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Numerical analysis on near field wireless power transfer system using reconfigurable transmitting/receiving antenna

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Abstract: In this letter, we propose a near field wireless power transfer (WPT) system using reconfigurable transmitting/receiving antenna. The reconfigurable antenna is composed of parasitic elements with switches. Impedance of WPT system is changed by switching open/short termination and impedance matching condition can be improved when the misalignment of transmitting/receiving antenna are occurred. Therefore, the impedance mismatching loss is reduced, the power transmission efficiency is greatly increased. Result of numerical simulation shows the performance of the proposed system.

Keywords: wireless power transfer, power transmission efficiency, reconfigurable antennas, parasitic elements, impedance matching
Classification: Antennas and Propagation

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1 Introduction

Recently, wireless power transfer (WPT) technologies using near field coupling have been attracting great attention due to a high power transmission efficiency [1]. On the other hand, it has been also known that the impedance matching conditions should be satisfied in order to keep the high power transmission efficiency. In other words, it is important to hold the predetermined arrangement of the transmitting/receiving antenna because the impedance matching condition is sensitive to the relative position of the transmitting/receiving antenna. However, it is difficult to keep the exact position in practical applications, for example, in the case of parking an electric car at the charging space. It has been reported that the reduction of the power transmission efficiency cannot be avoid when the impedance mismatching loss is occurred [2].

Previously, various methods for decreasing return loss have been reported. For example, a method using adaptive impedance matching circuit was proposed in [3]. However, in this methods, lumped elements were used as the impedance matching circuit, which usually caused a large conduction loss and a narrow bandwidth.

In this letter, a near field WPT system using reconfigurable transmitting/receiving antenna are proposed, and its performance is investigated numerically. The reconfigurable antenna can compensate the impedance change adaptively as distributed elements which have an advantage of low loss and wide bandwidth. It is shown that the power transmission efficiency is greatly improved even when the impedance mismatching loss is occurred due to the misalignment of the transmitting/receiving antenna.

2 Proposed antenna system

Fig. 1 shows the configuration of the proposed antenna system for WPT, which is composed of transmitting antenna (yellow layer), receiving antenna (pink layer) and parasitic elements with switches (blue layer). Meander line geometry is used for all elements to adjust the size of antennas easily. The number of parasitic elements is 10, which was decided by taking the tradeoff between calculation time and effectiveness of the reconfiguration techniques. Moreover, because the misalignment is toward to x or y direction in this simulation, the parasitic elements are arranged in x and y direction.

It is assumed that all parasitic elements are terminated by "open" circuit or "short" circuit and the termination conditions of each parasitic element are adaptively controlled from open to short vice versa when the misalignment of the transmitting/receiving antenna is occurred. Because the number of parasitic elements is 10, the number of combination is $2^{10} = 1024$.

In this research, the optimized switching conditions of parasitic elements were determined by calculating all the 1024 combinations, and the calculating time was about several minutes. However, in the practical use, it is assumed that the optimization is carried out by monitoring the level of received power while switching the termination conditions in real time. The time for determining the switching conditions is acceptable in the practical use if the speed of analogue switching is fast enough.

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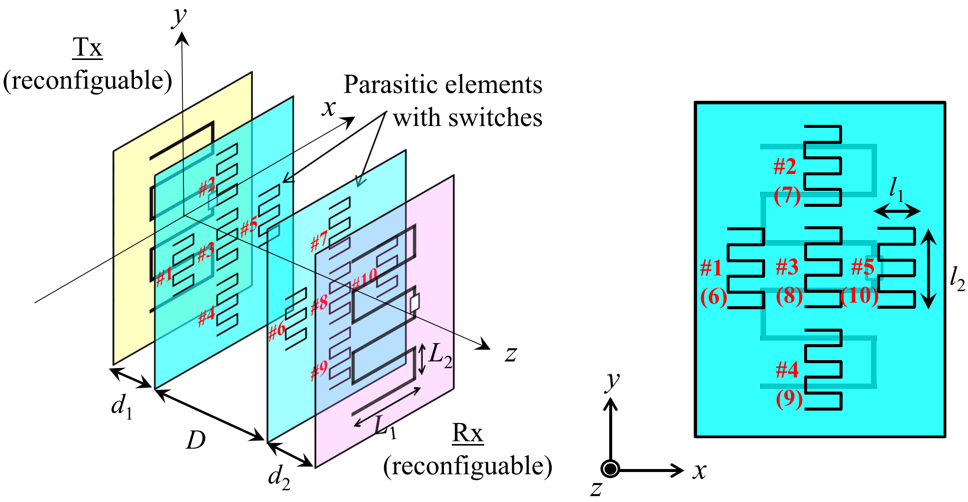

(a) Over view

(b) Top view of reconfigurable antennas

Fig. 1. Configuration of proposed WPT system.

3 Calculation method for power transmission efficiency

The proposed WPT antenna can be modeled as the equivalent circuit as shown in Fig. 2. The S-parameter of the system is expressed as

$$\begin{bmatrix} S_{TT} & S_{TR} & \boldsymbol{S_{TP}} \\ S_{RT} & S_{RR} & \boldsymbol{S_{RP}} \\ \boldsymbol{S_{PT}} & \boldsymbol{S_{PR}} & \boldsymbol{S_{PP}} \end{bmatrix} \tag{1}$$

where S_{TT} is the reflection coefficient at the transmitting antenna, S_{RR} is the reflection coefficient at the receiving antenna, S_{TR} and S_{RT} are transmission coefficients between the transmitting and receiving antenna, $\boldsymbol{S_{TP}}$ and $\boldsymbol{S_{PT}}$ are transmission coefficients among the transmitting antenna and parasitic elements, $\boldsymbol{S_{RP}}$ and $\boldsymbol{S_{PR}}$ are transmission coefficients among the receiving antenna and parasitic elements, and $\boldsymbol{S_{PP}}$ is the S-parameter of each parasitic elements. The reflection coefficient at ith parasitic element is represented by

$$\gamma_i = \frac{Z_i - Z_0}{Z_i + Z_0} \tag{2}$$

where Z_0 is the characteristic impedance, Z_i is the termination impedance of parasitic elements, which is ∞ in open circuit and 0 in short circuit for simplifying the calculation. The reflection coefficient matrix of Z_i is expressed as

$$\boldsymbol{\Gamma} = \begin{bmatrix} \gamma_1 & & 0 \\ & \ddots & \\ 0 & & \gamma_i \end{bmatrix} \tag{3}$$

Here, the cascade connection of the S-parameter is used for decreasing 12×12 S-parameter matrix to 2×2 S-parameter matrix by the following expression.

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$$\begin{bmatrix} S'_{TT} & S'_{TR} \\ S'_{RT} & S'_{RR} \end{bmatrix} = \begin{bmatrix} S_{TT} & S_{TR} \\ S_{RT} & S_{RR} \end{bmatrix} + \begin{bmatrix} \boldsymbol{S_{TP}} \\ \boldsymbol{S_{RP}} \end{bmatrix} (I - \boldsymbol{\Gamma S_{pp}})\boldsymbol{\Gamma}\begin{bmatrix} \boldsymbol{S_{PT}} & \boldsymbol{S_{PR}} \end{bmatrix} \tag{4}$$

The power transmission efficiency η can be expressed by using Eq. (4),

$$\eta = \frac{P_l}{P_{inc}} = \frac{|S'_{RT}|^2(1-\Gamma_S^2)(1-\Gamma_l^2)}{|1-\Gamma_S\Gamma_{in}|^2|1-\Gamma_l S'_{RR}|^2} \tag{5}$$

where P_{inc} is the incident power to the transmitting antenna, P_l is the received power of the load, Γ_S, Γ_l, and Γ_{in} are the reflection coefficient at the internal impedance of source Z_S, the load impedance Z_l, and the feeding point, respectively.

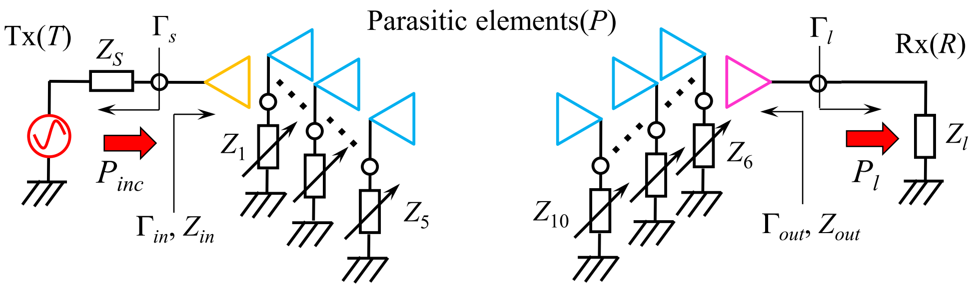

Fig. 2. Equivalent circuit of proposed WPT system.

4 Numerical simulation

The proposed WPT antenna in Sec. 2 was analyzed numerically by using method of moments (MoM). The power transmission efficiency was obtained by using Eq. (5) after the S-parameter was calculated by using the MoM.

The efficiency was calculated at three different conditions, which is (i) w/ Optimum load, (ii) w/ Switching, (iii) w/o Switching, respectively. (i) is an ideal power transmission efficiency. The termination loads of transmitting/receiving antenna are always optimum for each $dx(y)$. (ii) is the efficiency when the transmitting/receiving antenna is terminated with the load which is optimized at $dx(y) = 0$, and the termination conditions of parasitic elements are optimized for each $dx(y)$. (iii) is the power transmission efficiency without using reconfiguration techniques. The transmitting/receiving antenna is always terminated with the fixed load same as (ii), on the other hand, the termination conditions of parasitic elements are always same as an initial situation for each $dx(y)$.

Fig. 3 shows the numerical analysis results of the proposed WPT system. As the receiving antenna was moved in $x(y)$ direction, the power transmission efficiency of condition (iii) (blue line) degraded rapidly due to the impedance mismatching loss. On the other hand, the efficiency of condition (ii) (red line) was improved by switching the termination conditions of the parasitic elements. The power transmission efficiency was increased from condition (ii) to condition (iii), which is up to 65% in (a), 74% in (b), respectively. However, it is difficult to achieve condition (i) (black line) due to the lack of ability to satisfy the impedance matching condition.

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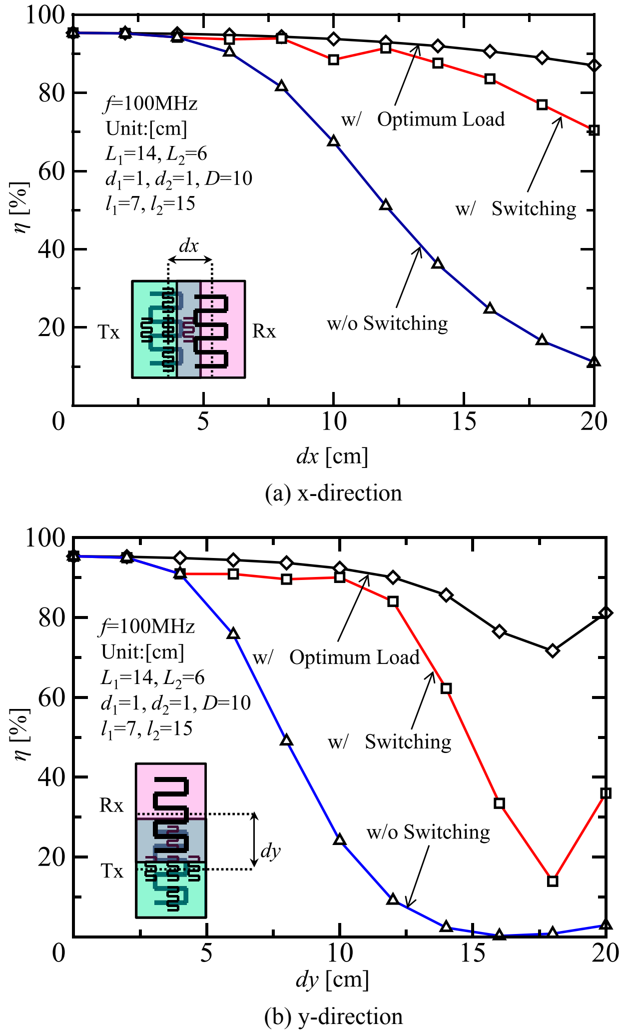

Fig. 3. Power transmission efficiency of proposed WPT system

It was found from the results that the proposed WPT system is capable of improving the impedance matching condition greatly and keeping the power transmission efficiency even when the impedance mismatching loss is occurred due to the misalignment of the transmitting/receiving antenna.

5 Conclusion

In this letter, a near field WPT system using reconfigurable transmitting/receiving antenna was proposed and studied by numerical simulation. The parasitic elements were installed near the transmitting/receiving antenna, and impedance of system were changed by switching the termination conditions. Therefore, the impedance matching condition could be improved even when the receiving antenna moved and impedance mismatching loss was occurred. Results of numerical simulation demonstrated that proposed WPT system could greatly improve the power transmission efficiency. Experiment of the proposed WPT system will be the future work.

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