Progress In Electromagnetics Research M, Vol. 19, 221–237, 2011

ANALYSIS ON TRANSMISSION EFFICIENCY OF WIRELESS ENERGY TRANSMISSION RESONATOR BASED ON MAGNETIC RESONANCE

J. Choi and C. Seo*

Wireless Communication RF System Lab., Department of Electronic Engineering, Soongsil University, 511 Sangdo-dong, Dongjak-gu, Seoul 156-743, Republic of Korea

Abstract—In this paper, a high-efficiency wireless energy transmission via magnetic resonance is experimentally implemented in a resonator with the various sizes of transmitting and receiving coils and the receiving coil having two shapes of rectangular and circular types. The transmission efficiency is analyzed by varying the transmission distance. The resonance between the transmitting and receiving coils is achieved with lumped capacitors terminating the coils. The transmission efficiency of the resonator consisting of a circular transmitting coil with a diameter of 60 cm and rectangular receiving coil with a one side length of 10 cm is about 80% at the transmission distance of 20 cm. The transmission efficiencies of the wireless energy transmission resonator consisting of a receiving coil with the size of iPhone4 are about 75% and 40% at the transmission distances of 20 cm and 50 cm.

1. INTRODUCTION

In recent years, there has been increasing interest in the research and development of wireless energy transmission technology to eliminate the last cable due to its wide range of applications in charging ubiquitous electronic devices such as MP3 players, PDA, tablet PC, mobile phones, and household robots without a cord. The portable devices are still constrained to the use of batteries or some other form of energy storage. Even with advances in the reduction of power consumption, the batteries are typically the largest and heaviest component in modern portable devices. The wireless energy

Received 9 May 2011, Accepted 5 July 2011, Scheduled 3 August 2011
* Corresponding author: Chulhun Seo (chulhun@ssu.ac.kr).

transmission can enable the creation of ambient power, where the devices send and receive the power to each other [1, 2].

Presently, the most popular wireless energy transmission technologies are the electromagnetic induction and microwave energy transmission. However, the electromagnetic induction has a short range and, and the microwave energy transmission has a low efficiency as it uses radiation. Recently, a highly efficient mid-range wireless energy transmission technology using magnetic resonance coupling has been proposed by WiTricity. It wirelessly transmits the energy in high efficiency at the mid-range. However, this wireless energy transmission technology has used large transmitting and receiving coils. Therefore, it has not been used to wirelessly charge small-sized ubiquitous electronic devices due to the large size of the receiving coil [3–6].

In this paper, we have simulated and measured the wireless energy transmission resonators consisting of various sizes of transmitting and receiving coils and the receiving coil having two shapes of rectangular and circular types. Also, the wireless energy transmission resonator consisting of the receiving coil with the size of iPhone4 is experimentally implemented to charge mobile phones.

2. COMPARISON ON TRANSMISSION EFFICIENCY BETWEEN CIRCULAR AND RECTANGULAR WIRELESS ENERGY TRANSMISSION RESONATORS

As shown in Fig. 1, the wireless energy transmission resonator having large transmitting and small receiving coils has been simulated by varying the transmission distance. The transmitting and receiving coils have a circular shape. The diameters (D_{Tx1}, D_{Tx2}) of coupling and resonance loops in the transmitting coil are 40 cm and 60 cm, and the diameters (D_{Rx1}, D_{Rx2}) of coupling and resonance loops in the receiving coil are 10 cm. The widths (W_{Tx}, W_{Rx}) of transmitting and receiving coils are 3 cm and 0.5 cm. The separation (S_{Tx}) of transmitting coil varies as the transmission distance for impedance matching. The separation (S_{Rx}) of receiving coil is 0.5 cm. The capacitors (C_{Tx1}, C_{Rx3}) terminating the resonance loops in the transmitting and receiving coils generate the resonance between the transmitting and receiving coils. The capacitors (C_{Rx1}, C_{Rx2}) consisting of the coupling loop in the receiving coil have been used for $50\,\Omega$ matching network. The inductance of resonance loop and capacitance of the capacitor terminating the resonance loop are given

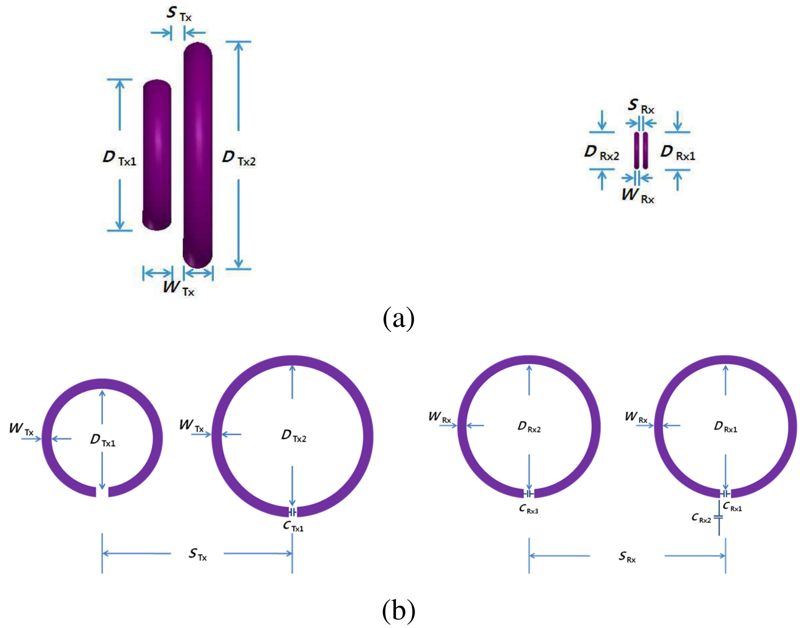


Figure 1. Wireless energy transmission resonator having large circular transmitting and small circular receiving coils. (a) Side view. (b) Front view.

by

$$L = -\frac{1}{\omega Im(Y_{11})}, \quad C = \frac{1}{\omega^2 L} \tag{1}$$

The inductances of resonance loops in the transmitting and receiving coils are 8.61 μH and 0.293 μH. The capacitances of C_{Tx1} and C_{Rx3} are 16 pF and 470 pF. The capacitances of C_{Rx1} and C_{Rx2} are 470 pF and 100 pF at the transmission distance of 20 cm. The capacitance of C_{Rx2} decreases as the transmission distance increases. The values of S_{Tx} are 24 cm, 29 cm, and 34 cm at the transmission distances of 20 cm, 30 cm, and 40 cm.

Figure 2 shows the simulated s-parameters versus the transmission distance of the wireless energy transmission resonator consisting of large circular transmitting and small circular receiving coils. The simulation has been implemented by using the High Frequency Structural Simulator (HFSS). The transmitting power of all data specified in this paper is 5 W. As shown in Fig. 2, and the transmission properties (S_{21}) are −0.81 dB, −1.367 dB, and −1.898 dB at the transmission distance of 20 cm, 30 cm, and 40 cm. The transmission

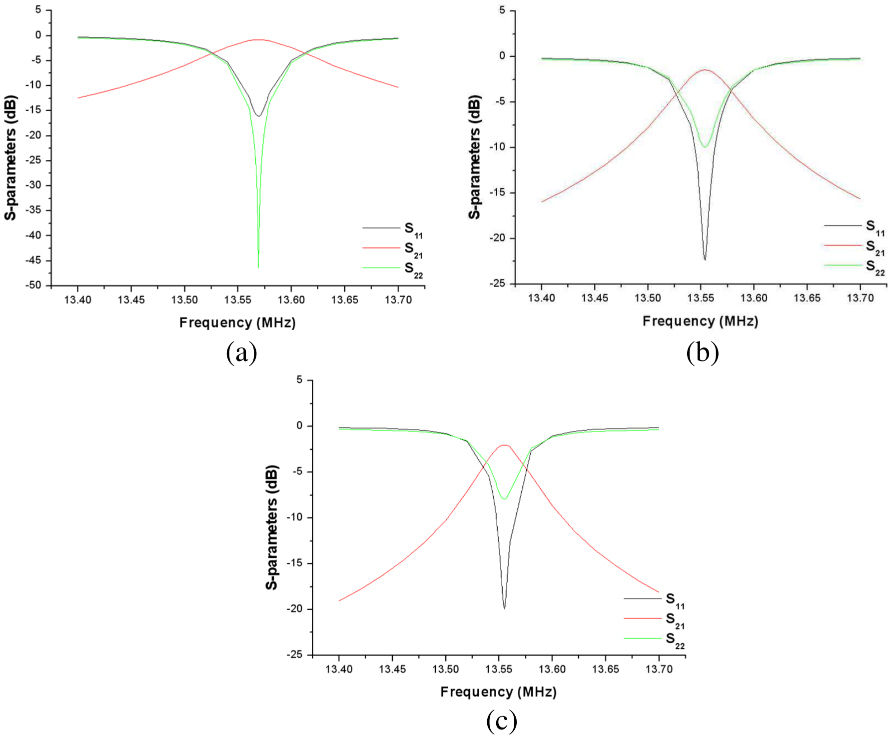


Figure 2. Simulated s-parameters versus transmission distance of wireless energy transmission resonator consisting of large circular transmitting and small circular receiving coils. (a) 20 cm. (b) 30 cm. (c) 40 cm.

efficiency has been calculated by S_{21}, then the transmission efficiencies at the transmission distance of 20 cm, 30 cm, and 40 cm are about 83.0%, 73.0%, and 64.6%. The resonance frequency is 13.56 MHz.

As shown in Fig. 3, the wireless energy transmission resonator having large circular transmitting and small rectangular receiving coils has been simulated by varying the transmission distance. The diameters (D_{Tx1}, D_{Tx2}) of coupling and resonance loops in the transmitting coil are 40 cm and 60 cm, and the lengths (D_{Rx1}, D_{Rx2}) of one side of coupling and resonance loops in the receiving coil are 10 cm. The widths (W_{Tx}, W_{Rx}) of transmitting and receiving coils are 3 cm and 0.5 cm. The separation (S_{Tx}) of transmitting coil varies as the transmission distance for the impedance matching. The separation (S_{Rx}) of receiving coil is 0.5 cm. The capacitors (C_{Tx1}, C_{Rx3}) terminating the resonance loops in the transmitting and

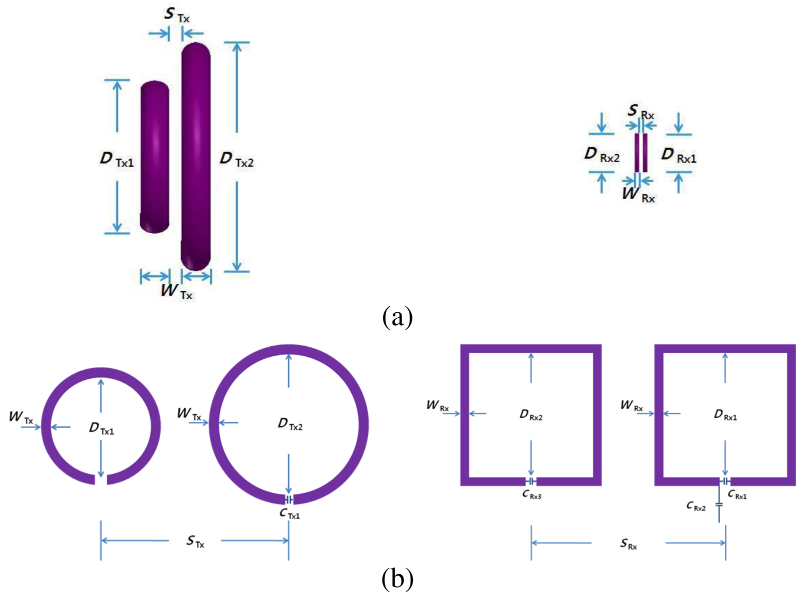


Figure 3. Wireless energy transmission resonator having large circular transmitting and small rectangular receiving coils. (a) Side view. (b) Front view.

receiving coils generate the resonance between the transmitting and receiving coils. The capacitors (C_{Rx1}, C_{Rx2}) consisting of the coupling loop in the receiving coil have been used for 50 Ω matching network. The inductances of resonance loops in the transmitting and receiving coils are 8.61 μH and 0.353 μH. The capacitances of C_{Tx1} and C_{Rx3} are 16 pF and 390 pF. The capacitances of C_{Rx1} and C_{Rx2} are 390 pF and 100 pF at the transmission distance of 20 cm. The capacitance of C_{Rx2} decreases as the transmission distance increases. The values of S_{Tx} are 20 cm, 24 cm, and 28 cm at the transmission distances of 20 cm, 30 cm, and 40 cm. The resonance frequency is 13.56 MHz.

Figure 4 shows the simulated s-parameters versus the transmission distance of the wireless energy transmission resonator consisting of the large circular transmitting and small rectangular receiving coils. As shown in Fig. 4, the transmission properties (S_{21}) are −0.706 dB, −1.226 dB, and −1.7 dB at the transmission distance of 20 cm, 30 cm, and 40 cm, then the transmission efficiencies at the transmission distance of 20 cm, 30 cm, and 40 cm are about 85.0%, 75.4%, and 67.6%.

As shown in these results, the transmission efficiency of the

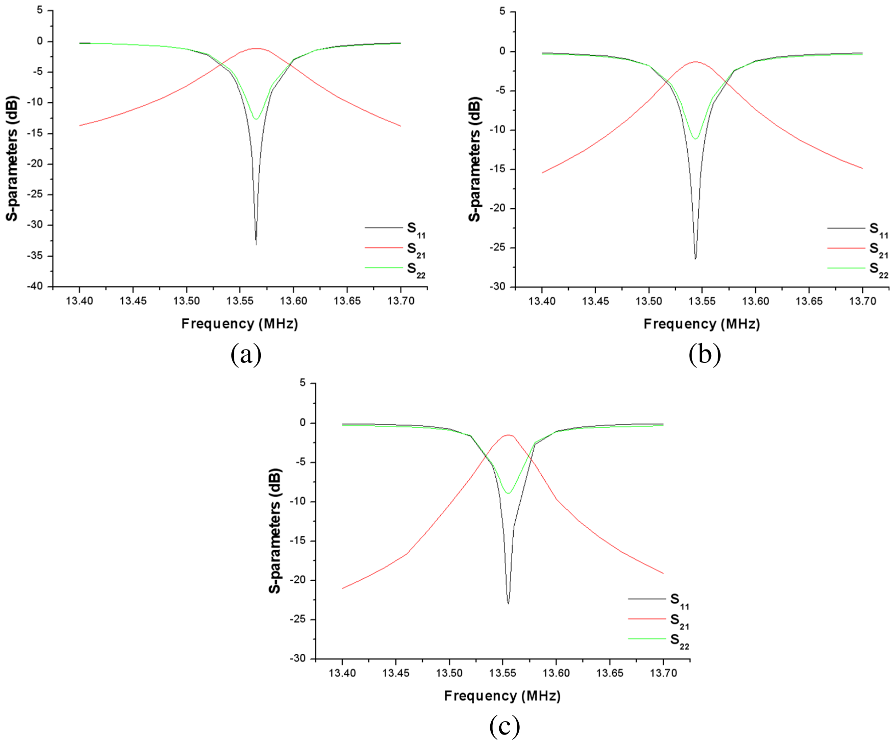


Figure 4. Simulated *s*-parameters versus transmission distance of wireless energy transmission resonator consisting of large circular transmitting and small rectangular receiving coils. (a) 20 cm. (b) 30 cm. (c) 40 cm.

wireless energy transmission resonator having a circular transmitting coil with a resonance loop of 60 cm in diameter and a rectangular receiving coil with a resonance loop of 10 cm in one side length is superior to that of the wireless energy transmission resonator having a circular transmitting coil with a resonance loop of 60 cm in diameter and a circular receiving coil with a resonance loop of 10 cm in diameter because the length of the resonance loop with a rectangular receiving coil is longer than that of the resonance loop with a circular receiving coil in the same square area. Namely, the inductance of the resonance loop with a rectangular receiving coil is larger than that of the resonance loop with a circular receiving coil in the same square area. Therefore, the capacitance of the capacitor terminating the resonance loop in the rectangular receiving coil is smaller than that of the capacitor terminating the resonance loop in the circular receiving coil, which is the reason that the transmission efficiency of the wireless energy transmission resonator using a rectangular receiving coil is superior to that of the wireless energy transmission resonator using a circular receiving coil.

Figure 5 shows the fabrication of the wireless energy transmission resonators using large circular transmitting and small circular receiving coils and large circular transmitting and small rectangular receiving coils. The wireless energy transmission resonator having a circular transmitting coil with a resonance loop of 60 cm in diameter and a circular receiving coil with a resonance loop of 10 cm in diameter and the wireless energy transmission resonator having a circular transmitting coil with a resonance loop of 60 cm in diameter and a rectangular receiving coil with a resonance loop of 10 cm in one side length have been fabricated on the copper pipes with the widths of 3 cm and 0.5 cm. Fig. 6 shows the measured s-parameters of the wireless energy transmission resonators at the transmission distance of 20 cm. As shown in the measured results, the transmission properties (S_{21}) and transmission efficiencies of the wireless energy transmission resonators using the large circular transmitting and small circular receiving coils and the large circular transmitting and small rectangular

(a) (b)

Figure 5. Fabrication of wireless energy transmission resonators. (a) Large circular transmitting and small circular receiving coils. (b) Large circular transmitting and small rectangular receiving coils.

receiving coils are -1.068 dB and 78.2%, and -0.991 dB and 79.6% at the transmission distance of 20 cm. The resonance frequency is 13.56 MHz. The impedance matching is perfectly implemented by adjusting the separation between the coupling and resonance loops of the transmitting coil and by the matching circuit on the coupling loop of the receiving coil in two wireless energy transmission resonators. Also, the measured results are similar to the simulated results. Fig. 7 shows the comparison on the transmission efficiency between the wireless energy transmission resonators using the small circular and

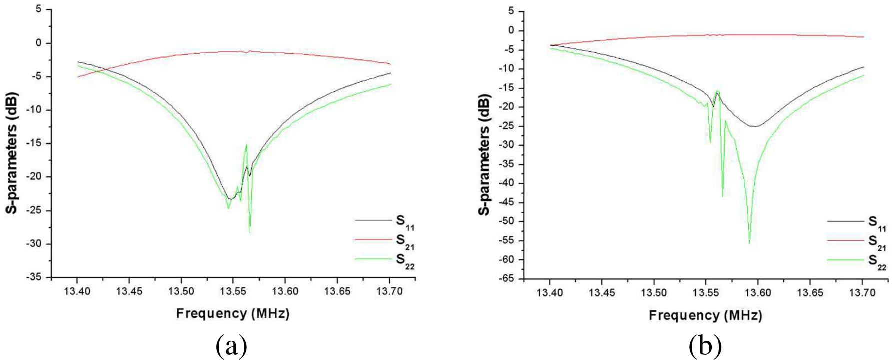


Figure 6. Measured *s*-parameters of wireless energy transmission resonators at transmission distance of 20 cm. (a) Large circular transmitting and small circular receiving coils. (b) Large circular transmitting and small rectangular receiving coils.

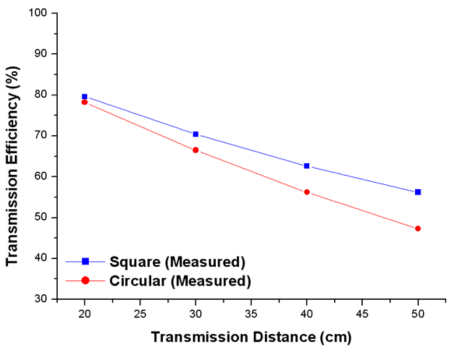


Figure 7. Comparison on transmission efficiency between wireless energy transmission resonators using small circular and rectangular receiving coils.

rectangular receiving coils as increasing the transmission distance. As shown in this result, the transmission efficiency of the wireless energy transmission resonator using a rectangular receiving coil is superior to that of the wireless energy transmission resonator using a circular receiving coil. The reason of this result is mentioned in the simulation results.

3. ANALYSIS ON TRANSMISSION EFFICIENCY OF VARIOUS SIZES OF WIRELESS ENERGY TRANSMISSION RESONATORS

As shown in Fig. 8, the wireless energy transmission resonators having the various-sized circular transmitting and receiving coils have been fabricated and measured at the transmission distance of 20 cm. In first case, the diameters (D_{Tx1}, D_{Tx2}) of coupling and resonance loops in the transmitting coil are 40 cm, and diameters (D_{Rx1}, D_{Rx2}) of coupling and resonance loops in the receiving coil are 10 cm. In second case, the diameters (D_{Tx1}, D_{Tx2}) of coupling and resonance loops in the transmitting coil are 20 cm, and diameters (D_{Rx1}, D_{Rx2}) of coupling and resonance loops in the receiving coil are 10 cm. In

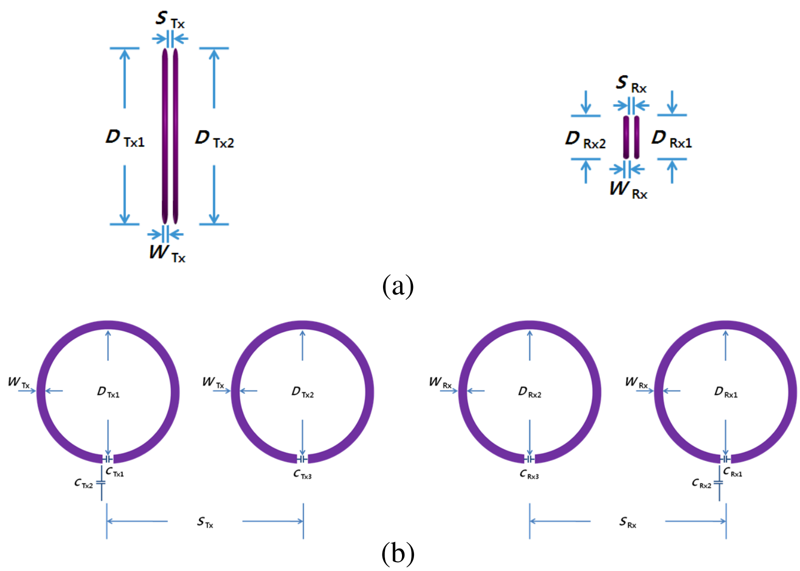


Figure 8. Wireless energy transmission resonators having various-sized circular transmitting and receiving coils. (a) Side view. (b) Front view.

third case, the diameters (D_{Tx1}, D_{Tx2}, D_{Rx1}, D_{Rx2}) of coupling and resonance loops in the transmitting and receiving coils are 10 cm. In all cases, the widths (W_{Tx}, W_{Rx}) of transmitting and receiving coils are 0.5 cm. The separations (S_{Tx}, S_{Rx}) of transmitting and receiving coils are 0.5 cm. The capacitors (C_{Tx3}, C_{Rx3}) terminating the resonance loops in the transmitting and receiving coils generate the resonance between the transmitting and receiving coils. The capacitors (C_{Tx1}, C_{Tx2}, C_{Rx1}, C_{Rx2}) consisting of the coupling loops in the transmitting and receiving coils have been used for 50 Ω matching network. In first case, the inductances of resonance loops in the transmitting and receiving coils are 3.257 μH and 0.314 μH. The capacitances of C_{Tx1} and C_{Rx1} are 42.3 pF and 439 pF, and capacitances of C_{Tx2} and C_{Rx2} are 42.9 pF and 47 pF at the transmission distance of 20 cm. The capacitances of C_{Tx3} and C_{Rx3} are 42.3 pF and 439 pF. In second case, the inductances of resonance loops in the transmitting and receiving coils are 0.918 μH and 0.315 μH. The capacitances of C_{Tx1} and C_{Rx1} are 150 pF and 437 pF, and capacitances of C_{Tx2} and C_{Rx2} are 39 pF at the transmission distance of 20 cm. The capacitances of C_{Tx3} and C_{Rx3} are 150 pF and 437 pF. In third case, the inductances of resonance loops in the transmitting and receiving coils are 0.334 μH and 0.334 μH. The capacitances of C_{Tx1} and C_{Rx1} are 470 pF, and capacitances of C_{Tx2} and C_{Rx2} are 39 pF at the transmission distance of 20 cm. The

(a) (b) (c)

Figure 9. Fabrication of wireless energy transmission resonators having various-sized circular transmitting and receiving coils. (a) $D_{Tx1} = D_{Tx2} = 40$ cm. (b) $D_{Tx1} = D_{Tx2} = 20$ cm. (c) $D_{Tx1} = D_{Tx2} = 10$ cm.

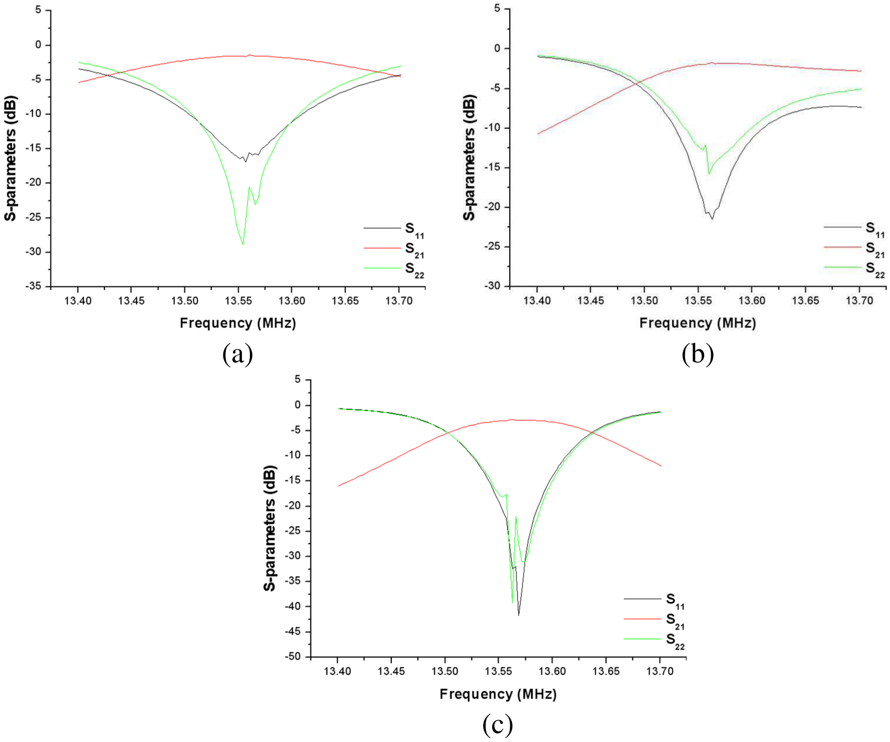
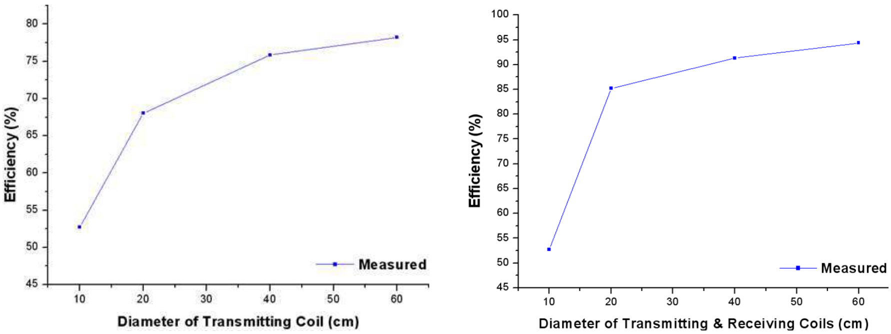


Figure 10. Measured s-parameters of wireless energy transmission resonators having various-sized circular transmitting and receiving coils at transmission distance of 20 cm. (a) $D_{Tx1} = D_{Tx2} = 40$ cm. (b) $D_{Tx1} = D_{Tx2} = 20$ cm. (c) $D_{Tx1} = D_{Tx2} = 10$ cm.

capacitances of C_{Tx3} and C_{Rx3} are 412 pF. In all cases, the resonance frequency is 13.56 MHz.

Figure 9 shows the fabrication of the wireless energy transmission resonators having the various-sized circular transmitting and receiving coils. Fig. 10 shows the measured s-parameters of the wireless energy transmission resonators having the various-sized circular transmitting and receiving coils. As shown in Fig. 10(a), the transmission property (S_{21}) and transmission efficiency of the wireless energy transmission resonator having a circular transmitting coil with coupling and resonance loops of 40 cm in diameter and a circular receiving coil with coupling and resonance loops of 10 cm in diameter are -1.2 dB and about 75.86% at the transmission distance of 20 cm. As shown in Fig. 10(b), the transmission property (S_{21}) and transmission efficiency of the wireless energy transmission resonator having a circular transmitting coil with coupling and resonance loops of 20 cm in diameter and a circular receiving coil with coupling and resonance loops of 10 cm in diameter are −1.673 dB and about 68.03% at the transmission distance of 20 cm. As shown in Fig. 10(c), the transmission property (S_{21}) and transmission efficiency of the wireless energy transmission resonator having circular transmitting and receiving coils with coupling and resonance loops of 10 cm in diameter are −2.779 dB and about 52.73% at the transmission distance of 20 cm. Fig. 11(a) shows the measured transmission efficiency as increasing the diameter of the transmitting coil in the receiving coil with the diameter of 10 cm at the transmission distance of 20 cm. As shown in the result, when the diameter of the transmitting coil increases above a certain threshold, it is expected that the contribution of increase of the transmitting coil size is progressively less significant. It is evident that increasing the diameter of the transmitting coil above a certain threshold does not produce any further improvement of the transmission efficiency in the short range. Additionally, the wireless energy transmission resonators having the same-sized circular transmitting and receiving coils have been experimented at the transmission distance of 20 cm. In first case, the diameters (D_{Tx1}, D_{Tx2}, D_{Rx1}, D_{Rx2}) of coupling and resonance loops in the transmitting and receiving coils are all 20 cm. In the second and third cases, the diameters are 40 cm and 60 cm. The other dimensions and conditions are the same as above experiments. Fig. 11(b) shows



(a) (b)

Figure 11. (a) When diameter of receiving coil is 10 cm, transmission efficiency as increasing diameter of transmitting coil at transmission distance of 20 cm. (b) Transmission efficiency versus diameter of same-sized transmitting and receiving coils at transmission distance of 20 cm.

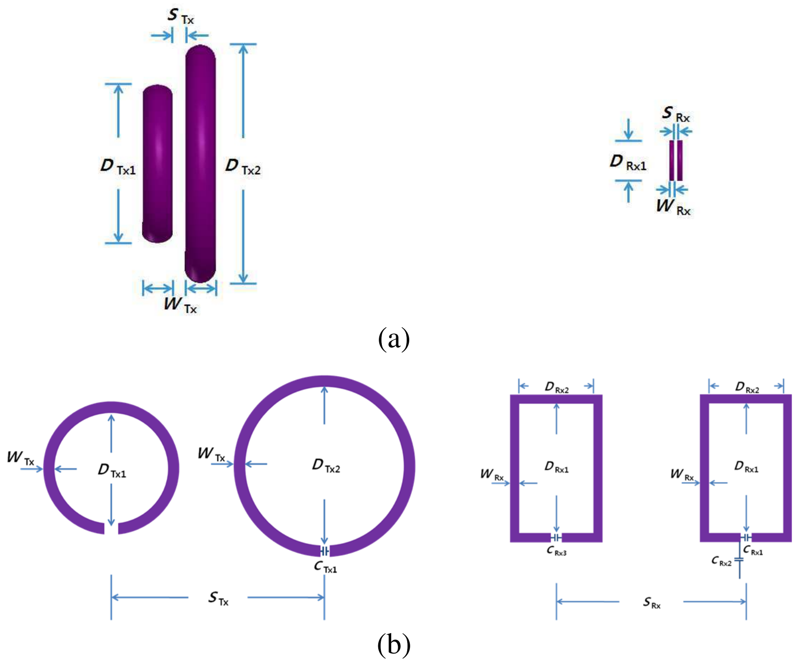


Figure 12. Wireless energy transmission resonator consisting of receiving coil with size of iPhone4. (a) Side view. (b) Front view.

the measured transmission efficiency versus the diameter of same-sized transmitting and receiving coils at the transmission distance of 20 cm. When the diameters of same-sized transmitting and receiving coils are 20 cm, 40 cm, and 60 cm, the transmission properties (S_{21}) and transmission efficiencies are -0.695 dB and 85.2%, and -0.395 dB and 91.3%, and -0.252 dB and 94.36%. The resonance frequency is 13.56 MHz. As shown in the result, when the diameter of same-sized transmitting and receiving coils increases above a certain threshold, the size increase of the transmitting and receiving coils does not produce any further improvement of the transmission efficiency in the short range. Therefore, the diameter of the coil must be selected by considering the transmission efficiency, transmission distance, and resonator size for preventing the unnecessary increase of the coil size.

As shown in Fig. 12, the wireless energy transmission resonator consisting of the receiving coil with the size of iPhone4 has been fabricated and measured to experimentally implement the mobile phone charging at the transmission distances of 20 cm and 50 cm. The diameters (D_{Tx1}, D_{Tx2}) of coupling and resonance loops in

Figure 13. Fabrication of wireless energy transmission resonator consisting of the receiving coil with the size of iPhone4.

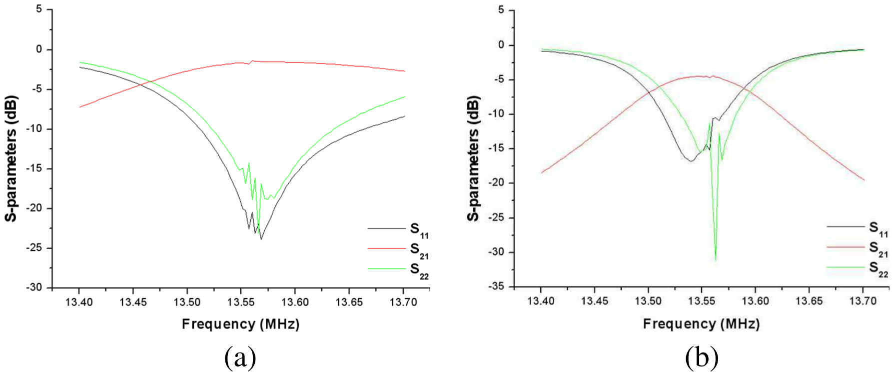


Figure 14. Measured s-parameters of wireless energy transmission resonator consisting of receiving coil with size of iPhone4 at transmission distances of 20 cm and 50 cm. (a) 20 cm. (b) 50 cm.

the transmitting coil are 40 cm and 60 cm, and the lengths (D_{Rx1}, D_{Rx2}) of length and width of coupling and resonance loops in the receiving coil are 11.52 cm and 5.86 cm. The widths (W_{Tx}, W_{Rx}) of transmitting and receiving coils are 3 cm and 0.5 cm. The separation (S_{Tx}) of transmitting coil varies as the transmission distance for the impedance matching. The separation (S_{Rx}) of receiving coil is 0.5 cm. The capacitors (C_{Tx1}, C_{Rx3}) terminating the resonance loops in the transmitting and receiving coils generate the resonance

Table 1. Summary of transmission efficiency of wireless energy transmission resonators.

Parameters	Resonance Frequency (MHz)	Transmission Distance (cm)	Transmission Efficiency (%)
Circular Tx (60 cm) Rectangular Rx (10 cm)	13.56	20	79.60
		30	70.40
		40	62.60
		50	56.20
Circular Tx (60 cm) Circular Rx (10 cm)	13.56	20	78.20
		30	66.50
		40	56.20
		50	47.30
Circular Tx (40 cm) Circular Rx (10 cm)	13.56	20	75.86
Circular Tx (20 cm) Circular Rx (10 cm)	13.56	20	68.03
Circular Tx (10 cm) Circular Rx (10 cm)	13.56	20	52.73
Circular Tx (20 cm) Circular Rx (20 cm)	13.56	20	85.20
Circular Tx (40 cm) Circular Rx (40 cm)	13.56	20	91.30
Circular Tx (60 cm) Circular Rx (60 cm)	13.56	20	94.36
Circular Tx (60 cm) Rectangular Rx (iPhone4)	13.56	20	75.00
		50	40.00

between the transmitting and receiving coils. The capacitors (C_{Rx1}, C_{Rx2}) consisting of the coupling loop in the receiving coil have been used for 50 Ω matching network. The inductances of resonance loops in the transmitting and receiving coils are 9.371 μH and 0.353 μH. The capacitances of C_{Tx1} and C_{Rx3} are 14.7 pF and 390 pF. The capacitances of C_{Rx1} and C_{Rx2} are 392 pF and 43 pF at the transmission distance of 20 cm, and those of C_{Rx1} and C_{Rx2} are 390 pF and 35 pF at the transmission distance of 50 cm. The capacitance of C_{Rx2} decreases as the transmission distance increases. The values of S_{Tx} are 15 cm and 29 cm at the transmission distances of 20 cm and 50 cm. The resonance frequency is 13.56 MHz.

Figure 13 shows the fabrication of the wireless energy transmission resonator consisting of a receiving coil with the size of iPhone4. Fig. 14 shows the measured s-parameters of the wireless energy transmission resonator consisting of a receiving coil with the size of iPhone4. As shown in Fig. 14, the transmission properties (S_{21}) and transmission efficiencies are -1.25 dB and about 75%, and -3.98 dB and 40% at the transmission distances of 20 cm and 50 cm.

The summary of the transmission efficiency of the wireless energy transmission resonators consisting of various sizes of transmitting and receiving coils and the receiving coil with two shapes of circular and rectangular types is shown in Table 1.

4. CONCLUSIONS

A high-efficiency wireless energy transmission via magnetic resonance is experimentally implemented in a resonator with various sizes of transmitting and receiving coils and the receiving coil having two shapes of rectangular and circular types. The transmission efficiency is analyzed by varying the transmission distance. The resonance between the transmitting and receiving coils is achieved with lumped capacitors terminating the coils. The transmission efficiency of the wireless energy transmission resonator with a rectangular receiving coil is superior to that of the wireless energy transmission resonator with a circular receiving coil. Increasing the diameter of the transmitting coil above a certain threshold does not produce any further improvement of transmission efficiency in the short range. The diameter of the coil must be selected by considering the transmission efficiency, transmission distance, and resonator size for preventing the unnecessary increase of coil size.

ACKNOWLEDGMENT

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2011-0000223).

REFERENCES

1. Choi, J. and C. Seo, “High-efficiency wireless energy transmission using magnetic resonance based on metamaterial with relative permeability equal to −1,” *Progress In Electromagnetics Research*, Vol. 106, 33–47, 2010.

2. Miranda, J. O. M., G. Fanti, Y. Feng, K. Omanakuttan, R. Ongie, A. Setjoadi, and N. Sharpe, "Wireless power transfer using weakly coupled magnetostatic resonators," *IEEE Energy Conversion Congress and Exposition*, 4179–4186, 2010.
3. Karalis, A., J. D. Joannopoulos, and M. Soljacic, "Efficient wireless non-radiative mid-range energy transfer," *Annals of Physics*, Vol. 323, No. 1, 34–48, 2008.
4. Kurs, A., A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljacic, "Wireless power transfer via strongly coupled magnetic resonance," *Science*, Vol. 317, No. 6, 83–86, 2007.
5. Cannon, B. L., J. F. Hoburg, D. D. Stancil, and S. C. Goldstein, "Magnetic resonant coupling as a potential means for wireless power transfer to multiple small receivers," *IEEE Transactions on Power Electronics*, Vol. 24, No. 7, 1819–1825, 2009.
6. Yuan, Q., Q. Chen, L. Li, and K. Sawaya, "Numerical analysis on transmission efficiency of evanescent resonant coupling wireless power transfer system," *IEEE Transactions on Antennas and Propagation*, Vol. 58, No. 5, 1751–1758, 2010.