MITSUBISHI ELECTRIC RESEARCH LABORATORIES
http://www.merl.com

Metamaterials for Wireless Power Transfer

Wang, B.; Teo, K.H.

TR2012-010 March 2012

Abstract

Recently, metamaterials have been developed for wireless power transfer applications. It has been shown that the near-field electromagnetic coupling between two resonant coils can be enhanced by a slab of metamaterial. With the assist of the metamaterial, the efficiency of wireless power transfer between the resonant coils can be greatly improved. In this paper, recent progress in this area will be presented: theoretical development of enhanced coil coupling with metamaterial will be briefly discussed; the design of metamaterial slabs for near-field wireless power transfer will be shown; recent experimental results on wireless power transfer efficiency improvement with metamaterial will also be presented.

IEEE International Workshop on Antenna Technology (iWAT)

Metamaterials for Wireless Power Transfer

Bingnan Wang*(1), and Koon Hoo Teo(1)

(1) Mitsubishi Electric Research Laboratories, 201 Broadway, Cambridge, MA 02139
Email:bwang@merl.com

ABSTRACT: Recently, metamaterials have been developed for wireless power transfer applications. It has been shown that the near-field electromagnetic coupling between two resonant coils can be enhanced by a slab of metamaterial. With the assist of the metamaterial, the efficiency of wireless power transfer between the resonant coils can be greatly improved. In this paper, recent progress in this area will be presented: theoretical development of enhanced coil coupling with metamaterial will be briefly discussed; the design of metamaterial slabs for near-field wireless power transfer will be shown; recent experimental results on wireless power transfer efficiency improvement with metamaterial will also be presented.

INTRODUCTION

Metamaterials, artificial materials composed of engineered structures, have been shown to possess peculiar electromagnetic properties not readily available in natural materials, such as negative-refractive index and evanescent wave amplification (For reviews, see [1-2]). Since the first experimental realization of metamaterials, various applications based on metamaterials have been proposed and realized, such as super-lens imaging devices [3], cloaking devices [4], novel antennas and other devices for communications [2]. Recently, metamaterials have found a new area of application in wireless power transfer (WPT), which is to transfer electric power wirelessly over a distance. It has been shown that power transfer efficiency can be greatly improved with the help of metamaterials [5-8].

The demand to cut the power cord and develop WPT technologies is rapidly increasing in recent years, largely due to the needs of wireless charging for emerging electronic devices such as cell phones, tablets. Different WPT technologies are being developed, among which inductive coupling and resonant coupling are dominant. Both methods are based on mutual induction of transmitting and receiving coils. Inductive coupling requires high coupling coefficient (>0.9) to achieve efficient power transfer. On the other hand, resonant coupling method can achieve efficient power transfer with much smaller coupling coefficient (0.2 or smaller), thus allows longer distance between transmitter and receiver, and is more tolerable to misalignment. Although investigated by Tesla over a century ago, it was until recently that this technology got picked up and improved. In an experiment by MIT [9], 40% power transfer efficiency is achieved at a distance of 2 m. However, the efficiency of WPT system based on near-field resonant coupling drops quickly with increasing distance.

In this paper, we will show how metamaterials can be applied to near-field WPT systems for coupling enhancement and efficiency improvement. Recent theoretical and experimental developments will be presented and discussed.

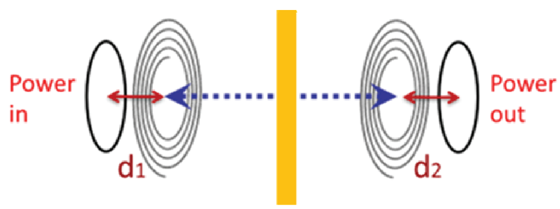
SUPERLENS FOR WPT

In 2000, Pendry showed that a negative-index metamaterial slab can be used as a “perfect lens” with super-resolution [10]. With such a lens, both far-field propagating waves and near-field evanescent waves can be restored at image: propagating waves are negatively refracted and refocused; evanescent waves which are decaying in free space are amplified in the lens. The evanescent wave amplification property is of great interest to WPT, as power is transferred via coupling of near-field evanescent waves of two coils. In Ref. [5], simulation results show that a metamaterial slab with negative refractive index can be used to enhance the near-field evanescent waves, so that the coupling between transmitting and receiving coils can be increased, and the power transfer efficiency of the WPT system can be improved. In Ref. [7], the coupling of two magnetic dipoles with a metamaterial lens is studied theoretically, and is shown to be enhanced with the metamaterial. With reasonable loss tangent, the system can still achieve power transfer efficiency improvement with a metamaterial slab.

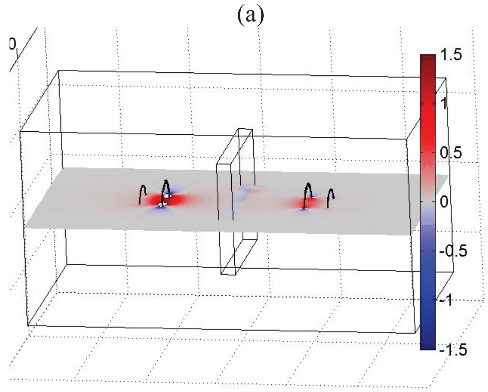
In general the device size and transfer distance of a WPT system are both much smaller than the wavelength at working frequency, which means the system is in deep sub-wavelength limit. Also magnetic field and electric field decouple at near-field, and WPT is realized via coupling of near-field magnetic field. In this case, the "perfect lens" can be realized with simplified conditions. Instead of having "double-negative" parameters of ε and μ, only "single-negative" of μ is required [10]. This makes the metamaterial much easier to design and fabricate. Plus, power loss in metamaterials can be better controlled with the simplified condition of single-negative metamaterials. In [6] and [8], μ-negative metamaterial slabs are developed for WPT.

EXPERIMENT REALIZATIONS

Fig. 1(a) shows the basic components in a WPT system. A non-resonant coil is used to couple energy to a resonant coil, which is coupled to a second resonant coil for power transfer, another non-resonant coil is used to pick up power and deliver it to load. A metamaterial slab is inserted in the middle of two resonators and serves a near-field lens. Fig. 1(b) shows a magnetic field distribution of such a system with a μ-negative metamaterial slab, which is obtained by numerical simulation in COMSOL. Strong fields are localized at the two resonant coils and decay rapidly away from these coils. At the metamaterial slab, the evanescent field is amplified, thus the coupling between coils is enhanced. Simulation results also show power transfer efficiency improvement with the metamaterial slab [5].



(a)



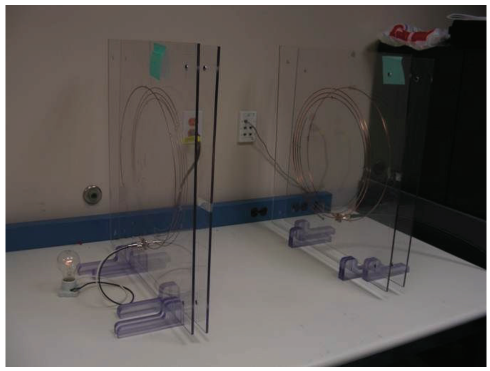
(b)

Fig. 1 (a) A WPT system includes a drive coil, two resonant coils, and a load coil. A metamaterial slab in the middle is used as lens. (b) Magnetic field distribution at resonant frequency, given by simulation in COMSOL.

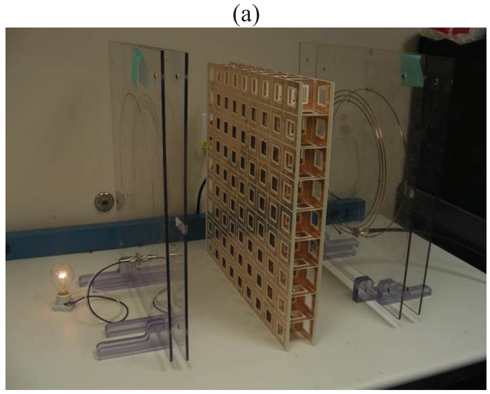
Loss is inevitable in metamaterials. Although metamaterials have been realized for near-field imaging for super-resolution, WPT needs even lower loss-tangent for the metamaterial, due to the power efficiency requirement. Moreover, the metamaterial needs to be able to handle relatively high power level. The WPT system is design to operate at 27MHz with system size one order smaller than wavelength, which requires a very compact metamaterial design.

Considering these requirements, a double-side square spiral is designed as unit cell of the magnetic metamaterial. In this design, the metallic structures on two sides of a dielectric substrate are electrically connected by 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 (65mm by 65mm) can be achieved. In terms of wavelength to unit cell ratio, the current design is about 170, while conventional split-ring resonator is around 10. The compact design allows strong coupling between neighbouring cells. A magnetic metamaterial is made by arranging the double-side spirals in cubic lattice and is shown in Fig. 2(b). Negative μ is achieved at the operating frequency with loss tangent lower than 0.1. 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 3D metamaterial. This is considered as an anisotropic metamaterial and can be constructed by removing the interlocked structures of the metamaterial slab, as shown in Fig. 2(c).

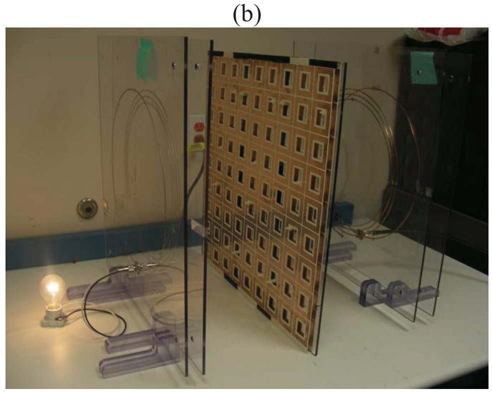
An experiment system is used to transfer power wirelessly to a 40W light bulb. As shown in Fig. 2, the light bulb is connected to the load coil. The power is provided by a HF transceiver to a drive coil, and the input power is set to 80W. Two spiral coils are used for resonant power transfer. For optimal 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 mismatch, so that the brightness of light bulb reflects the amount of power received. Fig. 2(a) shows the experiment without metamaterial, Fig. 2(b) shows the case with the 3d metamaterial slab, and Fig. 2(c) shows the case with the planar metamaterial slab. It is seen that efficiency is improved by metamaterials, while better result is achieved with the planar metamaterial, due to lower loss in the simplified structures.



(a)



(b)



(c)

Fig. 2 WPT experiment with different configurations: (a) system without metamaterial, (b) system with 3d metamaterial slab, and (c) system with planar metamaterial slab.

Power transfer efficiency is also measured by a network analyzer, with two port connected to the drive coil and the load coil. For each measurement, the distances between loop antennas and associated coil resonators are tuned so that the system is matched to the 50 Ohm ports of the network analyzer for optimal power transfer. The reflection parameters around resonance are both small and the changes due to the introduction of metamaterial are negligible. Thus the power transfer efficiency can be estimated by square of $|S_{21}|$. Fig. 3 shows the measurement results when the distance between two spiral resonators is 50 cm. When there is no metamaterial in the system, the maximum efficiency is 17%. With the 3d metamaterial slab, the peak efficiency is increased to 35%, while with the planar metamaterial, the peak efficiency is 47%. The results are consistent with the experiments shown in Fig. 2.

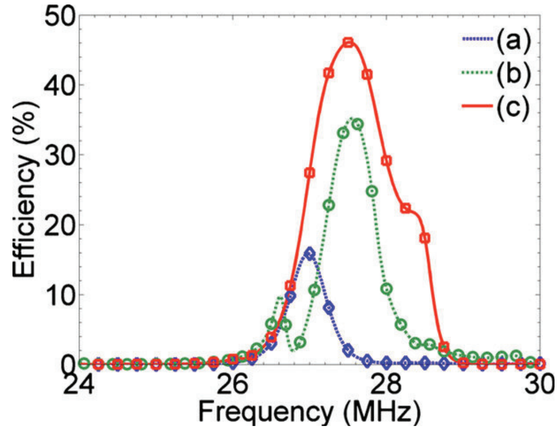


Fig. 3 Measured power transfer efficiency of different system configurations: (a) system without metamaterial, (b) system with 3d metamaterial slab, and (c) system with planar metamaterial slab.

CONCLUSIONS

In summary, we presented recent work on wireless power transfer by the assist of a metamaterial slab. Efficiency improvement with a metamaterial slab was revealed by theoretical and numerical studies and demonstrated by experiment measurements.

[1] D. R. Smith, J. B. Pendry, and M. C. K. Wiltshire, "Metamaterials and Negative Refractive Index," *Science*, 305, 788 (2004).

[2] N. Engheta, and R. W. Ziolkowski, "A positive future for double-negative metamaterials," *IEEE Trans. Microw. Theory Tech.* 53, 1535 (2005).

[3] N. Fang, H. Lee, C. Sun, and X. Zhang, "Sub-Diffraction-Limited Optical Imaging with a Silver Superlens," *Science*, 308, 534 (2005).

[4] D. Schurig, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, and D. R. Smith, "Metamaterial Electromagnetic Cloak at Microwave Frequencies," *Science*, 314, 977 (2006).

[5] B.Wang, T. Nishino, and K. H. Teo, "Wireless power transmission efficiency enhancement with metamaterials," *in Proceedings of Wireless Information Technology and Systems (ICWITS), 2010 IEEE International Conference* (Aug. 28 2010-Sept. 3 2010, Honolulu, HI)

[6] B. Wang, K. H. Teo, T. Nishino, W. Yerazunis, J. Barnwell, and J. Zhang, "Wireless Power Transfer with Metamaterials," *in Proceedings of European Conference on Antennas and Propagation (EuCAP 2011)* (April 11–15 2011, Rome, Italy)

[7] Y. Urzhumov and D. R. Smith, "Metamaterial-enhanced coupling between magnetic dipoles for efficient wireless power transfer," *Phys. Rev. B* 83, 205114 (2011)

[8] B. Wang, K. H. Teo, T. Nishino, W. Yerazunis, J. Barnwell and J. Zhang, "Experiments on wireless power transfer with metamaterials," *Appl. Phys. Lett.* 98, 254101 (2011)

[9] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher and M. Soljiacic, "Wireless power transfer via strongly coupled magnetic resonances," *Science*, 317, 83 (2007)

[10] J. B. Pendry, "Negative refraction makes a perfect lens," *Phys. Rev. Lett.* 85, 3966 (2000)