Coil Design with Frequency-Insensitive Characteristics for Wireless Power Transfer

#Wang-Sang Lee, Wang-Ik Son, Kyoung-Sub Oh, Jong-Won Yu
Department of Electrical Engineering, KAIST, Daejeon, Korea
wsang@kaist.ac.kr
ksfaraday@msn.com
wangik@kaist.ac.kr
drjwyu@ee.kaist.ac.kr

Abstract

This paper proposes the frequency-insensitive coil and its optimal design for uniform transfer efficiency according to the distance. The proposed technique achieves the frequency variation six times less than that of the conventional unidirectional loops, and improves the power efficiency to a maximum of 87%.

Keywords : Wireless power transfer, Frequency insensitive, Coil design

1. Introduction

With the increasing deployment of wireless technologies, portable devices such as laptops, PDAs, and cellular phones takes the essential part of daily life. Such devices require high mobility and minimal size, and use rechargeable batteries. Since the available battery duration after recharge cannot satisfy the amount of using devices, users feel inconvenience in charging the batteries with power cords or replacing the batteries. To solve this problem, the studies for wireless power transfer (WPT) technologies have been actively done [1]-[3].

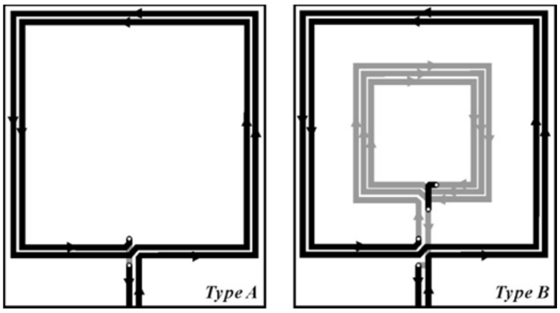
In order to achieve greater efficiency in the energy transfer, the coil radius related to the mutual inductance between the resonant coils needs to be larger. However, if it is close to the coil distance, the coupling coefficient between the transmitting and receiving resonant coils increases. This phenomenon causes the separation of the resonant frequencies and the efficiency degradation problem. Since the transfer efficiency can be varied in the non-radiative WPT technology according to the distance between the coils, short distances rapidly degrade the efficiency [4].

To solve the problem of low efficiency with respect to the receiving coil location, WPT systems generally achieve the maximum power transfer efficiency through the addition of automatic frequency tuning circuits [5]. However, the addition of automatic frequency tuning techniques complicates the system structure because the impedance matching circuit should be tuned according to the transmitted power and reflected power. Therefore, this paper presents the WPT system using the forward and reverse loops without the need for additional system configuration to solve the transfer efficiency variation according to the distance between the coils.

2. Frequency-Insensitive Coil Design

This study concentrates on the WPT using the 13.56 MHz frequency band for application to HF RFID and NFC targeting for mobile phone application. The configuration of the transmitting with forward or reverse resonant loops is depicted in Fig. 1. Fig. 1(a) shows the typical transmitting coil having the forward resonant loops, whereas Fig. 1(b) is the proposed coil design using the forward and reverse resonant loops. The receiving coil uses the inlay model of the TI Tag-it HF-I Transponder.

The conventional unidirectional transmitting and receiving loops are forced to increase the mutual inductance as they move closer together. As mentioned above, the performance of the WPT systems drops significantly due to the resonant frequency splitting. In the proposed transmitting resonant loops, as the transmitting loops moves closer to a receiving coil, the reverse loop located in the center shows the effects of suppressing the increase in the mutual inductance. Then, it maintains the same mutual inductance at the same level within the working range. Since the outer forward and inner reverse resonant loops are fixed in the transmitting coils, the mutual inductance between the two is constant regardless of the distance variation from the receiving coils.



(a) (b)

Fig. 1 (a) Coil structure (Type A) with the conventional unidirectional resonant loops. (b) Proposed coil structure (Type B) with forward and reverse loops (in the two layer PCB, the black pattern is on the top layer, and the gray pattern is on the bottom layer).

Fig. 2 shows the equivalent circuit models. The mutual inductance between the resonant coils exists as a function of the coil distance (h). The mutual inductance of the two concentric coils depends on the geometry of the two resonant coils, primarily the distance between the coils. The mutual inductances (M_f (h), M_r(h)) between the forward or reverse transmitting loops and receiving loops are defined as a function of the distance between the coils, respectively. Using the superposition theorem, the total mutual inductance (M(h)) between the transmitting and receiving coils can be easily obtained from the sum of M_f (h) and M_r(h). Additionally, the mutual inductance (M_{fr}) between the forward and reverse transmitting loops regardless of the distance from the receiving loops is held constant.

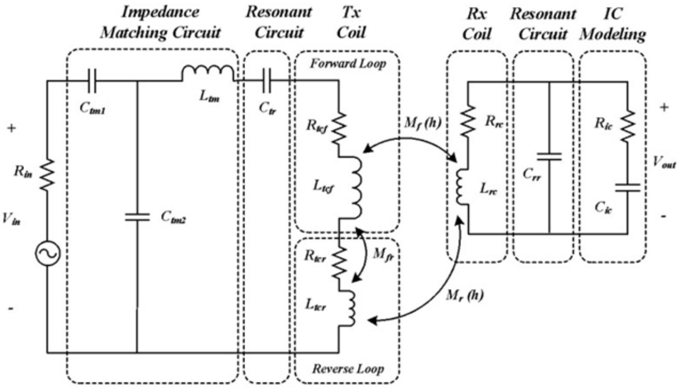


Fig. 2 Equivalent circuits of the power transfer system with impedance matching and resonant conditions between the transmitting and receiving coils.

$$S_{21} = \frac{\dfrac{-2j\omega M}{\omega^2 C_{tm2} C_{rr2}}}{[Z_T Z_{LP}^2 + Z_R Z_{SP}^2 + \omega^2 (Z_S + Z_L) M^2] + \dfrac{1}{Z_0}[Z_{SP}^2 Z_{LP}^2 + \omega^2 Z_L Z_S M^2] + (Z_T Z_R + \omega^2 M^2) Z_0} \tag{1}$$

where the related parameters are the following :

$$
\begin{aligned}
Z_{SP}^2 &= Z_T Z_S + \frac{1}{w^2 C_{tm2}^2}, \qquad & Z_{LP}^2 &= Z_R Z_L + \frac{1}{\omega^2 C_{rr2}^2},\\
Z_S &= \frac{1}{j\omega C_{tm1}} + \frac{1}{j\omega C_{tm2}}, \qquad & Z_L &= j\omega L_{pt} + \frac{1}{j\omega C_{rr2}} + \frac{1}{j\omega C_{pt}}\\
Z_R &= R_{rc} + j\omega L_{rc} + \frac{1}{j\omega C_{rr1}} + \frac{1}{j\omega C_{rr2}}, \qquad & Z_T &= R_{tc} + j\omega L_{tc} + j\omega L_{tm} + \frac{1}{j\omega C_{tm2}} + \frac{1}{j\omega C_{tr}},
\end{aligned}
\tag{2}
$$

3. Experiment Results

As the transmitting loops moves closer to a receiving coil, the reverse loop located in the center shows the effects of suppressing the increase in the mutual inductance. Then, it maintains the same mutual inductance at the same level within the working range.

In Fig. 3, when the distance between the coils is changed, S21 regarding the resonant frequency is plotted in the frequency domain to compare the frequency insensitive characteristics between the transmitting coil (Type A or Type B) and the receiving coil. Frequency splitting is clearly shown when the receiving coil approaches to Type A, However, the effect of the resonant frequency does not applear in Type B because the reverse loop of Type B inhibits the growth in the mutual inductance.

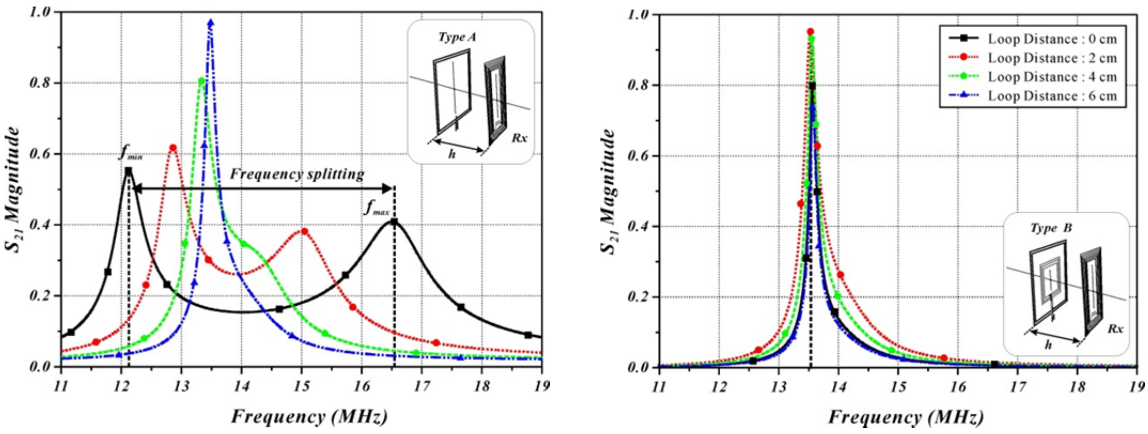


Fig. 3 Comparison of the frequency splitting characteristics in the CE between the transmitting coil(Type A or Type B) and the receiving coil.

Fig. 4(a) shows the comparison between the simulation and measurement for the contactless power transfer using the proposed coil structure. The simulated results are 5% higher than the measured results due to the implementation error or measurement uncertainty. Also, the performance of the frequency insensitivity between Type A and Type B are clearly distinguished from 1 cm to 5 cm. The proposed resonant loops (Type B) maintain uniform efficiency within the operating range. The gap of the two resonant frequencies in Type B is six times less than that in Type A. For the efficiency, Type B remains unchanged within the working range (1 cm - 5 cm), and is up to two times higher.

Fig. 4(b) shows the influence of the matching distance, which determines the uniform efficiency in the coil size . In the vicinity of the loop radius, the influence of the mutual inductance is shown. For this reason, it is difficult to obtain good performances (efficiency and frequency insensitivity) at the distance far from the radius of the loops.

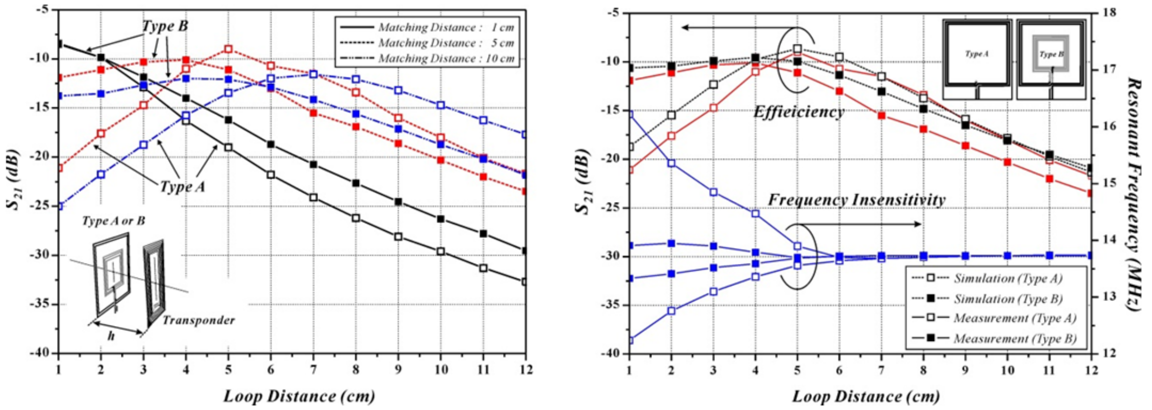


Fig. 4 (a) Simulated and measured results between the transmitting coil (Type A or Type B) and the receiving coil(matching distance = 5 cm). (b) S21 comparison between the transmitting coil (Type A or Type B) and the receiving coil regarding the matching distance.

In the NFC from the reader to the tag, sufficient voltage is required from the reader in order to operate the tag IC. Using the proposed system structures, the signal waveforms in the tag are analyzed through supplying the signal with data from the reader. The transmitting coil in the reader is connected to the signal generator with a 1 mWatt (0 dBm) magnitude and pulse modulation (pulse period = 16 us, pulse width = 8 us) at 13.56 MHz. The signal waveform of the tag is measured using an oscilloscope. The voltage levels obtained from the reader according to the transmitting coil types (Type A or Type B). If the received powers of Type A at 5 cm normalize those of Type B, the WPT efficiency of 87 % is improved at 1 cm in the proposed resonant loops (Type B).

4. Conclusion

In wireless power transfer systems using forward and reverse resonant loops, appropriate loop designs permit the uniform mutual inductance and insensitive resonant frequency characteristics. These resonant loops provide the improved efficiency of a maximum of 87 % and six times the frequency insensitivity characteristics compared with unidirectional resonant loops within the transferring range, regardless of the additional automatic resonant circuits.

References

[1] Chen C.-J., Chu T.-H., Lin C.-L., Jou Z.-C., “A study of loosely coupled coils for wireless power transfer,” Circuits and Systems II: Express Briefs, IEEE Transactions on, vol. 57, no. 7, pp. 536-540, Jul. 2010.

[2] Ick-Jae Yoon, Hao Ling, “Realizing efficient wireless power transfer using small folded cylindrical helix dipoles,” Antennas and Wireless Propagation Letters, IEEE, vol. 9, pp. 846-849, Aug. 2010.

[3] Awai I., Komori T., “A Simple and versatile design method of resonator coupled wireless power transfer system,” Communications, Circuits and Systems (ICCCAS), 2010 International Conference on, pp. 616-620, Jul. 2010.

[4] Imura T., “Study on maximum air-gap and efficiency of magnetic resonant coupling for wireless power transfer using equivalent circuit,” Industrial Electronics (ISIE), 2010 IEEE International Symposium on, pp. 3664-3669, Jul. 2010.

[5] Sample P., Meyer T.,Smith R., “Analysis, experimental results, and range adaptation of magnetically coupled resonators for wireless power transfer,” Industrial Electronics, IEEE Transactions on, Feb. 2011.