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Abstract

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Experiments on wireless power transfer with metamaterials

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In this letter, we propose the use of metamaterials to enhance the evanescent wave coupling and improve the transfer efficiency of a wireless power transfer system based on coupled resonators. A magnetic metamaterial is designed and built for a wireless power transfer system. We show with measurement results that the power transfer efficiency of the system can be improved significantly by the metamaterial. We also show that the fabricated system can be used to transfer power wirelessly to a 40 W light bulb. © *2011 American Institute of Physics*. [doi:10.1063/1.3601927]

Recently, the research and development of wireless power transfer (WPT) technologies is expanding rapidly, due largely to the increasing demand of wireless charging for portable electronic devices and electric vehicles.[1–4] Depending on different application requirements, different technologies are being developed. Microwave power transmission method is used for long distance (thousands of kilometers) and high power (megawatts to gigawatts) transmission, and primarily developed for space solar power satellites.[5] For short range applications where the transfer distance varies from a few centimeters to a few meters, technologies based on near-field coupling are being developed. The major technologies are inductive coupling, and more recently, resonant coupling. Compared to inductive coupling, resonant coupling is more flexible in terms of tolerance to device misalignment and transfer distance.

Resonant coupling method uses resonant transmitter and receiver, which are equivalently LC resonators, for efficient WPT. The transmitter and receiver are tuned to have the same or similar resonant frequency. By working on resonance, efficient WPT can be achieved when the transmitter and receiver have a small coupling coefficient, or when the transmitter and receiver are a distance away from each other. The basic principle has been discovered many years ago; however, the research and application has been quite limited. In previous studies, the required transfer distance is just a few centimeter and the required power level is relatively low.[6–8] In 2007, WPT over a distance of up to 2 m, with moderate efficiency and power level is achieved.[1] Since then, the technology has been more widely studied and adapted to various applications.

Metamaterials are artificial materials composed of engineered structures and have been shown to possess peculiar electromagnetic properties not seen in natural materials, such as negative-refractive index and evanescent wave amplification (for a review, see Ref. 9). The effective parameters of metamaterials are determined by the engineered structures and almost arbitrary parameters can be achieved by carefully designing these structures. In 2000, Pendry showed that a negative-index metamaterial slab can refocus propagating waves and amplify evanescent waves, thus can be used to construct a "perfect lens," for imaging with theoretically unlimited resolution.[12] The properties of metamaterials, especially evanescent wave amplification, are of interest to WPT too because the resonant coupling is essentially coupling of evanescent waves. At resonance, electromagnetic fields are mostly confined inside the resonators. Outside the resonators, fields decay evanescently and do not carry away energy unless coupled to the tail of the evanescent wave of another resonator. With a metamaterial slab, the amplitude of evanescent waves can be enhanced and the coupling coefficient of two resonators can be improved. It has been proposed and shown with numerical simulation results that negative-index metamaterials can be used to enhance the evanescent near-field and eventually improve the power transfer efficiency in WPT systems based on resonant coupling.[10] Very recently, a theoretical analysis on metamaterials to enhance the coupling between magnetic dipoles for WPT has been published.[11] Here we present our work on the implementation of a magnetic metamaterial in a WPT system. We show experimentally that the power transfer efficiency can be improved significantly by a metamaterial. With the fabricated metamaterial, 40 W power can be transferred wirelessly to a light bulb.

In general, a negative-index metamaterial requires both effective permittivity ϵ and permeability μ to be negative. However, in deep subwavelength limit, the magnetic field and electric field decouple, and only one parameter is required to be negative to achieve evanescent wave amplification.[12] This simplifies the design and fabrication process of metamaterials. The same concept can be adapted to a WPT system based on coupling of evanescent near-fields. In most resonant WPT systems, the system size is much smaller than working wavelength, which falls in the deep subwavelength limit. Moreover, most resonant WPT systems use primarily magnetic coupling for safety concerns. It is thus sufficient to use magnetic metamaterials, which has a negative effective μ but a positive effective ϵ, instead of negative-index metamaterials, for evanescent wave amplification and efficiency improvement. Metamaterials with negative μ have previously been used in magnetic resonance imaging.[13]

Next we start to design and fabricate a magnetic metamaterial and a WPT system to prove the concept. We plan to build an experiment system working at the ISM band

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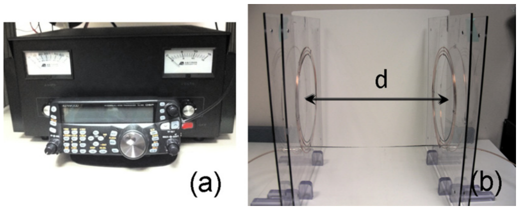

FIG. 1. (Color online) (a) The HF transceiver with power amplifier, and (b) the fabricated resonant coils and loop antennas.

centered at 27.12 MHz. A high-frequency transceiver with power amplifier [shown in Fig. 1(a)] is used to provide frequency-tunable power of up to 200 W. The transceiver is connected to a loop antenna, which is inductively coupled to a resonant coil; the coil is resonantly coupled to a second resonant coil on the receiver side, which is again inductively coupled to a second loop antenna connected to a resistive load. As shown in Fig. 1(b), the loop antennas are made of 12 gauge copper wires, and has a radius of 20 cm. The two resonators are planar spirals made by 12 G copper wires. The spirals have three turns with outer radius 20 cm and spacing between neighboring turns 1.5 cm. Each of the loop antennas and spiral resonators are attached to a polyethylene terephthalate sheet, respectively, to be mechanically stable.

There are a few challenges in the design of metamaterial for WPT system. Although a metamaterial can enhance the coupling between transmitter and receiver, the metamaterial has to be low-loss. This is because the metamaterial introduces extra loss in the system, which has to be minimized. On the other hand, the free-space wavelength at the working frequency is over 11 m, thus the unit cell size of metamaterial has to be deep-subwavelength. Plus, most current metamaterials are designed for communications, where the power level is usually on the order of milliwatts; the metamaterial for our WPT however, needs to be capable of handling 40 W power or more.

Considering that the metamaterial needs to be compact in size, low in loss, and easy for fabrication and reproduce, we choose double-side square spiral as the design of unit cell for the magnetic metamaterial. In this design, the metallic structures on two sides of a dielectric substrate are electrically connected by a metallic via. The inductance of the resonator is provided by the metallic structures; the capacitance is provided mainly by the effective planar capacitor formed by the two metallic surfaces and the dielectric spacing. Larger effective inductance and capacitance can be generated from this design compared with conventional split-ring resonators, and very compact size can be achieved. The spiral on each side has three turns, with copper strip width of 3 mm and spacing 1 mm between neighboring strips. The width of the structure is 61 mm, and the unit cell width is 65 mm. The compact design allows strong coupling between neighboring cells. The metallic layers are 70 μm thick copper separated by a layer of Rogers RO4003C circuit board of thickness 1.5 mm. A magnetic metamaterial is made by arranging the double-side spirals in cubic lattice. Numerical simulation shows that the resonant frequency of the spirals is at 24 MHz. In the frequency region above the resonant frequency, a metamaterial slab composed of the spirals has a negative effective μ. Using a retrieval procedure proposed in Ref. 16, the effective permeability of the metamaterial slab can be calculated. At 27 MHz, the effective permeability of the metamaterial is around -1. It is worth to mention that, metamaterial with a larger negative effective μ can also achieve evanescent wave amplification. However, when the absolute value of the negative μ is larger, the frequency is closer to the resonant frequency of the composing spirals, causing larger loss in metamaterials, which is not good for power transfer efficiency improvement. This metamaterial design is very compact in size. In terms of wavelength to unit cell ratio, the current design is about 170 while conventional split-ring resonator is around 10.

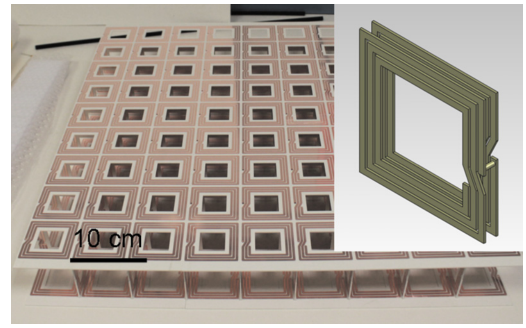

FIG. 2. (Color online) The fabricated metamaterial. The structure of the unit cell is shown in the inset.

The metamaterial structures are fabricated with standard procedure for printed circuit boards, which is very easy to reproduce. The structures are then assembled in cubic lattice, as shown in Fig. 2. The fabricated metamaterial slab is one cell thick and has 9×9 cells in plane, with finished size 58.5 cm$\times$58.5 cm.

The overall efficiency of the system is measured by a network analyzer (Agilent N5230A). The two loop antennas are connected to two ports of the network analyzer, and S-parameters between the two ports are measured. For each measurement, the distances between loop antennas and associated coil resonators are tuned so that the system is properly matched to the 50 Ω ports of the network analyzer for optimal power transfer.[14,15] When a metamaterial slab is added in the system, the optimal condition is modified. The distances between loop antennas and associated coil resonators are readjusted so that the optimal matching for power transfer is resettled. The reflection parameters S_{11} and S_{22} around resonance are both small (around -20 dB), and the changes due to the introduction of metamaterial are negligible. Thus the power transfer efficiency can be estimated by $|S_{21}|^2$. Figure 3 shows the measurement results when the distance between two spiral resonators is $d=50$ cm. When there is no metamaterial in the system, the efficiency as a function of frequency is shown by curve (a) in Fig. 3. A peak is seen at the resonant frequency of the spiral resonators. The maximum efficiency is about 17%. When the metamaterial slab is inserted in the middle of the two spiral resonators, the measured efficiency is plotted as curve (b) in Fig. 3. The peak efficiency in this case is about 35%, which is twice of the original system. The position of peak efficiency is shifted due to the mutual coupling between the metamaterial and the spirals and antennas.

Considering that the magnetic field in the WPT system is mainly in the direction along the axis of the spirals, it is sufficient to use a metamaterial having negative magnetic response in this direction, instead of a three-dimensional (3D) metamaterial. This is considered as an anisotropic metamaterial and can be constructed by removing the inter-

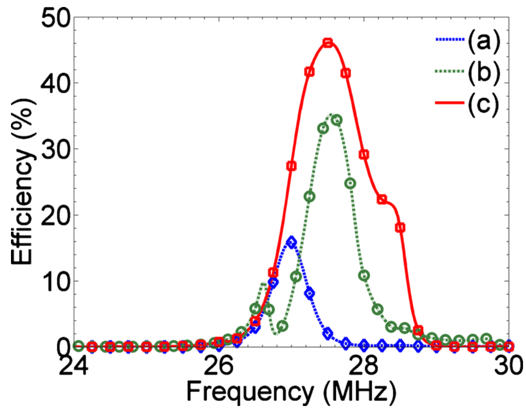

FIG. 3. (Color online) The measured power transfer efficiency of different system configurations: (a) original system without metamaterial, (b) with 3D metamaterial, and (c) with anisotropic metamaterial.

locked structures of the metamaterial slab and leaving only the two surface, as shown in Fig. 4. The two surfaces are separated by a distance $t=2$ cm, which is optimized to achieve highest power transfer efficiency of the system. The measured efficiency of the WPT system with the anisotropic metamaterial is shown by curve (c) in Fig. 3. It is shown that the peak efficiency is about 47%, significantly higher than the other two curves. This is because the loss is lower in the planar metamaterial due to the removal of unnecessary structures. In this design, evanescent wave amplification is achieved due to the excitation of surface waves on the two surfaces of the anisotropic metamaterial. Similar structures have been used for near-field imaging applications previously.[17]

Next we use the system to transfer power wirelessly to a 40 W light bulb. As shown in Fig. 5, the light bulb is connected to the receiving loop antenna. The power is provided by the high-frequency transceiver to a transmitting loop antenna, and the input power is set to 80 W. For optimal matching, the distances between loop antennas and associated spiral resonators are adjusted for each case. When the metamaterial slab is introduced, the matching process is repeated to minimize the affect of mismatch. The brightness of

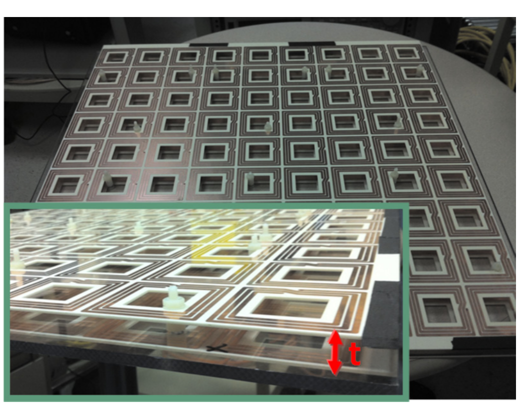

FIG. 4. (Color online) A picture of the planar metamaterial. Inset shows the details, with t the spacing between two planes.

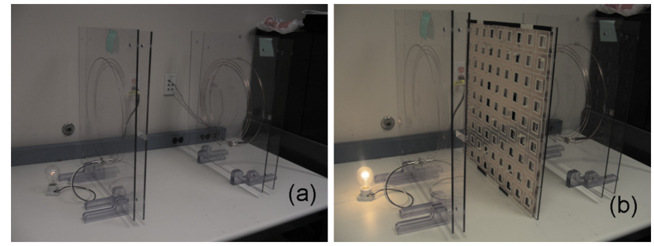

FIG. 5. (Color online) WPT experiment to a 40 W light bulb. Pictures are taken with same settings. (a) Original system and (b) system with anisotropic metamaterial.

light bulb thus reflects the amount of power transferred. The two pictures in Fig. 5 are taken in the laboratory at same settings. Figure 5(a) shows the system without metamaterial, where the light bulb barely glows; Fig. 5(b) shows the system with the anisotropic metamaterial, and the light bulb is much brighter. This shows that the efficiency is indeed improved significantly by the metamaterial. Moreover, the metamaterial is capable of handling the high power level.

In conclusion, we proposed the use of metamaterials for WPT. A metamaterial with very compact size and very low loss has been designed and fabricated. Experiments show power transfer efficiency of a WPT system can be improved from 17% to 47% by the metamaterial. This work shows that, other than communication and other low-power applications, metamaterials can also be used in high-power energy applications.

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