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A capacitor-loaded cylindrical resonant coil with parallel connection

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A capacitor-loaded cylindrical resonant coil with parallel connection for high effective wireless power transfer is presented. The characteristics of the proposed resonant coil are verified by the comparisons among the theoretical analysis, simulation results, and experimental measurements. By controlling the current in the capacitor-loaded resonant coil, the non-degraded overall transfer efficiency between the transmitting and receiving resonant coils can be improved up to 43% compared to the cylindrical coil regardless of the locations of the receiving coil at the transfer distance. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4744959]

Portable electronic devices, such as cellular phones, personal digital assistants (PDAs), portable media players (PMPs), moving picture experts group (MPEG) audio layer 3 players, or notebook computers, cannot be plugged into the regular power at home or office since they are generally used while the users are moving. Accordingly, the portable electronic devices are equipped with rechargeable batteries. Due to the contact failure of charging connectors or the collected humidity and dust on the connectors, the contact charging system using the power supply connectors has been used uncomfortably. On the other hand, to solve these problems, non-contacting charging systems using an inductive, capacitive, or electromagnetic coupling have been developed. Inductively or capacitively coupled wireless power transfer (WPT) has high efficiency, but the spacing between transmitting and receiving antennas must be very close (e.g., within thousandths of meters). Moreover, coupling alignment is also important.[1–5]

Recent years have seen attention focused on non-contacting charging systems based on magnetic resonance that relies on the electromagnetic resonant method. The non-contacting power feeding method based on the electromagnetic resonance is advantageous in that it allows for power transmission over a longer distance than inductively or capacitively coupled method.[6–9] Furthermore, the transmission efficiency using a resonant method does not degrade much even with somewhat poor alignment. To realize efficient non-radiative mid-range WPT, self-resonant coupling method which uses stray capacitance for a resonance in the transmitting and receiving resonant coils is being developed.

The transfer efficiency for WPT using a self-resonant coupling method is higher than inductor-capacitor (LC) resonant coupling method using discrete capacitors in a long distance due to the high Q-factor and low loss.[5,9] However, since portable devices with a wireless charging function are required to compact receiving coil for easy of carrying, LC resonant coupling method with direct feeding is used.[8] Furthermore, a general transmitting resonant coil with a larger loop size than that of a receiving resonant coil for charging portable devices possesses uneven magnetic field distribution above the charging surface, which causes the variation of transfer efficiency based on misaligned positions of a receiving device.[10–12] Therefore, the transmitting coil must have uniform magnetic field distribution for highly efficient WPT without regard to the positions of a receiving coil. Planar spiral coils[13] and multiple coils in parallel[14] to have a uniform characteristic are studied, but the degraded transfer efficiency at the edge of the large transmitting coil remains unchanged. In order to improve the uniform characteristics, a spatially structured coil[15] was presented. In case of large transmitting coil size, there is a problem that the vertical height becomes large. In this paper, by controlling the current using a loaded capacitor on the cylindrical resonant coil with concentrically parallel connection, a capacitor-loaded cylindrical resonant coil with perpendicularly uniform magnetic field distribution above the charging surface is presented. Figs. 1(a)–1(c) show a schematic representation of the conventional, cylindrical, and proposed structure for a transmitting coil, respectively.

Based on the Biot-Savart law to determine the magnetic field about a current (I) of a circular loop, the perpendicular magnetic field (H_z^{con}) with radius (r_1) and line width (w) at the transfer distance (h) from a circular-shaped conventional coil with a single turn shown in Fig. 1(a) can be calculated by Eq. (1).

$$H_z^{con}(\rho,\phi,h) = \frac{I}{2\pi w}\int_0^w f_c(\rho,h,l)\,dl, \tag{1}$$

where

$$f_c(\rho,h,l) = \frac{\left[K(k_1) + \dfrac{(r_1+l)^2-\rho^2-h^2}{(r_1+l-\rho)^2+h^2}E(k_1)\right]}{\sqrt{(r_1+l+\rho)^2+h^2}} \tag{2}$$

and $k_1^2 = \frac{4(r_1+l)\rho}{(r_1+l+\rho)^2+h^2}$. In Fig. 1(b), H_z^{ref} with radius (r_1) and height (w) at the transfer distance (h) from a cylindrical single loop can be calculated by Eq. (3) at $H_z(\rho,\phi,h)|_{n=1}$.

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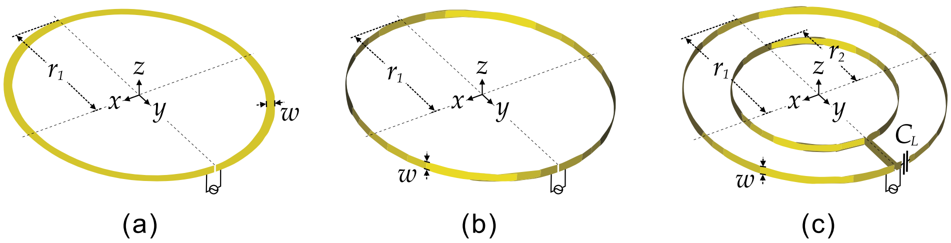

FIG. 1. The simplified geometry of transmitting coils with a single turn for WPT: (a) conventional coil structure, (b) cylindrical structure, and (c) proposed coil structure with a loaded capacitor.

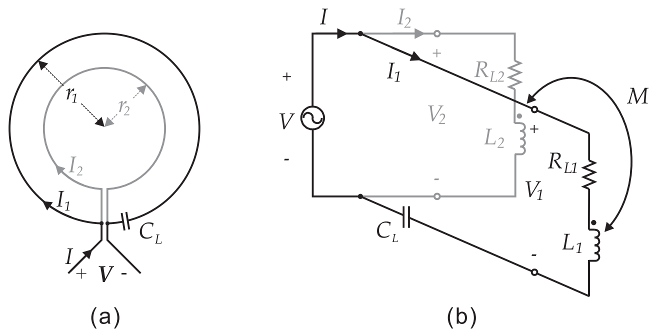

FIG. 2. The capacitor-loaded cylindrical parallel coil with different loop radii (r_1 and r_2): (a) proposed coil and (b) its equivalent circuit.

$$H_z(\rho,\phi,h) = \sum_{i=1}^{n} \frac{I_i}{2\pi w} \int_0^w f_p^i(\rho,h,l)\,dl, \tag{3}$$

where

$$f_p^i(\rho,h,l) = \frac{\left[K(k_i) + \frac{r_i^2 - \rho^2 - (h+l)^2}{(r_i-\rho)^2 + (h+l)^2} E(k_i)\right]}{\sqrt{(r_i+\rho)^2 + (h+l)^2}} \tag{4}$$

and $k_i^2 = \frac{4r_i\rho}{(r_i+\rho)^2+(h+l)^2}$. However, a proposed cylindrical coil with different size loops (r_1 and r_2) in Fig. 1(c) has a loaded capacitor (C_L) in the outer loop for the purpose of improved uniform magnetic field distribution. If the C_L is defined from appropriate current control in the inner and outer loops, its H_z^{pro} by using superposition to give the total contribution from inner and outer loops can be calculated by Eq. (3) at $H_z(\rho,\phi,h)|_{n=2}$.

Figs. 2(a) and 2(b) show a simplified top-view of capacitor-loaded proposed coil and its equivalent circuit, respectively. In order to have a uniform magnetic field distribution at the charging surface, total current (I) is divided into I_1 and I_2 at the different loops (r_1 and r_2) by using a loaded capacitor (C_L). Inner and outer loops in the proposed coil are expressed in terms of simple series resistor-inductor circuits, and the mutual inductance (M) between the circular loops is obtained.

To verify the operating principles and an improved performance compared to previous coils, the proposed capacitor-loaded coil having vertical line width ($w = 10$ mm) on inner and outer loops ($r_1 = 150$ mm and $r_2 = 95$ mm) is designed and fabricated on a metal sheet with copper thickness $t = 1$ mm. Applying for wireless powering and high data transmission to mobile devices, our target operation frequency was set to 13.56 MHz in the industrial, scientific, and medical (ISM) band. Using the finite-different time-domain (FDTD) method, the conventional, cylindrical, and proposed capacitor-loaded coils in Figs. 1(a)–1(c) are simulated. As shown in Fig. 3, the perpendicular magnetic field distribution at h_1 of the proposed structure shows the distinction from the previous structure. H_z^{con} of the conventional coil has a five times more peak value at the edge than at the center. Additionally, H_z^{ref} of the cylindrical coil is three times higher at

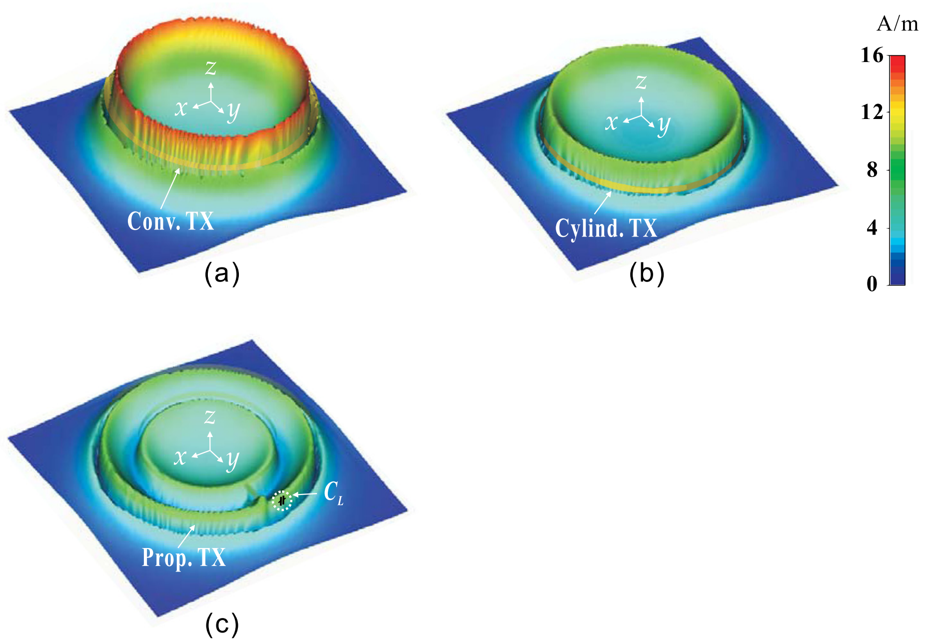

FIG. 3. The perpendicular magnetic field distribution at the distance ($h_1 = 5$ mm) from a (a) conventional, (b) cylindrical, and (c) proposed capacitor-loaded coil.

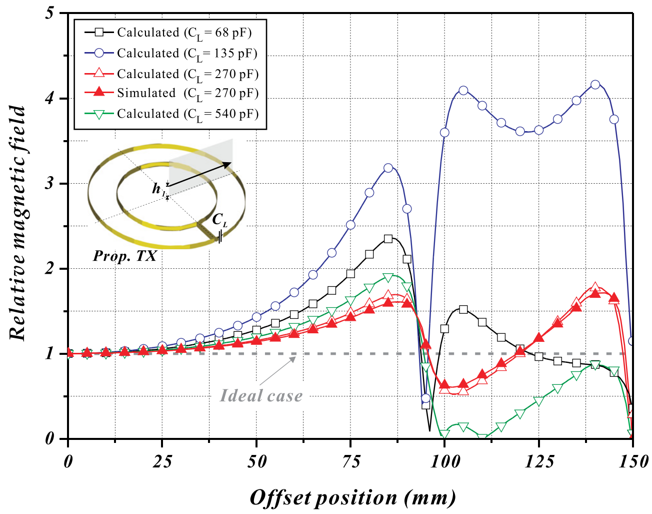

FIG. 4. Relative magnetic fields at the distance ($h_1 = 5\,\text{mm}$) according to various capacitors in the proposed capacitor-loaded coil.

the edge due to the low vertical height, whereas the H_z^{pro} of the proposed coil remains unchanged at the distance of h_1.

Inner and outer loops in the proposed capacitor-loaded coil are parallel-connected for uniform magnetic field distribution with the low vertical height. According to the loading capacitance, each current (I_1 and I_2) is inversely proportional to the impedances of outer and inner loops, respectively. From the equivalent circuit in Fig. 2, $R_{L1} = 0.09\,\Omega$ and $L_1 = 790\,\text{nH}$ in the outer loop, $R_{L2} = 0.06\,\Omega$ and $L_2 = 457\,\text{nH}$ in the inner loop, and $M = 146$ nH between the inner and outer loops are calculated. Therefore, the optimum current ratio of the outer to inner loop is approximately 7:3. As shown in Fig. 4, the appropriate capacitor (C_L) in the outer loop of the proposed coil is inserted for the required current distribution.

Using Eqs. (1) and (3) for the theoretical analysis, we can numerically calculate the H_z^{con}, H_z^{ref}, and H_z^{pro} at the distance of h_1 from the coil. When normalized on the basis of the H_z on the center, Fig. 4 compares the calculated and simulated relative magnetic fields for the center-to-edge direction at h_1. Approaching to the close proximity of the coil, the relative magnetic fields of the previous coils, such as conventional and cylindrical coils, are significantly higher than those of the proposed coil. Meanwhile, there is a good agreement between the calculated and simulated results.

To demonstrate the enhanced transfer efficiency of the proposed coil for WPT in both simulation and measurement, the conventional, cylindrical, and proposed coils are used as the transmitting coils, and the receiving coil having a single turn is made by the loop radius of 30 mm and line width of 5 mm. Moreover, series and parallel capacitors for impedance matching are added to the transmitting and receiving coils. When the receiving coil is located at a distance, h_1, from the center of the transmitting coil, the equivalent capacitances can be determined. In this case, the transmitting

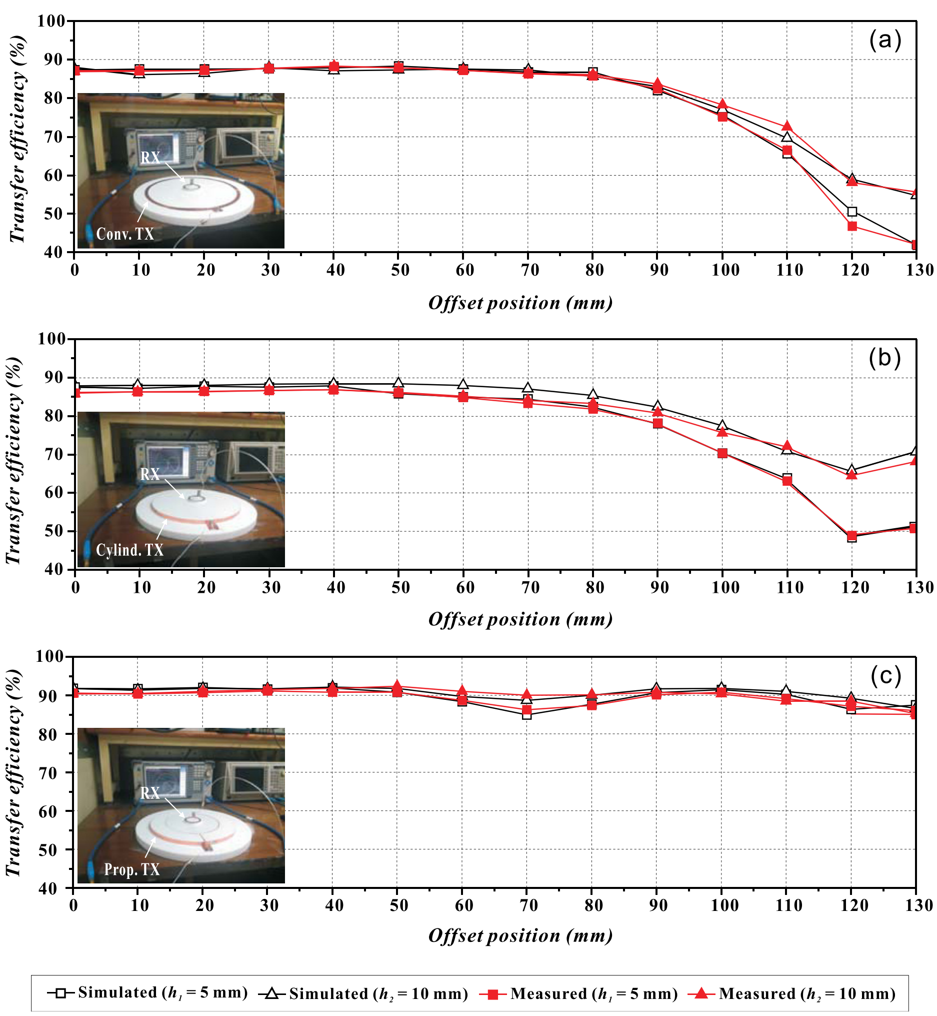

FIG. 5. The simulated and measured transfer efficiencies at the center and offset positions of the receiving coil from different distances of $h_1 = 5\,\text{mm}$ and $h_2 = 10\,\text{mm}$ on (a) the conventional, (b) cylindrical, and (c) proposed transmitting coil.

and receiving coils are in resonance, and the resonant frequencies of the transmitting and receiving coils are the same. The maximum transfer efficiency for WPT is obtained. The transfer efficiency between the transmitting and receiving coils is measured by connecting each of the transmitting and receiving coils to a two-port vector network analyzer (VNA).

Fig. 5 shows the simulated and measured transfer efficiencies of the transmitting coil with regard to the positions of the receiving coil from different distances ($h_1 = 5$ mm and $h_2 = 10$ mm). When the receiving coil is located at the center position, the impedance matching between the transmitting and receiving coils is done at h_1 and h_2, respectively. At the operating frequency of 13.56 MHz, the measured transfer efficiency significantly decreases from 87% to 42% when the receiving coil is moved away from the center of the conventional transmitting coil at h_1 as shown in Fig. 5(a). However, Fig. 5(c) shows that the proposed transmitting coil has no variation in the transfer efficiency regardless of the positions of the receiving coil at various charging distances. At the distance of h_1 from the proposed coil, the measured minimum efficiency is about 86%, which is significantly higher than that of the conventional and cylindrical transmitting coil in Figs. 5(a) and 5(b). Compared to the cylindrical coil, the proposed coil shows a relative improvement of 43% in transfer efficiency at h_1.

In conclusion, we proposed a capacitor-loaded cylindrical resonant coil with uniform magnetic field distribution for WPT. Based on the theoretical analysis and numerical simulation, the uniform characteristic of the proposed coil was demonstrated. Additionally, experimental validation by measuring the overall efficiency with regard to the position of the receiving coil was conducted and compared with the simulated results. The minimum transfer efficiency of 86% at $h_1 = 5$ mm can be achieved wherever the receiving coil is located at a transfer distance of h_1. The WPT system with the proposed coil shows an improved transfer efficiency of 43% compared to the cylindrical coil and verifies the non-degraded WPT efficiency with a uniform magnetic field distribution.

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[1] J. Hirai, T. Kim, and A. Kawamura, IEEE Trans. Power Electron. **15**, 335 (2000).
[2] B. Choi, J. Nho, H. Cha, T. Ahn, and S. Choi, IEEE Trans. Ind. Electron. **51**, 140 (2004).
[3] F. Segura-Quijano, J. García-Cantón, J. Sacristán, T. Osés, and A. Baldi, Appl. Phys. Lett. **92**, 074102 (2008).
[4] C. Liu, A. Hu, and N.-K. Nair, IET Power Electron. **4**, 808 (2011).
[5] A. Kurs, A. Karalis, R. Moffatt, J. Joannopoulos, P. Fisher, and M. Soljačić, Science **317**, 83 (2007).
[6] A. Kurs, R. Moffatt, and M. Soljačić, Appl. Phys. Lett. **96**, 044102 (2010).
[7] A. P. Sample, D. A. Meyer, and J. R. Smith, IEEE Trans. Ind. Electron. **58**, 544 (2011).
[8] A. Karalis, J. Joannopoulos, and M. Soljačić, Ann. Phys. **323**, 34 (2008).
[9] I. Sasada, J. Appl. Phys. **111**, 07E733 (2012).
[10] K. Fotopoulou and B. W. Flynn, IEEE Trans. Magn. **47**, 416 (2011).
[11] Q. Yuan, Q. Chen, L. Li, and K. Sawaya, IEEE Trans. Antennas Propag. **58**, 1751 (2010).
[12] T. Bieler, M. Perrottet, V. Nguyen, and Y. Perriard, IEEE Trans. Ind. Appl. **38**, 1266 (2002).
[13] J. J. Casanova, Z. N. Low, J. Lin, and R. Tseng, "Transmitting coil achieving uniform magnetic field distribution for planar wireless power transfer system," in IEEE Radio and Wireless Symposium, San Diego, CA, 18–22 January 2009.
[14] J. J. Casanova, Z. N. Low, and J. Lin, IEEE Trans. Ind. Electron. **56**, 3060 (2009).
[15] W.-S. Lee, H. L. Lee, K.-S. Oh, and J.-W. Yu, Appl. Phys. Lett. **100**, 214105 (2012).