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A novel resonant inductive magnetic coupling wireless charger with TiO_2 compound interlayer

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A nonradiative energy transformer exploiting TiO_2 nano-powder and $(C_4H_6O_2)_x$ latex as a combined interlayer is proposed. The transformer works on 'strong coupling' between two coils (i.e., resonators), which are physically separated from each other by distances that are longer than the characteristic sizes of each resonator, to realize efficient wireless energy transfer. Nonradiative energy transfer between the two resonators is facilitated through the coupling of their resonant-field evanescent tails. Finite element analysis and experiments have been carried out to facilitate quantitative comparison. The efficiency of the proposed system is 70.6% at 5 cm and 26.3% at 15 cm at an operating frequency of 1.74 MHz. When compared with typical magnetic inductive coupling energy transmission devices with low dielectric constants, the efficiency of the proposed system is much higher. © *2011 American Institute of Physics*. [doi:10.1063/1.3536558]

Since Witricity (short form of resonant inductive magnetic wireless electricity which is a new wireless powering technique based on strongly coupled resonance[1]) was reported by a Massachusetts Institute of Technology research team in 2007, it has attracted a great deal of attentions. Instead of spreading radiative and lossy electromagnetic fields to the environment,[2–5] the source resonator fills the surrounding with lossless nonradiative magnetic fields oscillating in the MHz range for this technology. Compared with conductive charging, the primary merit of Witricity is that it can work with no exposed conductors, no interlocks and no connectors, allowing it to work with far lower risks of electric shock hazards. Detailed theoretical and numerical analyses reveal that Witricity is efficient and practical for mid-range wireless energy exchange.[6]

Hitherto, Witricity works at the MHz range and some undesirable problems become inevitable. First is that devices working at MHz frequency are more expensive than their low frequency counterparts. Circuits working at MHz are sometimes unstable when the digital circuits are starting up, as the noise generated by the digital circuit affects the normal actions of circuits operating at frequencies in the MHz range. Also, realization of inductive charging at the MHz frequency range in electrical devices often results in relatively more radiation and heat generation.

A novel resonant inductive magnetic coupling wireless (RMCT) charger with TiO_2 nano-powder and $(C_4H_6O_2)_x$ latex combined interlayer is proposed. Finite element analysis (FEA) and corresponding experiments have also been carried out to showcase the performance of the charger.

Titanium exists in a number of crystalline forms and the most common two are anatase and rutile. Pure titanium dioxide does not occur in nature but can be derived from ilmenite or leuxocene ores. Figure 1 shows the photos of rutile TiO_2 nano-powder material and its structural model. Because of the relatively poor mechanical properties, applications using sintered titania are limited.

The resonant frequency of the proposed RMCT and other resonant magnetic coupling wireless systems, also known as eigenfrequency, is determined by the following equations:

$$\omega_{\mathrm{trans}} = 1/\sqrt{L_{\mathrm{trans}}C_{\mathrm{trans}}} \tag{1}$$

$$\omega_{\mathrm{rec}} = 1/\sqrt{L_{\mathrm{rec}}C_{\mathrm{rec}}} \tag{2}$$

where; L_{trans} and C_{trans} are, respectively, the equivalent inductance and equivalent capacitance of the transmitter coil, L_{rec} and C_{rec} are, respectively, the equivalent inductance and equivalent capacitance, of the receiver coil.

The resonant frequency will decrease if the capacitance goes up. Noting that capacitance is linearly proportional to its permittivity constant, it is important to find a good dielectric with high permittivity. In the novel transformer, a new compound material consisting of TiO_2 nano-powder and $(C_4H_6O_2)_x$ latex, is proposed as the dielectric material. Since the compound is bonded with high-purity TiO_2 nano-powder, it has a high permittivity and this is needed in order to lower the eigenfrequency of the systems. The interlayer is fabricated by fixing the TiO_2 compound on eight copper tapes through molds extruder and hot press machine. That interlayer has a high relative permittivity in the range of 12

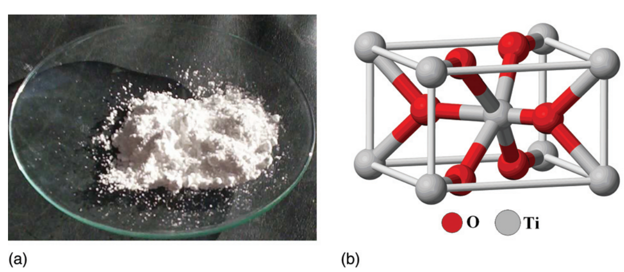

FIG. 1. (Color online) (a) TiO_2 nano-powder material; (b) The structural model of rutile TiO_2.

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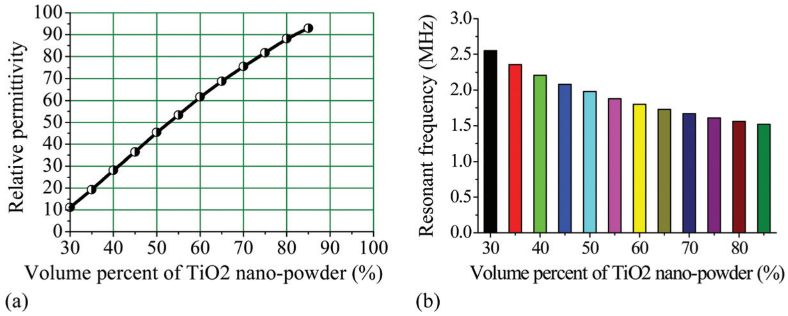

FIG. 2. (Color online) (a) Relative permittivity of the combined materials; (b) Coils' resonant frequency of the proposed RMCT charger.

to 93 as shown in Fig. 2(a). Thus the capacitance for both the transmitter and the receiver coils are higher than capacitor using normal dielectrics. It can also be seen that the relative permittivity becomes lower when the concentration of the TiO_2 nano-powder is lower.

The proposed RMCT charger consists of a source loop, a transmitter resonant cell, a receiver resonant cell, and a device loop. There is an insulation layer, which is one of the proposed interlayers, to separate the coil and the four copper tapes for both the transmitter and the receiver. Coils for the transmitter and for the receiver have the same structure.

The relative permittivity of the interlayer selected in this paper is 76, which represents a compromise on mechanical properties and the value of relative permittivity. Both cells are made of copper tapes with a thickness of 40 μm. The inductance is offered by the copper tapes and the capacitance is provided by the coil tape layer and the strip layer together. Figure 2(b) shows that as the volumetric percentage of TiO_2 increases, the relative permittivity of the capacitance increases to result in a decrease in resonance frequency, if other parameters remain the same.

In order to optimize the performance of the proposed RMCT charger, an interpolative FEA modeling method is introduced in this paper. In the proposed RMCT charger, it has a relatively high electric field when compared with those of the traditional magnetic coupling devices at the resonant frequency of 1.67 MHz at which efficient energy transfer is expected to occur. At that point, most of the energy is transferred from the primary coil to the secondary coil. Fig. 3 shows the receiver output voltage (with a distance of 4 cm) versus frequencies for the RMCT charger, the Witricity charger and the traditional one. In the figure the frequency is varied between 0.01 MHz to 10 MHz. It can be seen that the induced voltage of the RMCT charger has a peak value, i.e. 16.46 V at a frequency of about 1.67 MHz and that of the Witricity charger is 18.23 V at a frequency of about 4.8 MHz. Voltages of the traditional magnetic coupling model only increase slightly when the frequency rises.

A noticeable characteristic of the RMCT charger that needs to be considered is the wider band of near resonant fields, from 0.8 MHz to 3.5 MHz. This characteristic is helpful, in some cases, in the design of resonant wireless charger working at limited resonant frequencies. It should also be noted that the Witricity one has a narrow frequency band of about 0.9 MHz, from 4.5 MHz to 5.4 MHz. This narrowband may cause system failure when the frequencies fluctuate.

Although the output voltages are relatively high at the beginning for all chargers, Fig. 4 shows the decreasing trend becomes much more noticeable for the traditional magnetic coupling model as the physical distance increases.

For the RMCT charger, the peak value of the receiver output voltages is slightly lower than that of the Witricity charger. This characteristic is quite attractive when considering the lower operating resonant frequency and the wider band near the resonant fields of the proposed system. Indeed, the designed resonant frequency could be as low at about 600 kHz if the thickness of TiO_2 combined interlayer is the same as that of the non-TiO_2 interlayer, but currently it is difficult to fabricate due to the facility limitation of the mechanical process.

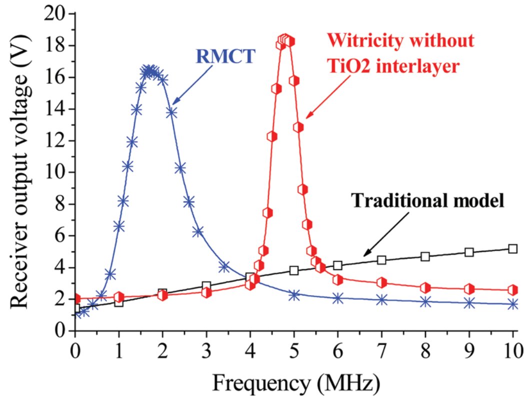

FIG. 3. (Color online) Receiver output voltage vs frequency with a distance of 5 cm.

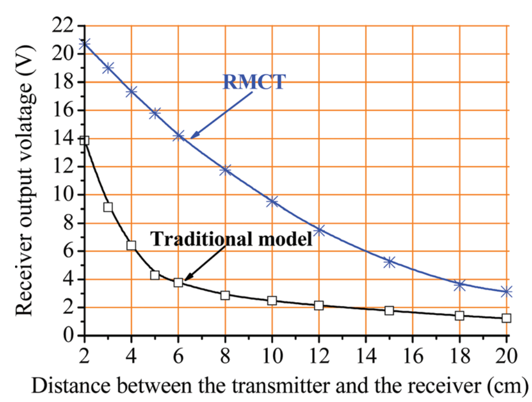

FIG. 4. (Color online) Receiver output voltage vs distance at the frequency of 1.67 MHz.

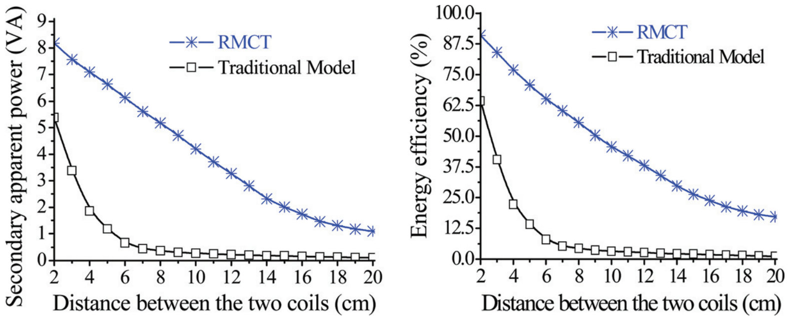

FIG. 5. (Color online) (a) Secondary apparent power versus distance; (b) Efficiency comparison between the RMCT and the traditional magnetic coupling charger.

Based on the design experience of Witricity chargers, a RMCT charger is prepared using laboratory facility to fabricate transmitter and receiver of equal size. The material of the interlayer is produced from 70 vol. % of TiO_2, and 30 vol. % of $(C_4H_6O_2)_x$ latex based on the theoretical analysis and FEM simulation results. The middle layer, made from polymers, serves as a skeleton framework and the proposed TiO_2 combined interlayers provide the electrical isolation between each coil and the four lower copper tapes. The magnetic field is generated by the upper layer which is fabricated by affixing spiral-type conductors consisting of 6 square turns with a separation distance of 1.2 mm between the conductors. The lower copper tapes consist of several conductive strips in parallel with the radial direction of the cell, forming capacitors with the overlapped parts of the upper coil.

The experimental setup comprises of a function generator together with a power amplifier that outputs a MHz sinewave to the source loop. A 0.1 Ω resistor is used as a load and the consumed power is calculated based on the measured voltage across the resistor. A second 0.1 Ω resistor is connected in series with the source to measure the power supplied. The measured resonant frequencies for the transmitter and the receiver are, respectively, 1.74 MHz and 1.73 MHz and their corresponding Q factors are 87.2 and 85.5. By checking the voltage across the 0.1 Ω resistor at 1.74 MHz, the source current and therefore the power supplied are measured.

The trends of the secondary apparent power for the three chargers as a function of distances are shown in Fig. 5(a). Though voltages for all of them decrease when the distances increase, the apparent powers of the proposed RMCT charger and Witricity partner are much higher than that of the traditional model, especially in the distance range of 2 cm to 10 cm. But the resonant frequency of the RMCT charger is about 1.74 MHZ, which is only one third of that of the Witricity. In general, the secondary apparent power decreases very rapidly as the distance increases in traditional inductive magnetic coupling model.

It can be seen from Fig. 5(b) that the efficiency of RMCT charger is 70.6% at 5 cm and 26.3% at 15 cm. If the traditional inductive coupling method is used, the physical separation distance must be limited to less than 1 cm and 4 cm, respectively, in order to realize similar efficiencies. The studies indicate that RMCT is a suitable and practical technology for providing wireless power to charge a wealth of electrical devices, especially over relative large distance and slightly variable frequencies.

The measured results indicate that when the proposed charger operates at the resonant frequency, which is much lower than that of the Witricity model without TiO_2 combined interlayers, satisfactory performances is realized.

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