Numerical Analysis on Efficient Evanescent Resonant Coupling Wireless Power transmission System

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1. Introduction

Wireless power transmission is of interest again because of its potential application to charge laptops, cellphones, household robots, MP3 players and other portable equipments without cords [1] [2]. A team from MIT has experimentally demonstrated efficient evanescent resonant coupling power transmission by using two strongly coupled helical coils [1]. Comparing with the magnetic induction method [3], the evanescent resonant coupling method can transmit the energy for longer distance. Comparing with the radiation mode method which was proposed by Nicoka Tesla, the evanescent resonant coupling method is more efficient without wasting a vast majority energy due to omni-directional antennas. Directive radiation modes, using lasers or highly directional antennas, can be efficiently used for energy transmission,even for long distances, but require existence of uninterruptible line-of-sight and a complicated tracking system in the case of mobile objects.

In [4], the resonance width and the coupling coefficient, which are based on the coupled-mode theory and calculated by FDTD method, are used for investigating the power transmission efficiency of two dielectric disks and two capacitive loaded conducting-wire loops resonant coupling, showing the applicability of the transmission systems even in the presence of extraneous environmental objects, but the analysis results are difficult to be used to fine-tune the resonant frequency efficiently in order to obtain the optimum transmission efficiency.

In this paper, like antenna transmitting and receiving system in radiation mode, the power transmission efficiency is directly defined as the ratio of the receiving power at the receiving element and the input power at the source element and calculated by the full wave solver. A more practical wireless transmission system consisting of a larger rectangular wire loop and a small square wire loop with a parasitic square helical coil is proposed. The larger rectangular wire loop is used as the source element which can be built-in the office room wall, while the small rectangular wire loop with a parasitic helical coil is used as receiving element which can be built-in a mobile personal computer. The MoM is selected as the full wave solver in our analysis. Along with the transmission efficiency, the input impedance of transmitting element and receiving element are also investigated to seek a technique to tune the resonance frequency, further to obtain the optimum transmission efficiency. The effects of the relative position of the receiving element and source element, the number more than one receiving element and the non-resonant object such as human body will also be investigated in this paper.

2. Wireless Power transmission System

A schematic model of wireless power transmission system is proposed as shown in Fig.1. Rectangular loop S with the side length of s_a and s_b is linked to the driving circuit. s_a and s_b are set to be 6m and 2m, respectively. The size of the Loop S can be adjusted to meet the size of the office room where the wireless power transmission system is applied. A square loop D with side length of D_a is attached to a load, usually built-in a mobile receiving terminal to charge the mobile receiving terminal. Here, D_a is set to be 0.3m, which can be built in a mobile personal computer. Also, the size of receiving element can be adjustable to compromise with the practical mobile terminal size. The resonant frequency tuning and matching circuit for the receiving element is realized by using a parasitic square helical C. The side length , the pitch and the turn number of the helical C are set to be 0.3m, 0.02m, 5, respectively. The radius of the cross section for all wires including loop S, loop D and helical C is set to be 2mm.

3. Power transmission Efficiency

The power transmission efficiency for a wireless power transmission system is a critical parameter, which is directly defined in this paper by

$$\eta = P_D/P_S, \tag{1}$$

where P_S and P_D are the driving power of loop S at excitation port and receiving power at the load port of loop D, respectively. Both two powers are calculated by using full wave solver FEKO which is based on the MoM. In MoM process, the driving power at transmitting element can be obtained by the current at the excitation port if the excitation voltage at the feed point is supposed to be 1V, that is

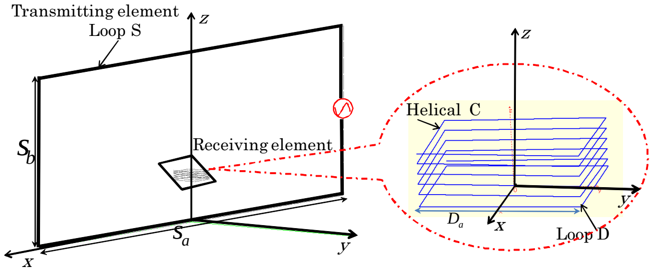

Figure 1: A schematic model of wireless power transmission system

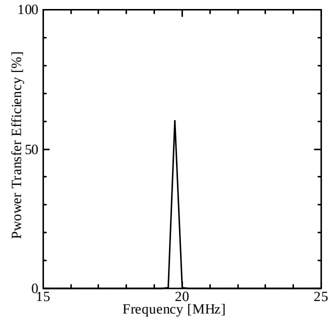

Figure 2: Power transmission efficiency as a function of frequency

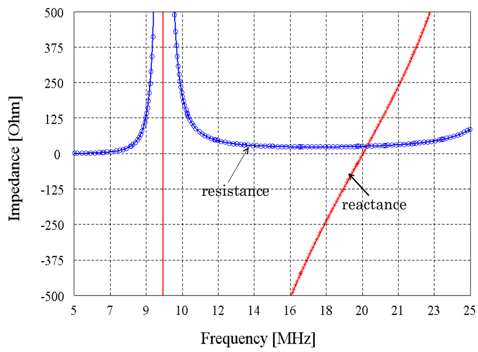

Figure 3: Input impedance of loop S

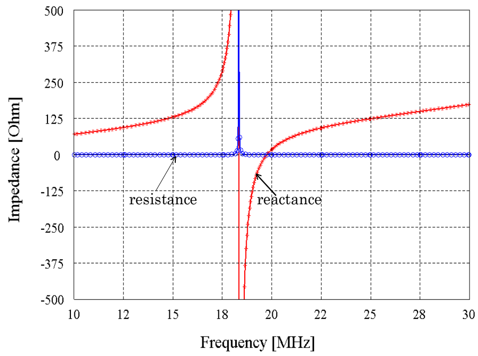

Figure 4: Input impedance of loop D with parasitic helical

$$P_S = \Re\{I_{feed}\}/2. \tag{2}$$

where I_{feed} represents the current at the excitation port.

On the other hand, the receiving power is calculated by the current at the load port by

$$P_D = \mid I_{load} \mid^2 R_{load}/2 \tag{3}$$

where R_{load} represents the resistance of the receiving load, and I_{load} is the current at the load port. Because the circumference of receiving loop D at 19.75MHz is less than 0.1 wavelength, much smaller than one wavelength, the input impedance at the load segment of receiving antenna is very small. In order to obtain the higher receiving power, the R_{load} should be selected a suitable one.

The power transmission efficiency versus frequency when the center of the receiving loop D is placed at the position of $(x = 0, y = 0, z = 0.5m)$ is shown in Fig.2. The maximum transmission efficiency is achieved at spot frequency of 19.75MHz which is nothing but so-called resonant frequency. Fig.3 and Fig.4 show the input impedance as a function of frequency for loop S and loop D with parasitic helical C , respectively. It can be observed that both source loop S and device loop D get resonant nearly at the frequency of 19.75MHz when the reactance achieves zero, further confirming that the efficient power transmission is realized when the transmitting element and receiving element get resonant.

4. Effects of position and number of receiving element

In a practical application, the receiving element is movable and more than one receiving element maybe included. Assume a receiving element is movable on *xy*-plane of *z*=0.5m, corresponding to the situation when the receiving element is buried into a mobile personal computer which is used on a desk anywhere in a office room. The power transmission efficiency at the resonant frequency versus the receiving element position is shown in Fig. 5, demonstrating much higher transmission efficiency can be achieved in the area of (| x |≦1m, | y | ≦1m). The resonant frequency versus receiving element position is also plotted in Fig. 6. Although, the power transmission efficiency changed greatly when the relative distance between the source element and the receiving element is changed, the resonant frequency almost keeps to 19.75MHz except the position of (*x*=-1m,*y*=-1m,*z*=0.5m) resonating at 19.5MHz.

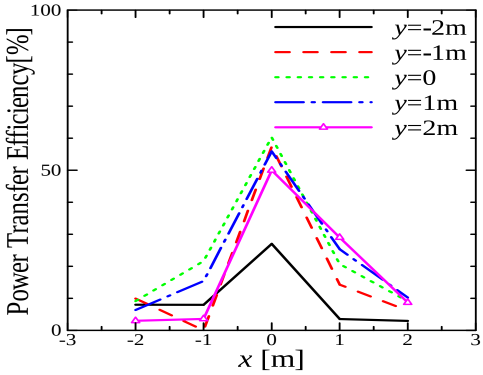

Figure 5: Power transmission efficiency versus receiving position

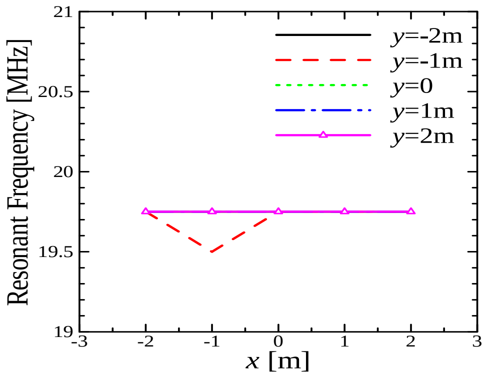

Figure 6: Resonant frequency versus receiving position

The power transmission efficiencies and the resonant frequencies for two receiving elements in the proposed wireless power transmission system are shown in Fig.7 - Fig.10, respectively, where user A stands in the position of (0,0,0.5m), while user B moves along *xy*-plane of *z*=0.5m. The results demonstrate that the power transmission efficiency and the resonant frequency of each receiving element are not affected significantly by the existence of the other user unless the relative distance between two receiving users is less than 0.5m. This suggests that two users should be keep a distance more than 0.5m if they want to charge their electrical devices efficiently at the same time from the proposed wireless charge system.

5. Effect of human body

Usually, a mobile device is used near to a non resonant object such as a human body, it is expected that the resonant frequency and the power transmission efficiency will not be influenced seriously by the existence of a human body, and on the other hand the human body also will not absorb the energy of the evanescent field of the wireless power as less as possible. For the simplicity, the human body is approximated to a rectangular dielectric box of dimensions 0.5m × 0.5m× 1.5m and permittivity $\varepsilon_r = 49 - 16i$(human muscles). The power transmission efficiency when the receiving element at the position of (0,0,0.5m) with a human body whose center is located at (0.65m,0,0.75m) is compared with that without a human body in Fig.11. It can be observed that the resonant frequency of receiving element is not affected at all even a human body is so close to the receiving element. However, the power transmission efficiency is decreased from 60 percent to 20 percent due to the existence of a human body. The volume average SAR for human body and the driving power in the loop S are shown in Fig.12 , demonstrating the volume average SAR achieves maximum value of 7.42e-6 [W/kg] at the resonant frequency of 19.75MHz, that is the reason why the power transmission efficiency is decreased. The driving power of transmitting element is 0.01[W] at the resonant frequency. Because the human body near to a receiving element absorbs the electromagnetic energy greatly, the driving power of transmitting element should be designed carefully to meet the safety levels with respect to human exposure to RF electromagnetic fields in the proposed wireless power system.

6. Conclusions

A more practical wireless transmission system consisting of a larger rectangular wire loop and a small square wire loop with a parasitic square helical coil has been proposed for efficient evanescent resonant coupling wireless power transmission system in a office room. The power transmission efficiency has been directly defined as the ratio of the receiving power at the receiving element and the input power at the source element and further calculated by the full wave solver. It has been found that the resonant frequency of the system can be tuned from investigating the input impedance of transmitting element and receiving element as an antenna design usually carries out. The simulation results have shown that the power transmission efficiency and the resonant frequency are affected by the relative distance of the transmitting element between the receiving element, suggesting the receiving element should be placed in the central area of ($|x| \leq$1m, $|y| \leq$1m) to obtain higher transmission efficiency. The results also have shown that two users should be separated for a distance more than 0.5m in order to obtain higher power transmission efficiency and stable resonant frequency. Although the resonant frequency of the proposed system is not affected by a nearby human body, the power transmission efficiency is decreased together with higher volume average SAR of human body. How to alleviate the mutual couping between human body and receiving element will be our next research target.

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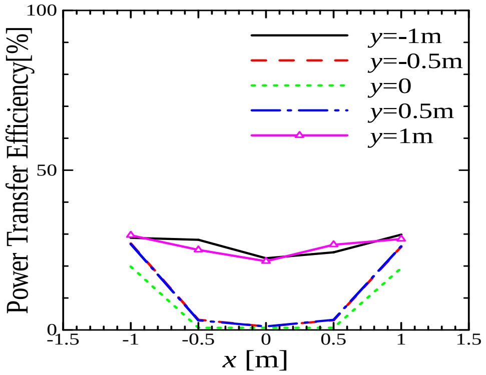

Figure 7: Power transmission efficiency of user A

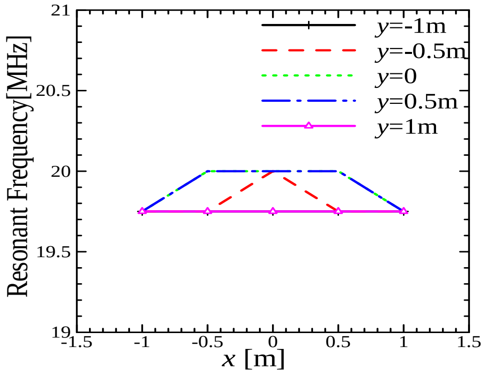

Figure 8: Resonant frequency of user A

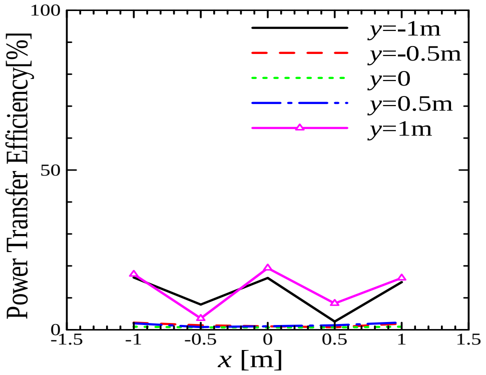

Figure 9: Power transmission efficiency of user B

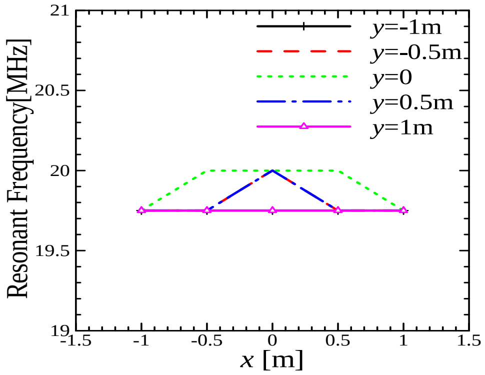

Figure 10: Resonant frequency of user B

References

[1] Kurs, Aristeidis Karakis, Robert Moffatt, J. D. Joannopoulos, Peter Fisher, Marin Soljacic,"Wireless Power transmission via Strongly Coupled Magnetic Resonances," *SCIENCE*, Vol.317, pp. 83-86, 6 July 2007.

[2] Anthony Grbic, Lei Jiang, Roberto Merlin,"Near-Field Plates:Subdiffraction Focusing with Patterned Surfaces," *SCIENCE*, Vol. 320, pp. 512-513, April, 2008.

[3] K. Hatanaka, F. Sato, H. Matsuki, S. Kikuchi, J. Murakami, M. Kawase, T. Satoh,"Power Transmission of a Desk With a Cord-Free Power Supply,"*IEEE Trans on magnetics*, Vol. 38, pp. 3329-3331, No. 5, Sept. 2002.

[4] Aristeidis Karalis, J.D. Joannopoulos, and Marin Soljacic ,"Efficient wireless non-radiative mid-range energy transfer ," *Annels Physics*, 323(2008), pp.34-48.

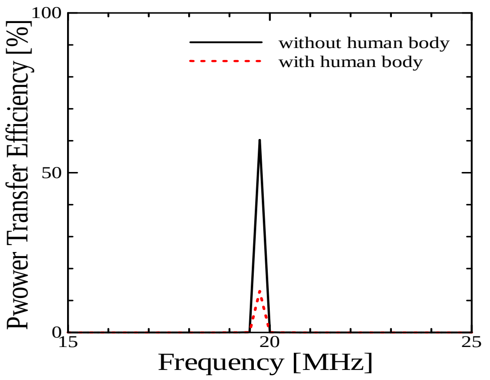

Figure 11: Power transmission efficiency with a human body

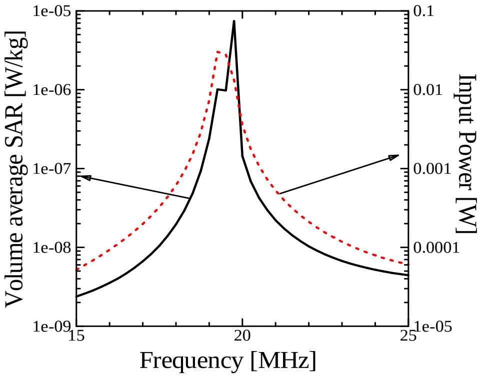

Figure 12: Volume average SAR