured to adjust the coupling based on a coupling factor between the receiving antenna and the tuning loop.

17. The receiver of claim **14**, further comprising a coupling loop configured to inductively receive the transmitted power from the receiving antenna and provide the received power to the load.

18. The receiver of claim **17**, wherein the size of the coupling loop is less than that of the receiving antenna.

19. The receiver of claim **17**, wherein the size of the coupling loop is substantially similar to that of the tuning loop.

20. The receiver of claim **14**, wherein the tuning loop at least partially overlaps a perimeter of the receiving antenna.

21. The receiver of claim **14**, further comprising a carriage connected between the receiving antenna and the tuning loop, the carriage being configured to move the receiving antenna and the tuning loop.

* * * * *