Numerical Analysis on Transmission Efficiency of Evanescent Resonant Coupling Wireless Power Transfer System

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***Abstract*—A practical wireless power transmission system consisting of a large rectangular wire loop and a small square wire loop with a parasitic square helical coil is proposed for use as an efficient evanescent resonant coupling wireless power transmission system in an indoor environment. In addition, a full wave-based numerical analysis on the resonant frequency of and the power transmission efficiency of wireless power transmission system are performed in this paper. The effects of the following on power transmission efficiency and the resonant frequency are numerically investigated: The load of the receiving element and the presence of non-resonant objects such as a conducting box or human body. The numerical results show that a power transmission efficiency of nearly 50% can be achieved when the proposed system is used to charge only one user with the optimized load. The results also show that power transmission efficiency is reduced significantly when a human body is in very close proximity to the receiving element. This reduction in efficiency can be alleviated significantly, however, if the relative distance between the receiving element and the human body is greater than 0.5 m or 0.03λ at a resonant frequency of 19.22 MHz.**

***Index Terms*—Efficiency, evanescent, human body, power transfer, resonant, SAR, wireless.**

I. Introduction

THERE has been a renewed focus on wireless power transmission (WPT) technology due to its wide range of applications in charging ubiquitous electronic devices such as MP3 players, mobile phones, and household robots without a cord [1]–[5]. The authors in [1] have experimentally demonstrated that efficient power transmission can be achieved by using two strongly coupled helical coils, which suggests that this technology has potential for use in charging electronic devices. The evanescent resonant coupling method can transmit energy over longer distances than the near magnetic field induction method [2], [3], and it is also more efficient than the far field radiation method [6]–[11] given that it does not waste the vast majority of the energy as a result of using omni-directional antennas.

In [5], the resonance width and the coupling coefficient, which are based on the coupled-mode theory (CMT), are used to calculate the power transmission efficiency of two dielectric disks and two capacitively loaded conductive wire loops, demonstrating the applicability of the wireless transmission system even in the presence of extraneous environmental objects. However, because the approach is based on using CMT to analyze the transmission efficiency, it is difficult to devise a way of making the transmitting or receiving element resonate at the desired frequency, and it is also difficult to provide an optimum load for the receiving element that will dominate the resonance width or resonant decay coefficient.

In this paper, we propose the use of a practical wireless transmitting system consisting of a large rectangular wire loop and a small square wire loop with a parasitic square helical coil. The advantage of this WPT system is that it can offer more stable transmission efficiency in a wider area than the WPT in [1]. Like with a transmitting and receiving antenna system for a radiation application, power transmission efficiency is defined as the ratio of the power received at the receiving element to the power input at the transmitting element, and is analyzed by using a full-wave solver and further compared with the measurement results. A commercial software FEKO which is based on the method of moments (MoM) is used as the full-wave solver in this paper. Furthermore, this paper investigates the input impedances of the transmitting element and the receiving element so as to identify a technique that can be used to tune the resonant frequency. In addition, the effects of the following on the transmission efficiency have been investigated numerically to obtain the maximum power transmission efficiency (MPTE): The various loads, various locations of the receiving element, and the presence of a non-resonant object.

The paper is arranged as follows: A brief description of the proposed wireless power transfer system, calculated near fields or evanescent fields of the transmitting and receiving elements are presented in Section II; the resonant frequency, the mechanism of power transfer based on the resonant near-field coupling and power transmission efficiency are described in Section III; the optimum load for maximum power transmission efficiency is analyzed by using scattering parameters in Section IV; the effects of the positioning of the receiving element are investigated by both numerical analysis and experiment in Section V; the effect of the presence of a non-resonant object is investigated by numerical analysis in Section VI.

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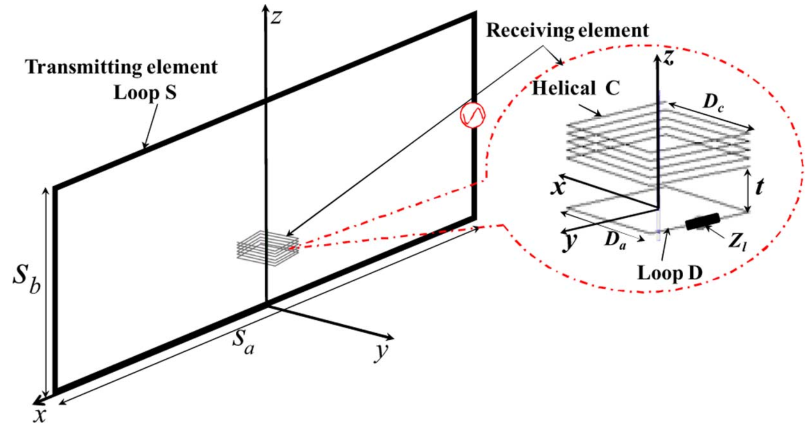

Fig. 1. A schematic model of WPT system.

II. A Practical WPT System

A schematic model of proposed WPT system is shown in Fig. 1. The WPT system is assumed to be applied to a room with a height of 2 m and a width of 6 m. A rectangular loop S with side lengths of $S_a = 6\,\mathrm{m}$ and $S_b = 2\,\mathrm{m}$ is linked to the driving circuit and used as the transmitting element. The operating frequency is 19.22 MHz which is the one-wavelength resonant frequency of loop S calculated by the MoM as shown in Section II. A square loop D with a side length of $D_a = 0.3\,\mathrm{m}$ that is connected to a load Z_l is assumed to be mounted on a mobile receiving terminal to charge the terminal. The radii of all the wires including loop S, loop D and helical coil C are 2 mm. All wires are assumed to be made of copper with a conductivity of $5.8 \times 10^7\,\mathrm{S/m}$. Similar to [1], a parasitic square helical coil C in the receiving element is used to increase the inductance of electrical small square loop D and makes the receiving element resonate at a frequency of 19.22 MHz. The gap t between square loop D and helical coil C, the side length D_c, the pitch and the number of turns for the parasitic helical coil can be adjusted to achieve the required resonant frequency. In the present case, the values for the gap t, the side length D_c, the pitch and the number of turns for the helical coil C are selected to be 0.01 m, 0.3 m, 0.02 m and 4.5, respectively.

Although the frequency for a commercial available WPT system has not yet been officially assigned, the frequency should be low enough to make transmission possible at a relatively long distance because the system operates within the near-field region. Certainty, the size of both the transmitting and receiving elements should be tuned to resonant at the officially assigned frequency and meet the actual application environment. It is not a difficult issue to change the resonant frequency because the approach to tune the resonant frequency of the loop antenna with a parasitical helical can be found in references such as [12].

As similar to the principle described in [1], the energy exchanges in the proposed WPT system is also realized by utilizing the strong coupling between the resonant near fields or evanescent fields of the transmitting and receiving elements. Figs. 2 and 3 show the amplitude distributions of magnetic field of rectangular loop S and small loop D with parasitic helix C when they are used as the transmitting antenna, individually. In the magnetic field calculation, loop S is located in the xz plane, and its base is consistent with x axis, while loop D parallels to xy plane and its center is located at the position of (0, 0, 0.5 m). From Fig. 2, it is observed that the magnetic field decreases as the observation point gets away from the antenna, and decreases by a factor of $1/y$ when y exceeds about 3 m or 0.2 wavelength at operating frequency of 19.22 MHz, indicating that the near field exits dominantly in the area where y is less than 3 m. In Section V, it will be demonstrated that the energy exchange with high efficiency occurs just in the area where the near field is the dominant component. The magnetic field distributions along lines which are parallel to x axis are compared between the rectangular loop S and small loop D with parasitic helix C in Fig. 3. It is observed that the large transmitting rectangular loop S used in proposed WPT system has more uniform near field in wider area than that of the small loop transmitting

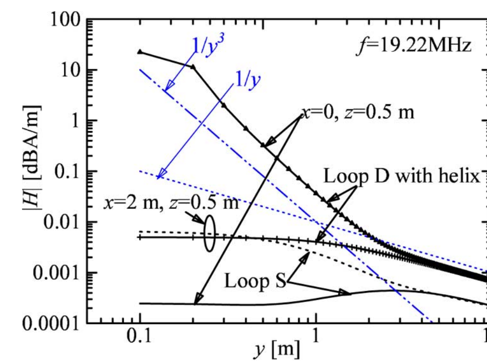

Fig. 2. Magnetic field distribution along lines which are parallel to y axis.

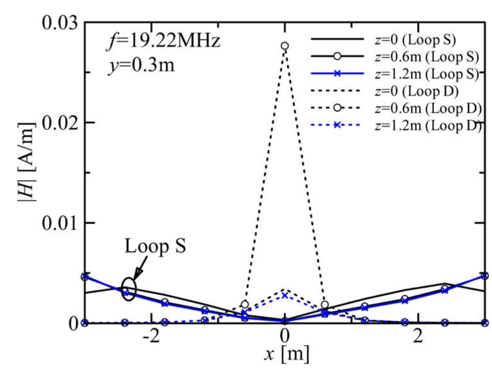

Fig. 3. Magnetic field distribution along lines which are parallel to x axis.

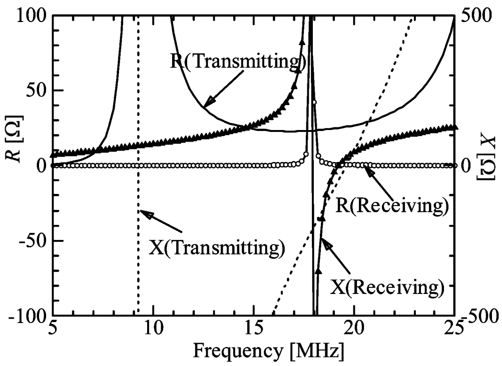

Fig. 4. Input impedances of loop S and loop D.

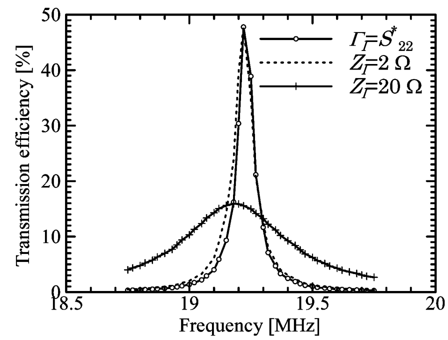

Fig. 5. Power transmission efficiency with different loads.

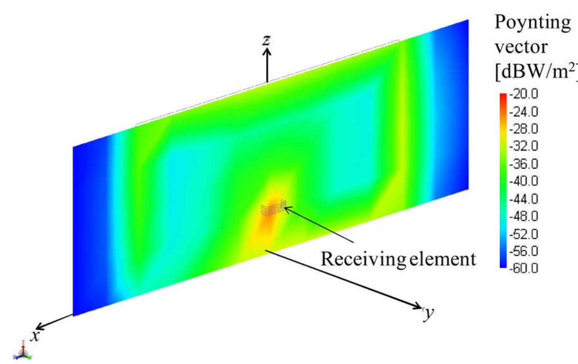

Fig. 6. At the resonant frequency of 19.22 MHz.

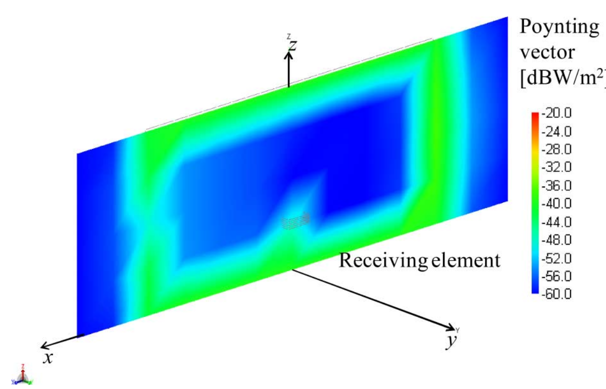

Fig. 7. At off-resonant frequency of 19 MHz.

element used in [1]. As a result, the present system can offer more stable transmission efficiency in a wider area.

III. Resonant Frequency and Power Transmission Efficiency

Resonant coupling is a phenomenon whereby two same-frequency resonant objects tend to couple, while interacting weakly with other off-resonant environmental objects. Therefore, the resonant frequencies of the transmitting element and the receiving element are the most important parameters in the WPT system. The resonant frequencies of both the transmitting and receiving elements have to be known in advance and should be adjusted so that they match each other. In this section, a full-wave electromagnetic field simulation is performed, similar to that performed in an analysis of the characteristics of an antenna.

Fig. 4 shows the input impedances of the transmitting element and the receiving element calculated by using the MoM, indicating that both the transmitting element and receiving element resonant at a frequency of about 19.22 MHz. From Fig. 4, it can be predicted that the proposed WPT will transfer power efficiently at the resonant frequency using the above elements.

The power transmission efficiency, which is a critical parameter for a WPT system, is directly defined by

$$\eta = \frac{P_D}{P_S} \tag{1}$$

where P_S is the power input at the excitation port of transmitting loop S, and P_D is the power received at the load port of receiving loop D. Both the input power and the received power are calculated using the current distribution obtained by the MoM. The input power at the transmitting element is obtained directly by the following formula:

$$P_S = \frac{\mathrm{Re}\left[V_f I_f^*\right]}{2} \tag{2}$$

where V_f and I_f represent the excitation voltage and the current at the excitation port, respectively. * represents the conjugate. The receiving power, on the other hand, is calculated by the current at the load port by

$$P_D = \frac{|I_l|^2 R_l}{2} \tag{3}$$

where I_l represents the current at the load port and R_l represents the resistance of the receiving load Z_l.

Fig. 5 shows the transmitting efficiencies versus the frequency, where the center of the receiving loop is located at (0, 0, 0.5 m) and the loads are 2 Ω resistance, 20 Ω resistance and the load satisfying to the matching condition of $\Gamma_l = s_{22}^*$, respectively. It is found that the transmission efficiency achieves its maximum value when the frequency is 19.22 MHz for different loads, indicating that energy is transmitted effectively when the transmitting element and the receiving element are resonant with each other at a frequency of 19.22 MHz.

In order to investigate the mechanism of the proposed near-field coupling WPT system, the amplitude of the near-field Poynting vector in the plane of $y = 0.05$ m at a resonant frequency of 19.22 MHz is compared with that at an off-resonant frequency of 19 MHz, as shown in Figs. 6 and 7. These figures

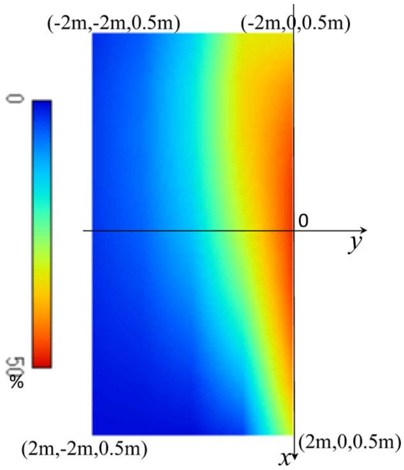

Fig. 8. Equivalent 2-ports network.

show that a strong near-field coupling between the transmitting element and receiving element occurs when the two elements resonate at a frequency of 19.22 MHz.

IV. Optimum Load for Maximum Power Transmission Efficiency

The WPT system shown in Fig. 1 is equivalent to the two-port lossy network shown in Fig. 8, where the transmitting port is denoted as port 1 and the receiving port is denoted as port 2. The power transmission efficiency of the WPT system is identical to the transmission efficiency between port 1 and port 2 which is

$$\eta = \frac{|s_{21}|^2\left(1-|\Gamma_l|^2\right)}{|1-s_{22}\Gamma_l|^2\left(1-|\Gamma_{in}|^2\right)} \tag{4}$$

where Γ_l is the reflection coefficient in relation to the load impedance, which is defined as

$$\Gamma_l = \frac{Z_l - Z_0}{Z_l + Z_0} \tag{5}$$

and Γ_{in} is the reflection coefficient at the port 1, which is defined as

$$\Gamma_{in} = s_{11} + \frac{s_{12}s_{21}\Gamma_l}{1-s_{22}\Gamma_l} \tag{6}$$

where s_{11}, s_{21}, s_{12} and s_{22} are the scattering parameters which can be obtained by the MoM simulation or by experiment. Z_0 is the characteristic impedance of the transmission line, which is 50 Ω. The transmission efficiency calculated using (4) is identical to that calculated using (1). If mismatching at the transmitting port is omitted, the maximum transmission efficiency can be achieved only when the load meets the following matching condition,

$$\Gamma_l = s_{22}^*(f). \tag{7}$$

The transmission efficiencies for $Z_l = 2\ \Omega$ and $Z_l = 20\ \Omega$ are compared in Fig. 5. This figure shows that the maximum value for transmission efficiency is achieved when $Z_l = 2\ \Omega$.

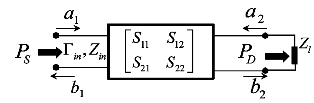

Fig. 9. Power transmission efficiency versus receiving location.

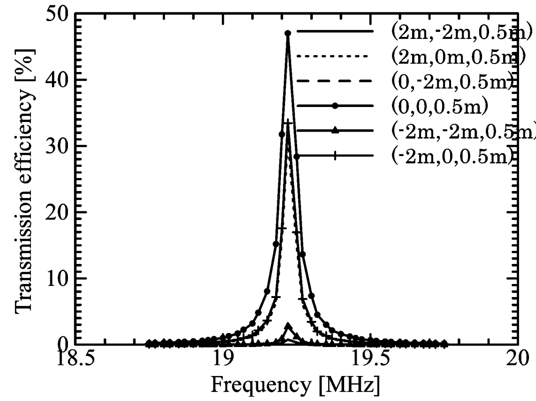

Fig. 10. Power transmission efficiency versus frequency and receiving location.

Because the reflection coefficient when $Z_l = 2\ \Omega$ almost satisfies the matching condition $\Gamma_l = s_{22}^*$, the maximum value for transmission efficiency is approached when $Z_l = 2\ \Omega$. In practical case, a detection diode which has low resistance may be possibly used as a load of 1–2 Ω to realize the matching condition given in the (7).

V. Effect of the Location of Receiving Element on Power Transmission Efficiency

Fig. 9 shows power transmission efficiency versus the receiving element's location. For the simulation, a resistance of 2 Ω is loaded for the receiving element. The receiving element is assumed to move within a rectangular area in the plane of $z = 0.5\ \mathrm{m}$. The four vertexes of the rectangular area are (-2 m, -2 m, 0.5 m),(2 m, -2 m, 0.5 m), (2 m, 0, 0.5 m) and (-2 m, 0 m, 0.5 m), respectively. Fig. 9 only shows the power transmission efficiency for when the receiving element is located within the area where $y < 0$. The efficiency for when the receiving element was located within the area where $y > 0$ is equal to that obtained within the area where $y < 0$ due to the symmetrical structure about the x-axis. The results show that a relatively higher transmission efficiency can be achieved when the receiving element is located within an area where $|x| \le 2\ \mathrm{m}$ and $|y| \le 1\ \mathrm{m}$. Fig. 10 shows power transmission efficiency as a function of frequency at five different receiving locations. The results show that the frequency of maximum efficiency does not change whenever the receiving element is located in the concerned rectangular area.

The power transmission efficiency of the proposed WPT system is compared with that of a WPT system consisting of two small loops with parasitic helices known as the 2-small loops system in Fig. 11, where the receiving element is moved along the lines of $x = 0$, $z = 0.5\ \mathrm{m}$ and $x = 2\ \mathrm{m}$, $z = 0.5\ \mathrm{m}$. The structures of transmitting element and receiving element are the same in 2-small loops WPT system, and both of them

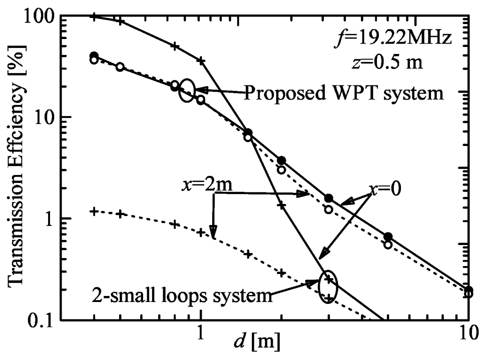

Fig. 11. Transmission efficiency comparison between proposed WPT system and 2-small loops.

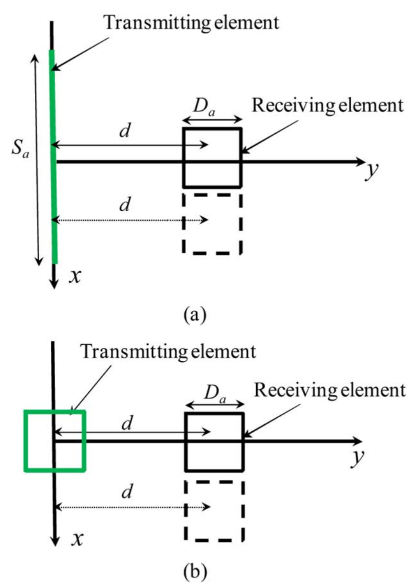

Fig. 12. Definition of d in WPT systems.

are also the same to the receiving element used in the proposed WPT system. The parameter d is defined as the distance between the transmitting element and the receiving element in the y direction, as shown in Fig. 12. If the receiving element is moved along the line of $x = 0$, $z = 0.5\ \mathrm{m}$, the transmission efficiency of the proposed WPT system decreases as the distance d increases and is less than 10% when the distance d exceeds 1 m. Under the same conditions, the transmission efficiency of the 2-small loops system is higher than that of the proposed WPT system when $d < 1\ \mathrm{m}$, however it decreases rapidly to be less than 10% if the distance d exceeds 1 m. If the receiving element is moved along the line of $x = 2\ \mathrm{m}$, $z = 0.5\ \mathrm{m}$, the transmission efficiency of the proposed WPT varies in accordance with the distance d in the same way as that when the receiving element is moved along the line of $x = 0$, $z = 0.5\ \mathrm{m}$. However, the transmission efficiency of the 2-small loops system is less than 2% in this case, considerably lower than the case when the receiving element is moved along the line of $x = 0$, $z = 0.5\ \mathrm{m}$, proving that the proposed WPT system can be operated with a relative high efficiency in a wider area.

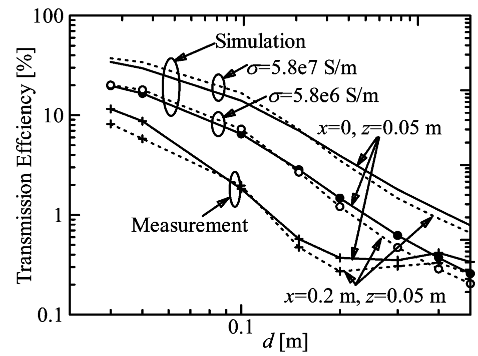

Fig. 13. Measured transmission efficiencies of proposed WPT system.

Fig. 13 shows the measured power transmission efficiencies of the proposed WPT system when the receiving element is moved along the lines of $x = 0$, $z = 0.05\ \mathrm{m}$ and $x = 0.2\ \mathrm{m}$, $z = 0.05\ \mathrm{m}$. A scale-model concept is used in the experiment because the size of transmitting element shown in Fig. 1 is too large to make a measurement in a microwave anechoic chamber. The scale-model using the 1/10 side lengths of transmitting element and receiving element except the radii, the gap between the square loop D and the helical coil C, the pitch and the number of turns for the helical coil C. The radii of all the wires-including loop S are 1.75 mm, those of loop D and helical coil C are 0.375 mm. The values for the gap between the square loop D and the helical coil C, the pitch and the number of turns for the helical coil C are adjusted to be 1 mm, 4 mm and 4.5, respectively. According to the simulation results, the scale model resonates at a frequency of about 197 MHz, near to the expected resonant frequency of 192.2 MHz as a 1/10 scale model. The simulation results shown in Fig. 13 are calculated again for the scale model, therefore they are slightly different to those in Fig. 11. From Fig. 13, it is also observed that the transmission efficiency of the proposed WPT system decreases as the distance d increases and is less than 10% when the distance d exceeds 0.1 m.

The calculated transmission efficiencies are higher than those measured ones. The reason of underestimation of conducting loss in numerical analysis when a antenna size is electrically small is explained in [13]–[15]. Usually, we reduce the conductivity in the numerical analysis to 1/10 of the theoretical one to compensate the underestimation. From Fig. 13, it is observed that the difference between the simulation results and the measurement results are reduced greatly if the conductivity of copper is set to $5.8 \times 10^6\ \mathrm{S/m}$ in the MoM simulation. Therefore, if the conducting loss for the electrical small antenna can be treated correctly in full-wave based numerical analysis, the calculated transmission efficiency agrees with the measurement one within a several percent error. Finally, it should be noted that the measured results in Fig. 13 does not appear valid for $d > 0.2\ \mathrm{m}$ because the amplitude of S_{21} is too small to be measured correctly.

VI. Effect of a Non-Resonant Object on Power Transmission Efficiency

The effect of nearby objects on the transmission efficiency is investigated in this section. The objects are assumed to be a human body, conducting scatters, etc., which are not electrically

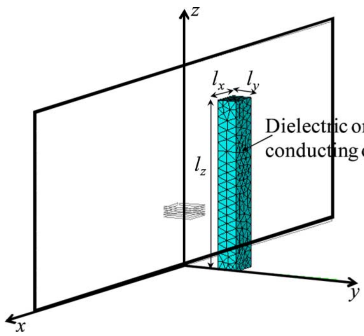

Fig. 14. WPT system with non-resonant object.

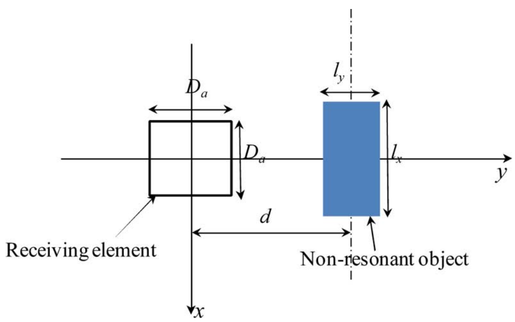

Fig. 15. Relative distance between non-resonant object and receiving element.

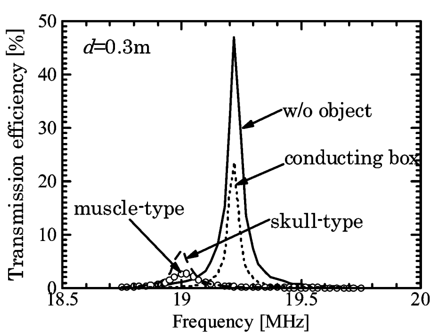

Fig. 16. Transmission efficiency with/without non-resonant object.

resonant at the frequency of transmission and called non-resonant objects. As shown in Fig. 14, the human body has, for simplicity, been modeled as a rectangular dielectric box with a size of 0.5 m × 0.2 m × 1.7 m. The distance between the center of the non-resonant object and the center of the receiving element in the y direction is denoted by d, as shown in Fig. 15. Muscle-type dielectric material with a relative dielectric constant of 107.2 and conductivity of 0.67 S/m and skull-type material with a relative dielectric constant of 36.6 and conductivity of 0.092 S/m which are based on the body tissue dielectric parameters published by FCC are used to represent the human body approximately. The conducting box has the same size as the human body.

The power transmission efficiencies for three different kinds of objects are compared in Figs. 16 and 17. In Fig. 16, the center of the receiving element is located at (0, 0, 0.5 m) while the bottom center of the human body is located at (0, 0.3 m, 0), therefore, the distance d is 0.3 m. In Fig. 17, the receiving element is located in the same position as that in Fig. 16, but d is 0.5 m. When $d = 0.3$ m, the frequency of the maximum efficiency of the WPT system shifts down to 19.00 MHz, with about a 40% reduction in power transmission efficiency occurring due to the presence of the muscle-type human body or the skull-type human body. As shown in Fig. 17, for the case when $d = 0.5$ m, however, there is less of a shift in the frequency of the maximum efficiency of the WPT system and less of a reduction in the transmission efficiency even at the presence of the muscle-type human body or the skull-type human body. The conducting box has less effect on the shift of the frequency of the maximum efficiency of the WPT system and the reduction in the transmission efficiency than the human body even for small d.

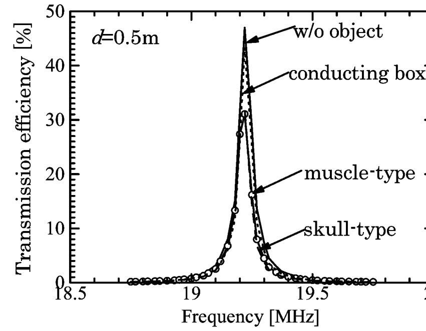

Fig. 17. Transmission efficiency with/without non-resonant object.

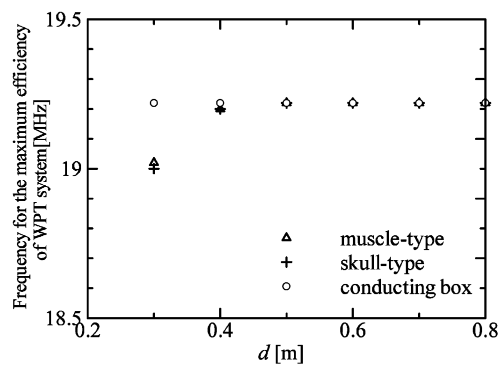

Fig. 18. Frequency for the maximum efficiency of the WPT system as a function of d.

Fig. 18 shows the frequency of the maximum efficiency of the WPT system as a function of distance d where $Z_l = 2\ \Omega$. Fig. 19 shows the input impedance of the receiving element with and without the muscle-type human body present. In Fig. 18, it can be observed that the frequency of the maximum efficiency of the WPT system shifts down when the human body comes close to the receiving element. This shift in the frequency of the maximum efficiency of the WPT system is almost the same as the shift in the resonant frequency of the receiving element as shown in Fig. 19.

Finally, power transmission efficiency as a function of d is shown in Fig. 20, which indicates that the effect of a non-resonant object such as a human body or conducting box on transmission efficiency becomes much less when the distance d is over 0.5 m.

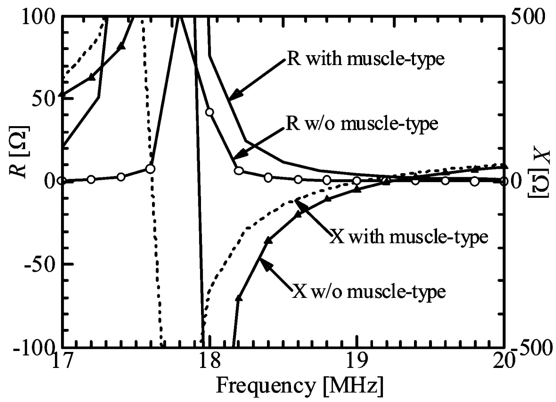

Fig. 19. Input impedance of receiving element with/without human body.

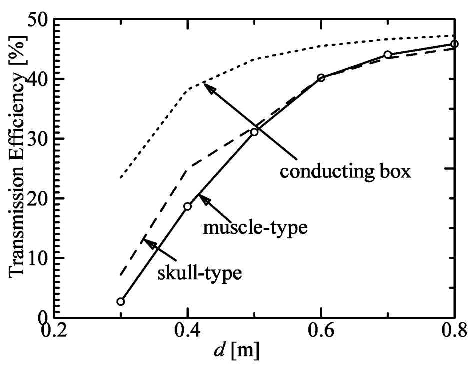

Fig. 20. Power transmission efficiency as a function of d.

VII. Conclusion

A practical wireless power transmission system consisting of a large rectangular wire loop and a small square wire loop with a parasitic square helical coil has been proposed for use as an efficient evanescent resonant coupling wireless power transfer system in an indoor environment. The advantage of this WPT system is that it can offer more stable transmission efficiency in a wider area. As is usually carried out in an antenna design, it has been suggested that the resonant frequency of the wireless power transmission system be tuned by investigating the input impedances of the transmitting element and the receiving element. At the same time, power transmission efficiency has been directly defined as the ratio of the power received at the receiving element to the power input at the source element, and this is calculated using a full electromagnetic wave solver. The optimum load for maximum power transmission efficiency has been demonstrated by using scattering parameters and the simulation results have shown that a power transmission efficiency of almost 50% can be achieved for one user with a 1–2 Ω resistance load. The simulation results have also shown that power transmission efficiency changes in accordance with the distance between the transmitting element and the receiving element, suggesting that the receiving element should be placed in a central area of $(|x| \leq 2\ \mathrm{m}, |y| \leq 1\ \mathrm{m})$.

The effect of the presence of a non-resonant object has also been investigated, revealing that the reduction in power transmission efficiency that results from the presence of a non-resonant object is serious when the non-resonant object is in very close proximity to the receiving element. The reduction caused by the presence of a human body is much larger than that caused by presence of a conducting box. However, this reduction in power transmission efficiency can be alleviated significantly if the non-resonant object is kept at a distance from the receiving object of more than 0.5 m (or 0.03λ at 19.22 MHz).

The validity of the numerical analysis on the transmission efficiency has been confirmed by measuring the transmission efficiency versus the relative locations of the receiving element of the proposed WPT. It has been found that if the conducting loss for the electrically small antenna is treated correctly in full-wave electromagnetic field simulation, the calculated transmission efficiencies agree with the measurement results within a several percent error.

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