Improvement of Near-Field Power Transfer Efficiency by switching Parasitic Elements

呉　銘達, 陳　強 (東北大学大学院工学研究科)
袁 巧微 (仙台高等専門学校)

Abstract-Power transfer efficiency (PTE) of wireless power transfer (WPT) system using near-field coupling will be low while the Transmitting (Tx) antenna and Receiving (Rx) antenna is not aligning. This problem will be more serious when the deviation between Tx antenna and Rx antenna getting larger. In this paper, we found the PTE could be improved when misregistration happened by inserting several parasitic elements into the WPT system and switching the Open/Short status of these parasitic elements. The numerical calculation is conducted with the help of the Scattering Parameters (S-parameter). So it is convenient to investigate some factors that will affect the PTE, such as the geometry of the parasitic elements and the position of the parasitic elements.
Keyword: Wireless Power Transfer, Power Transfer Efficiency, Misregistration, Parasitic Element, Open/Short Status Switching, Near-Field, Scattering Parameters

1. INTRODUCTION

Wireless power transfer (WPT) attracts great attention because of its potential application to charge laptop computers, mobile phones, portable audio players and other electronic devices without cords [1]-[6]. Researches even showed the application prospect of charging motor vehicles wirelessly. It was also experimentally demonstrated that very efficient power transmission can be achieved by using the strongly-coupled resonance method [1]. It was shown that the strongly-coupled resonance method can transmit energy for a longer distance than the preciously used near-field induction method [2]. Again, the strongly-coupled resonance method was shown to be more efficient than the far-field radiation method [3], where most energy is wasted due to the transmission loss [4]-[5].

Recent years, petroleum price approached its highest level for almost ten years. Hybrid electric vehicles or even electric vehicles are expected to replace the motor vehicles using gasoline in the coming decade. As mentioned above, electric vehicles can be charged wirelessly. Instead of the gasoline station, electric vehicles can get charged conveniently by just parking the car into a charge station. The electric power from the transmitting (Tx) terminal buried under ground will charge into the receiving (Rx) terminal hidden in the vehicle.

Problems come if the Tx antenna and the Rx antenna are not aligning very well, the power transfer efficiency (PTE) will decrease compared with the aligning one. That means if the Tx and Rx antennas are not aligning with each other, more power will be radiated into the surrounding environment. In the application case of high power WPT system just like vehicle charging, even 1 percent of the power is radiated outside, this radiated power will have serious human hazard to people around it. So how to improve the PTE when the Tx antenna and Rx antenna have misregistration become an urgent issue.

The power transfer efficiency (PTE) is one of the most important parameters to evaluate the performance of a WPT system. If the transmitting antenna and receiving antenna are described as a two-port network circuit, the power transfer between the transmitting antenna and receiving antenna in the WPT system can be indicated by using the scattering parameters of the network circuit and further the PTE can be calculated by using the scattering parameters. Because the scattering parameters of a WPT system can be measured by a vector network analyzer and calculated by a full-wave numerical analysis, the scattering parameters are a very efficient tool in analyzing and designing the antennas and parasitic elements.

A fundamental study focused on the PTE of a WPT system composed of dipole and loop antennas as the transmitting and receiving antennas was carried out by the present authors, where a two-port scattering parameters calculated by the method of moments (MoM) were used to analyze the system and it was found the largest PTE was obtained when the near-field coupled antennas of both transmitting and receiving sides were conjugate-matched with the impedance of the transmitting and receiving circuits, respectively [6]. The optimum load for maximum transfer efficiency of a practical WPT system was derived when the WPT system was equivalent to a 2-port lossy network [7] also by the present authors.

This paper shows the result when the misregistration between the Tx antenna and Rx antenna happened, we can first insert several parasitic elements and then by modify the open/short status of these parasitic element, therefore, we can improve the PTE of this WPT system.

2. ANALYSIS OF 2-PORT NETWORK

A generalized 2-port network is shown in Fig. 1, which represent a WPT system with one transmitting antenna

2013 年 12 月 24 日
東北大学　電気・情報系 451・453 会議室

and one receiving antennas. By using the Method of Moment (MoM), a 2×2 scattering parameters of this 2-port network can be achieved. The reflection coefficients at 2 port are labeled in the Fig. 1, and the reference impedance is $Z_0 = 50\ \Omega$. P_{inc} is the power available from the source, P_l is the power delivered to the load. Therefore, if this WPT system is impedance matched, two equations can be obtained:

$$\Gamma_{in} = {\Gamma_s}^* \quad \Gamma_{out} = {\Gamma_l}^* \tag{1}$$

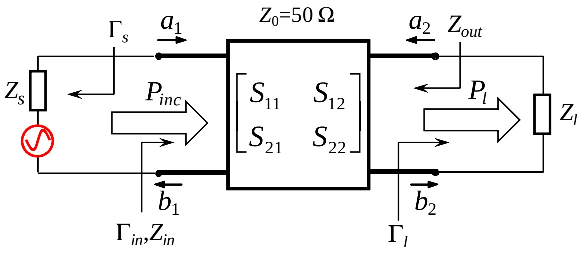

Fig 1: 2-port network

From the definition of the S-parameter, follow equations can be obtained:

$$\eta = \frac{|S_{21}|^2 \left(1 - |\Gamma_l|^2\right)}{|1 - S_{22}\Gamma_l|^2 \left(1 - |\Gamma_{in}|^2\right)} \tag{2}$$

In equation (2), η is the PTE efficiency of this 2-port WPT system. Γ_s, Γ_l are the reflection coefficients at the transmitting antenna side and the receiving antenna side, respectively.

If the whole system is impedance conjugated matched, the Γ_s and Γ_l can be solve by following equations [6]:

$$\Gamma_s = \frac{B_1 \pm \sqrt{{B_1}^2 - 4|C_1|^2}}{2C_1} \tag{3}$$

$$\Gamma_l = \frac{B_2 \pm \sqrt{{B_2}^2 - 4|C_2|^2}}{2C_2} \tag{4}$$

where,

$$\begin{aligned} B_1 &= 1 + |S_{11}|^2 - |S_{22}|^2 - |\Delta|^2 \\ B_2 &= 1 + |S_{22}|^2 - |S_{11}|^2 - |\Delta|^2 \\ C_1 &= S_{11} - \Delta S_{22}^* \\ C_2 &= S_{22} - \Delta S_{11}^* \\ \Delta &= S_{11}S_{22} - S_{12}S_{21} \end{aligned}$$

If the whole system is not impedance matched, the Γ_s and Γ_l is depand on the load impadance at both Tx side and Rx side, and they can be solve by following relationships:

$$\Gamma_s = \frac{Z_s - Z_0}{Z_s + Z_0} \tag{5}$$

$$\Gamma_l = \frac{Z_l - Z_0}{Z_l + Z_0} \tag{6}$$

The characteristic impedance above Z_0 is 50 Ω in following calculations and discussions.

3. PTE OF 2-PORT WPT SYSTEM WHEN MISREGISTRATION

A 2-port WPT system with its Tx and Rx antennas all loop antennas are shown in Fig.2 and Fig.3. Fig.2 is the side view of this model and Fig.3 is the 3-D view of this model for following numerical simulation. The Tx loop antenna and Rx loop antenna have same geometry with radius $R = 20$ cm. Five helical structures is inserted into the 2 loop antennas as parasitic elements. The radius of the five helical structures is $r = 10$ cm. The height of these five helical structures is $h = 4$ cm. The turn number of these helical structures is $N = 5$. The distance between the Tx antenna and the bottom of the helical structures is $z = 5$ cm. The distance between the center of each helical structure is $r = 22$ cm. The distance between Tx loop antenna and Rx loop antenna $H = 50$ cm. All the antenna material in this model is chosen to be PEC with wire radius of 2 mm. The frequency used to calculate and analyze is 30 MHz.

In Fig.2, dy means the misregistration between the Tx loop antenna and the Rx loop antenna. We choose $dy = 0$ cm, 5 cm, 10 cm $\cdots$ 35 cm, 40 cm for further analysis.

At last, the Fig.4 shows the top view of the model and detail structure of the helix, we also labeling five helixes with number from one to five. The helix can be switched open/short status arbitrarily.

By using the equation (3)-(4) we can figure out the optimal load when five helixes are all open by using S-parameter. In the model shown in Fig.2 and Fig.3, we insert the optimal load mentioned above to the Z_s and Z_l. In this case, Z_s = 225.56-421.64j Ω and Z_l = 1.60-230.90j Ω.

The Fig.5 shows, the PTE of the model shown in Fig.2 and Fig.3 when misregistration happened. The X-axis is the misregistration dy between Tx loop antenna and the Rx loop antenna. The Y-axis is the PTE of the 2-port WPT system. Because we inserted five helixes between two loop antennas, which means totally we have 32 open/short statue combinations of these five helixes.

The black line with rectangle marks shows the PTE of the model inserted with optimal loads Z_s = 225.56-421.64j Ω and Z_l = 1.60-230.90j Ω varied when dy getting larger. The red line with diag. cross marks shows

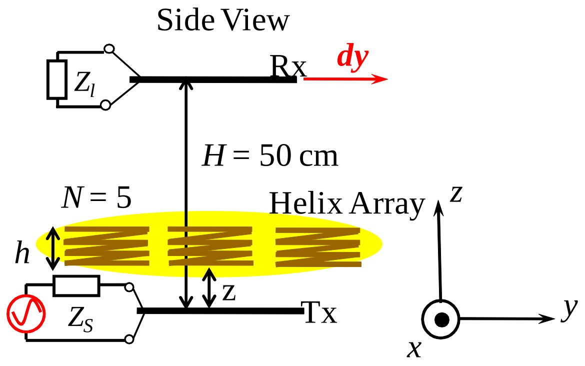

Fig 2: Analysis model: 2-port WPT system when misregistration by side view

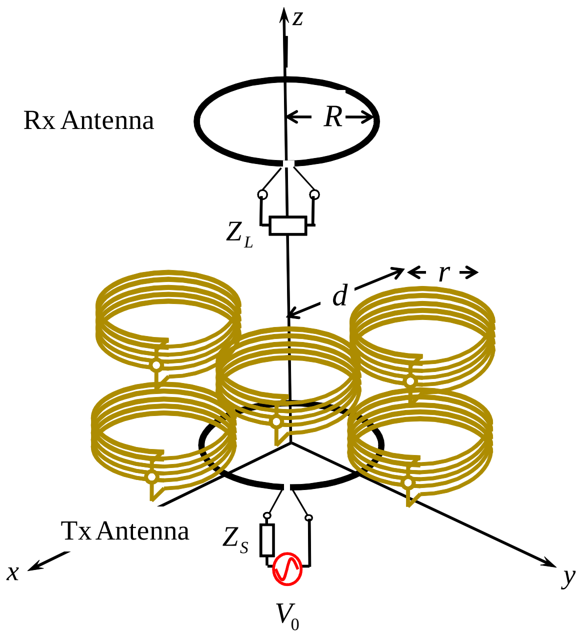

Fig 3: Analysis model: 2-port WPT system when misregistration by 3-D view

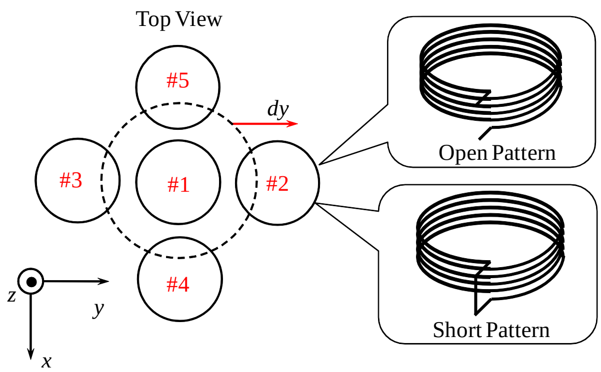

Fig 4: Open/Short Statue Switch

the best PTE we can achieve by switching five helixes' open/short status.

From the Fig. 5 we found, the PTE of 2-port WPT system would be low if misregistration happened and decrease when this misregistration dy getting larger. Also we could see, by switching the open/short status of five parasitic elements (helixes this time) the PTE of the system could be improved.

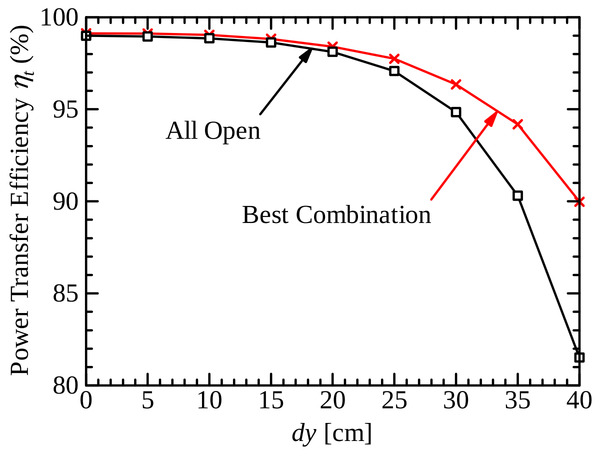

Fig 5: PTE of the model shown in Fig.2 and Fig.3 when misregistration happened

Therefore, we were quite interested about the factor that will affect this improvement. In this paper, we will later show the helix turn number N and the helixes vertical position z will have great effect on this PTE improvement.

First, we investigated the relationship between the PTE improvement and the helix turn number N. Same model was chosen shown in Fig.2 and Fig.3, but this time the helix turn number N was set to be 4, 5, 6 and 7. At the same time, the preassembled load impedance when all helixes are all short with no misregistration was set to Z_s = 0.39-226.35j Ω and Z_l = 0.51-231.24j Ω when N = 4, Z_s = 0.38-226.25j Ω and Z_l = 0.50-231.26j Ω when N = 5, Z_s = 0.39-226.21j Ω and Z_l = 0.52-231.26j Ω when N = 6, Z_s = 0.38-226.20j Ω and Z_l = 0.51-231.26j Ω when N = 7 for further calculation and analysis.

The Fig.6-9 shown the improvement of the PTE when different helix turn number N was chosen. From these 4 graphs we found when N = 5 the PTE improvement of the 2-port WPT system was the largest, the final PTE is largest when N = 5. We can see, the helix turn number N have great effect on the improvement of the PTE caused by the misregistration. This also means the electrical length of parasitic element is very important to improve the PTE.

Compared with the Fig.5 and Fig.7, all the other pa-

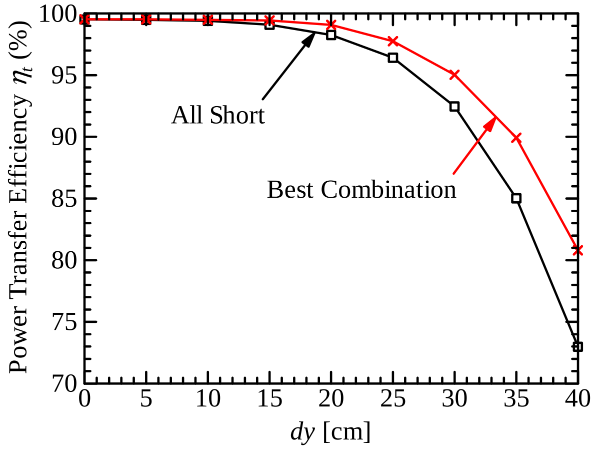

Fig 6: PTE of the model shown in Fig.2 when misregistration happened and $N = 4$

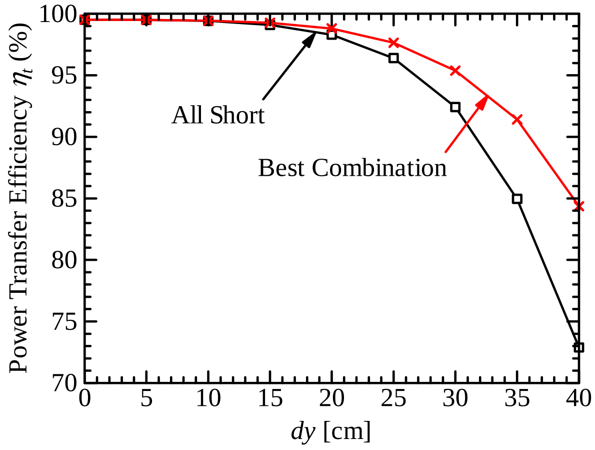

Fig 7: PTE of the model shown in Fig.2 when misregistration happened and $N = 5$

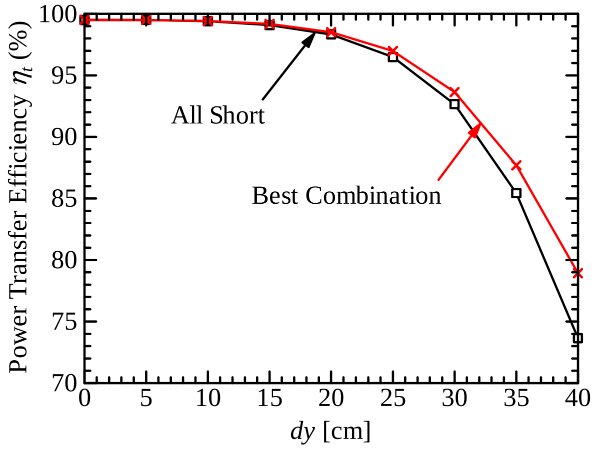

Fig 8: PTE of the model shown in Fig.2 when misregistration happened and $N = 6$

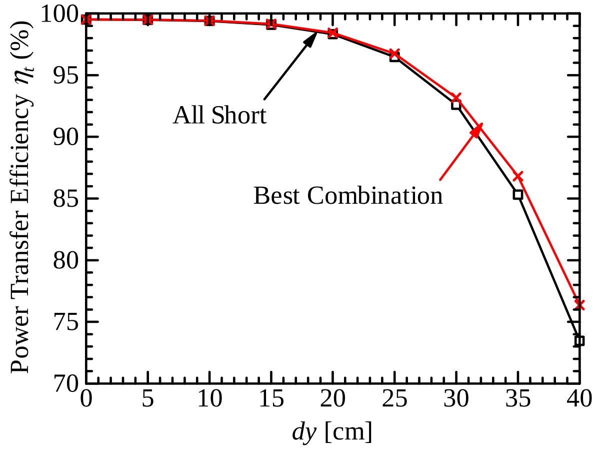

Fig 9: PTE of the model shown in Fig.2 when misregistration happened and $N = 7$

rameters are the same except the load impedance. In Fig.5, load impedance is chosen to be the optimal load when all helixes are all open and $dy = 0$. However, in Fig.7, load impedance is chosen to be the optimal load when all helixes are all short. We can find, when the load impedance was chosen as the optimal load when all helix are open, after switching the open/short status, the final PTE is better than the model choose optimal load when all helix are short as its load impedance. This fact shows it's important to choose impedance load Z_s and Z_l.

Then, we investigated the relationship between the PTE improvement and the vertical position z. In the model shown in Fig.2 and Fig.3, the parasitic element was placed above the Tx loop antenna. This time, we choose the z = -7 cm, -9 cm, -11 cm. Because the definition of the z is the distance from the Tx loop antenna to the bottom of the helix. So when z is chosen to be -7 cm, -9 cm, -11 cm, the distance between the Tx loop antenna and the top of the helix is 3 cm, 5 cm and 7 cm, respectively. At the same time, the preassembled load impedance when all helixes are all open with no misregistration was set to Z_s = 874.01-207.72j Ω and Z_l = 0.99-232.39j Ω when z = -7, Z_s = 778.59-133.23j Ω and Z_l = 0.91-232.57j Ω when z = -9, Z_s = 645.30-53.12j Ω and Z_l = 0.84-232.74j Ω when z = -11 for further calculation and analysis.

From Fig.10-12, when the misregistration is small, the model with parasitic element vertical position z = -7 cm will have good PTE improvement. However, when the misregistration is large, the model with parasitic element vertical position z = -11 cm will have good PTE improvement.

The Fig.13 shows the final PTE of the 2-port WPT system with z = -7 cm, z = -9 cm, z = -11 cm. From

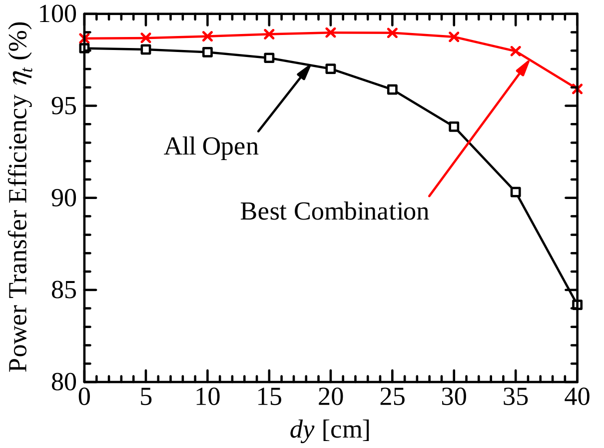

Fig 10: PTE of the model shown in Fig.2 when misregistration happened and z = -7

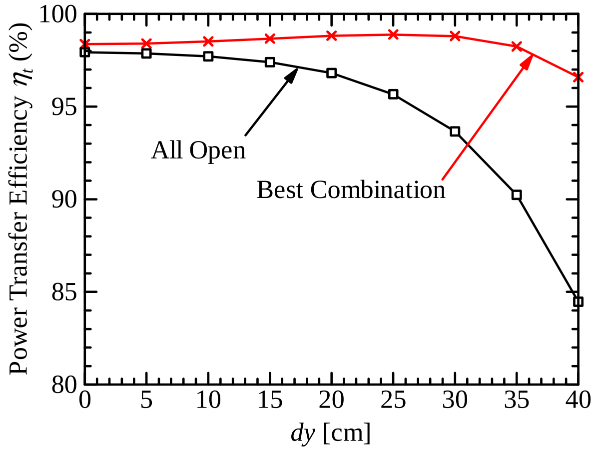

Fig 11: PTE of the model shown in Fig.2 when misregistration happened and z = -9

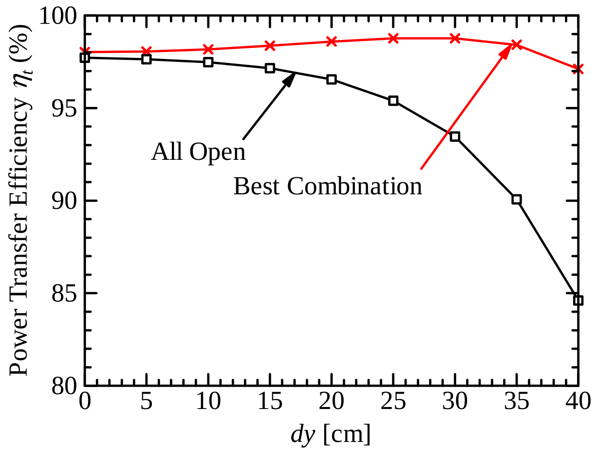

Fig 12: PTE of the model shown in Fig.2 when misregistration happened and z = -11

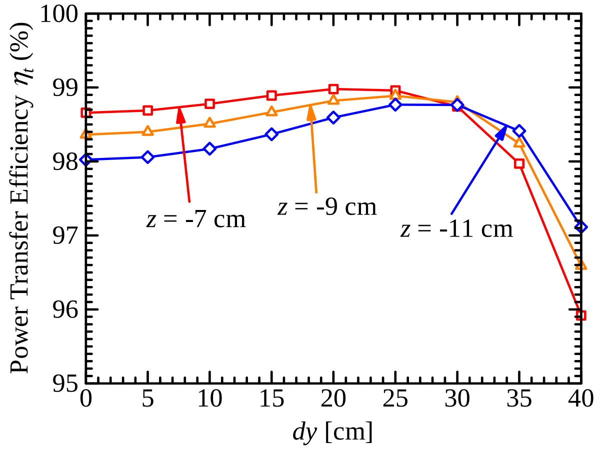

Fig 13: PTE of the model shown in Fig.2 when misregistration happened with different z

the graph, when the misregistration is small, dy is less than 30 cm in this case, the parasitic element close to the Tx antenna will have a good performance. However, when the misregistration is large, dy is larger than 30 cm in this case, the parasitic element far away from the Tx antenna will have a good performance.

Above all, we find out that the vertical position of the parasitic element will have great effect on the PTE improvement of the 2-port WPT system.

4. CONCLUSIONS

In this paper, PTE of a 2-port WPT system with misregistration has been investigated corresponding to electric vehicle charging situations. It was shown that the PTE of a 2-port WPT system would be quite low when misregistration happened. Also, it was shown that adding parasitic elements into the 2-port network would offset this effect and finally improve the PTE of the system. Simulation result shows that the geometry, electric length, and the located position of the parasitic element will greatly affect this improvement.

5. ACKNOWLEDGMENT

This research was partly supported by Adaptable & Seamless Technology Transfer Program through Target-driven R&D (A-STEP) of The Japan Science and Technology Agency (JST). This work was also partly supported by JSPS Grant-in-Aid for Scientific Research (C) of Grant Number 25420353.

参考文献

[1] A. Kurs, A. Karakis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljacic, "Wireless Power

Transfer via Strongly Coupled Magnetic Resonances,"Science, vol. 317, no. 5834, pp. 83-86, July 2007.

[2] J. Murakami, F. Sato, T.Watanabe, H. Matsuki, S.Kikuchi, K. Harakaiwa, and T. Satoh, "Consideration on Cordless Power Station - Contactless Power Transmission System," IEEE Transactions on Magnetics, vol. 32, no. 5, pp. 5017-5019, September 1996.

[3] W. C. Brown, "The History of Power Transmission by Radio Waves," IEEE Transactions on Microwave Theory and Techniques, vol. 32, no. 9, pp. 1230-1242, September 1984.

[4] H. Matsumoto, "Research on Solar Power Satellites and Microwave Power Transmission in Japan," IEEE Microwave Magazine, vol. 3, no. 4, pp.36-45, December 2002.

[5] C. T. Rodenbeck and K. Chang, "A Limitation on the Small-Scale Demonstration of Retrodirective Microwave Power Transmission from the Solar Power Satellite, " IEEE Antennas and Propagation Magazine, vol. 47, no. 4, pp. 67-72, August 2005.

[6] Qiang Chen, Kazuhiro Ozawa, Qiaowei Yuan, and Kunio Sawaya, "Antenna Characterization for Wireless Power-Transmission System Using Near-Field Coupling," IEEE Antennas and Propagation Magazine, vol. 54, no. 4, pp. 108-116, Aug. 2012.

[7] Qiaowei Yuan, Qiang Chen and Kunio Sawaya, "Numerical Analysis on Transmission Efficiency of Evanescent Resonant Coupling Wireless Power Transfer System," IEEE Transactions on Antennas and Propagation, vol. 58, no. 5, pp. 1751 - 1758, May 2010.