

A Quantitative Analysis of Coupling for a WPT System Including Dielectric/Magnetic Materials

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Abstract—Dielectric or magnetic materials introduced in a wireless power transfer (WPT) system affect the properties of WPT. This paper quantitatively studies the coupling between the transmitting and receiving elements for a WPT system including either dielectric or magnetic materials. The transmitting and receiving elements are open spirals and solenoid coils which are usually used in WPT systems. The analysis method is the perturbation method which can calculate the total coupling coefficient k , the electric coupling component k_e and the magnetic coupling component k_m simultaneously. This paper gives quantitatively analyzed data on k_m and k_e to indicate how much k_m and k_e are affected by a dielectric or magnetic material introduced in a WPT system.

1. INTRODUCTION

Electromagnetic induction, coupling and radiation are 3 methods for Wireless Power Transfer (WPT) [1–4]. Electromagnetic coupling WPT is widely studied around the world since a MIT group reported their WPT system [2]. In an electromagnetic coupling WPT, energy transfer is realized by the magnetic and electric coupling between the transmitting and receiving elements [1–5]. It is very important to understand the physical nature and the strength of electromagnetic coupling for a WPT system [4, 5]. The coupling depends on many properties of WPT systems, such as the type of transmitting and receiving elements, the structure of elements and the distance between the elements. Our previous studies have presented some results on the coupling of WPT systems [6, 7].

The electromagnetic coupling is also affected by a dielectric or a magnetic material introduced in the WPT system, which is usual for many potential WPT applications. Generally, the intruded matter is a dielectric matter. For example, human body or furniture may appear in the transfer path in a home wireless power distribution. Human tissues must be penetrated when an electromagnetic power is transferred to a small device like artificial cardiac pacemaker implanted in the human body. It is essential to understand what is the effect from such introduced dielectric material on the WPT coupling. On the other hand, magnetic materials are introduced in some WPT systems. It is well known that a magnetic core inserted into a solenoidal coil is able to strengthen magnetic coupling. We need to evaluate how much of coupling is improved by the magnetic material.

Not only the total coupling coefficient, but also the nature of coupling, i.e., the electric and magnetic components of coupling need to be investigated. The information on the electric and magnetic coupling components will greatly help an engineer to design a good WPT system. For example, a WPT system can be designed as a main magnetic coupling to avoid interruption from the introduced dielectric material.

It is obvious that a dielectric or a magnetic material affects the electromagnetic coupling. Some physical phenomena are well known and have been accepted in the EM community. Unfortunately, there are very few reports on the quantitative study of coupling for the WPT systems including dielectric

Received 20 October 2017, Accepted 10 January 2018, Scheduled 17 January 2018

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and/or magnetic materials. The quantitative data is important for a WPT system, especially after the formulas between the efficiency of energy transfer and kQ product is revealed [2, 5, 8, 9]. This paper focuses on the analysis of the coupling. It gives a quantitative analysis of coupling for a WPT system including dielectric or magnetic materials. The transmitting and receiving elements under study are spiral resonators and solenoidal resonators which are most often used as the transmitting and receiving elements in WPT system, for example, as reported in [1, 2, 6, 7, 10, 11] etc.. We analyze the coupling coefficient using the perturbation method [12]. The perturbation method can calculate the total coupling coefficient, as well as gives the electric coupling component and magnetic coupling component.

2. METHOD TO OBTAIN THE COUPLING COEFFICIENT AND THE ELECTRIC AND MAGNETIC COUPLING COMPONENTS

Coupling coefficient is a key parameter for many electric devices, such as microwave filters, electron paramagnetic resonance probes, stereometamaterials and WPT systems [13–15]. The coupling coefficient mainly describes the strength of energy exchange between the resonators. The conventional method to calculate coupling coefficient between the resonators is the frequency method [13]. The frequency method uses the following equation to obtain the coupling coefficient k ,

$$k = \frac{2(f_h - f_l)}{f_h + f_l}, \quad (1)$$

where f_h and f_l are the higher and lower split frequencies of the coupled resonators, respectively. The frequency method is simple and widely used in determinations of coupling coefficient. However, it only gives the total coupling coefficient. There is no other physical information on the coupling between the resonators.

In this study, the total coupling coefficient and the electric and magnetic coupling components are calculated by the perturbation method. Using the perturbation method [12], electric coupling component k_e and magnetic coupling component k_m can be separated using the next equation,

$$k = \frac{\int_{ev} \mu |\mathbf{H}_1|^2 dv - \int_{ev} \varepsilon |\mathbf{E}_1|^2 dv}{\int_v \varepsilon |\mathbf{E}|^2 dv} = k_m - k_e, \quad (2)$$

where \mathbf{E} is the electric field of resonator 1, and \mathbf{E}_1 , \mathbf{H}_1 are the evanescent fields of resonator 1 extending outside of the symmetry plane between the two resonators. As indicated by Eq. (2), not only the total coupling coefficient is given, but also the magnetic coupling component k_m and the electric coupling component k_e are obtained by the perturbation method. It should be noted that the perturbation method is only suitable for the resonators in a symmetric alignment [12]. Our previous study also shows that the electric coupling will cancel the magnetic coupling if k_m and k_e are in the same sign and otherwise they will be added up [6, 7].

The validity of the perturbation method has been proved in the previous study [12]. Here, we give an analyzed example for a WPT system shown in Figure 1, which is the result of coupling coefficient for the open spiral resonators. The values of coupling coefficient in Figure 1(c) were obtained by 3 methods, which are the frequency method (Eq. (1)), the perturbation method (Eq. (2)) and the measurement method. The measurement method uses the experimental setup shown in Figure 1(b) to obtain the split resonant frequencies f_l and f_h , and then determine k according to Eq. (1). The two loop coils are used for electromagnetic wave exciting and receiving respectively. In the measurement, a $0.5 \text{ m} \times 0.5 \text{ m} \times 1.0 \text{ m}$ metal box is used to contain the loop coils and the spiral resonators, to correspond with the boundary condition in the simulation. We can see that the results by 3 different methods fit well.

3. COUPLING ANALYSIS FOR A WPT SYSTEM WITH A DIELECTRIC MATERIAL

In this section, a WPT system with a dielectric material is studied. At first, the effect from the dielectric material on the resonant frequency is investigated. Figure 2 shows the simulated result of resonant

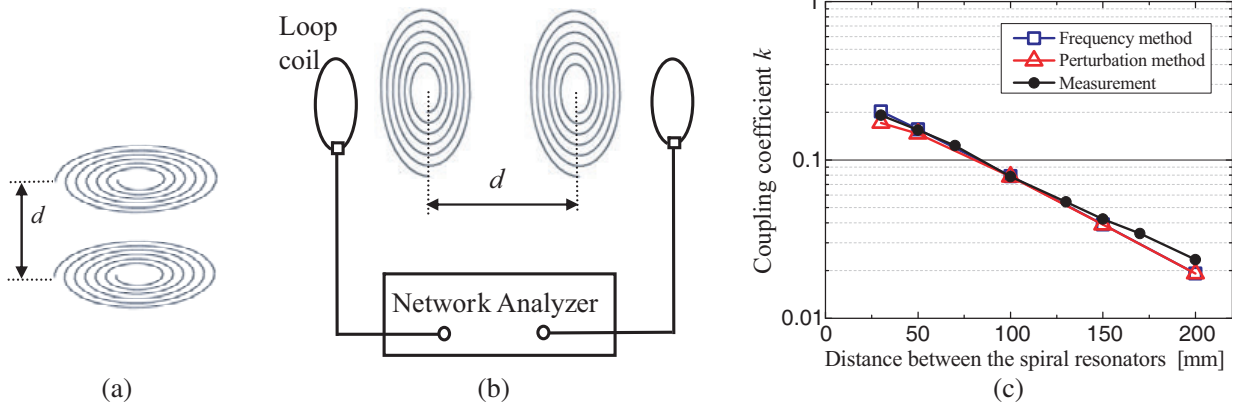


Figure 1. Comparisons of coupling coefficients obtained by 3 methods. (a) Open spiral resonators in a symmetric alignment. Structure of open spiral: Wire diameter $d_w = 1$ mm, out diameter $D = 120$ mm, turn $T = 18$ and pitch $p = 6$ mm. (b) Measurement setup for the coupled spiral resonators. (c) Simulated and measured coupling coefficients for the open spiral resonators as a function of the distance between the resonators.

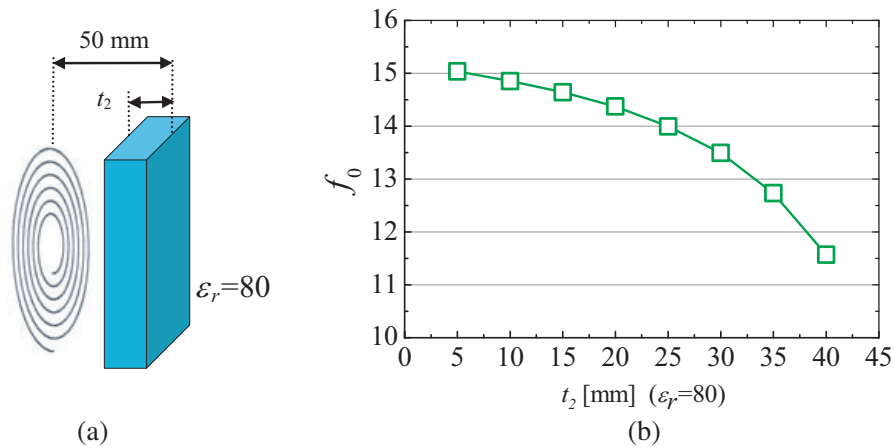


Figure 2. (a) Simulation model. Open spiral is the same as that of Figure 1. Size of dielectric slab: $300 \text{ mm} \times 300 \text{ mm}$, ϵ_r of dielectric slab: 80. (b) Resonant frequency f with respect to the thickness of dielectric slab.

frequency affected by a dielectric slab. It indicates that the resonant frequency does not remain at a constant value. The resonant frequency decreases when a dielectric slab comes close.

Next, the coupling is investigated when a dielectric slab is inserted between the open spiral resonators. Figure 3 shows k , k_m and k_e as a function of the thickness of dielectric slab when the distance between the open spirals is 100 mm. The open spiral is the same as that of Figure 1. The calculated results show that k_m is constant because it is not affected by the dielectric slab. k_e is very small even when the thickness of slab is large as much as 80 mm. The dielectric slab has little effect on the total coupling coefficient k at $d = 100$ mm.

The dielectric slab affects the coupling when the distance between the resonators is small. Figure 4 shows the coupling coefficient k , k_m and k_e as a function of ϵ_r at $d = 30$ mm and $d = 100$ mm. The open spirals are still the same as that of Figure 1. The results show that all of k , k_m and k_e at $d = 30$ mm have larger values. At $d = 30$ mm, k_m keeps as 0.50 despite that ϵ_r increases from 1 to 10, and k_e decreases from 0.33 to 0.21 when ϵ_r increases from 1 to 10. k increase with the slab ϵ_r increasing because of $k = k_m - k_e$. k at $\epsilon_r = 10$ is almost twice as strong as k at $\epsilon_r = 1$ (without dielectric slab). At $d = 100$ mm, the dependences of k , k_m and k_e on ϵ_r are similar to those at $d = 30$ mm, but the

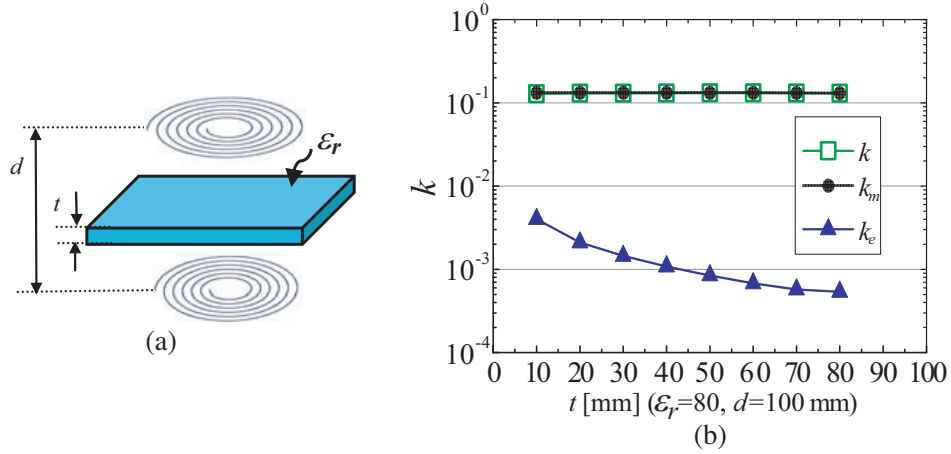


Figure 3. (a) Simulation model of the coupled spirals with a dielectric slab. $d = 100$ mm. Dielectric slab size: $300\text{ mm} \times 300\text{ mm}$, $\epsilon_r = 80$. (b) k , k_m and k_e with respect to the thickness of dielectric slab.

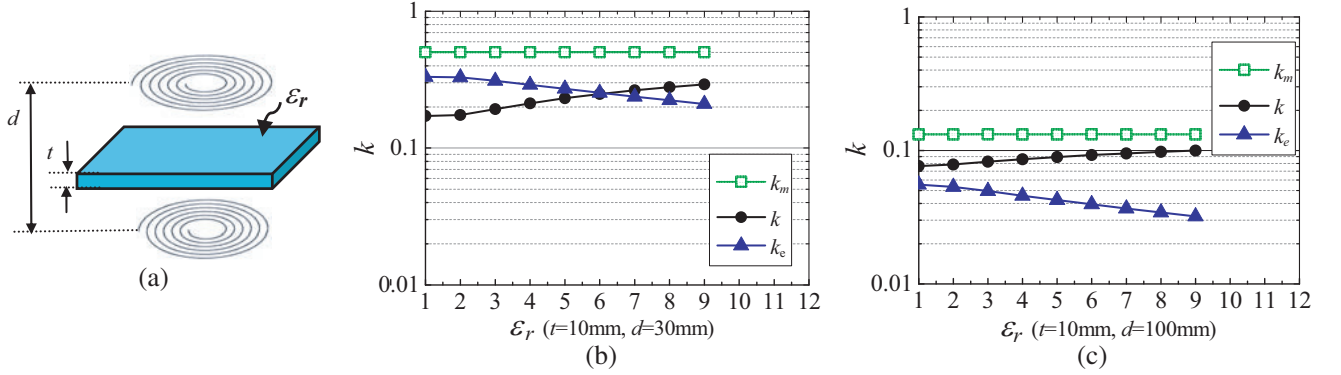


Figure 4. k , k_m and k_e with respect to the dielectric constant of dielectric slab. (a) Simulation Model. Dielectric slab size: $300\text{ mm} \times 300\text{ mm} \times 10\text{ mm}$. (b) k , k_m and k_e at $d = 30$ mm. (c) k , k_m and k_e at $d = 100$ mm.

values are small because of the weak coupling.

According to Figures 2, 3 and 4, the analysis results can be summarized as follows

1. Dielectric slab has no effect on the k_m .
2. Dielectric slab affects k_e . k_e decreases as ϵ_r of slab increases.
3. Dielectric slab has little effect on k if k_e is very weak. However, when the spiral resonators become close, electric coupling becomes strong and the total k is markedly affected by the inserted dielectric slab.
4. For open spiral resonators, k_m is larger than k_e .
5. k_e is fairly strong, especially when the resonators are close. It is around half of k_m .

Usually it is not expected that the total coupling coefficient varies due to an introduced dielectric material. Our previous study has shown that an open spiral added with a capacitor makes the coupling less affected by an introduced dielectric material [7, 16]. The resonator is made of a double-spiral coil connected with a lumped capacitor, as shown in Figure 5(a). Such a resonator can enclose the electric field in the resonator, hence a WPT system with such resonators is almost immune to the dielectric material [7, 16]. Figure 5(b) shows the results of k , k_m and k_e for the proposed resonator loaded with a capacitor. It is shown that k_e is very small because the electric field is almost enclosed in the resonator, thus k and k_m are both constant with ϵ_r changing.

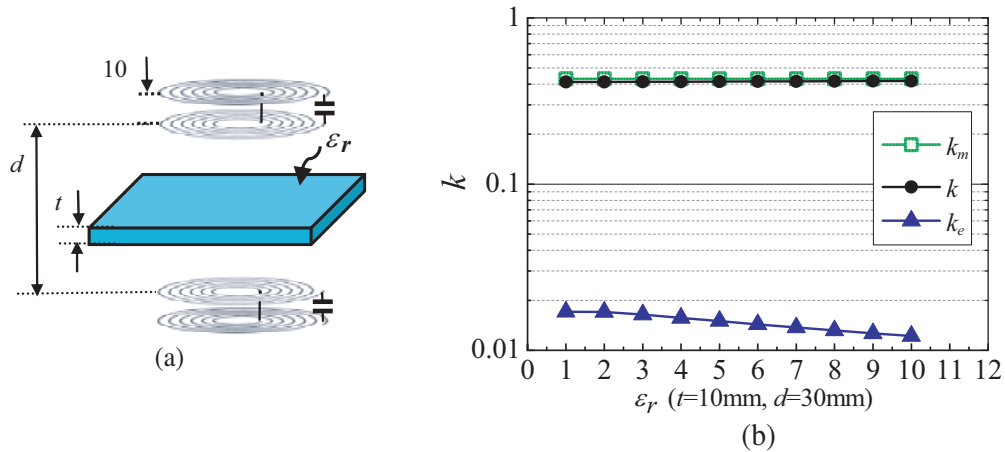


Figure 5. Coupling analysis for the spiral resonator loaded a capacitor. (a) Simulation model. Open spiral: Out diameter $D = 120$ mm, Turn $T = 5$, Pitch $p = 21$ mm. Capacitor $C = 2.4$ pF. Dielectric slab size: 300 mm \times 300 mm \times 10 mm. $d = 30$ mm. (b) k , k_m and k_e with respect to the dielectric constant of dielectric slab.

4. COUPLING ANALYSIS FOR A WPT SYSTEM WITH A MAGNETIC MATERIAL

In this section, a WPT system with a magnetic material is studied. The transmitting and receiving elements are the solenoidal coils. Solenoidal coil is another basic resonator used for wireless power transfer. It is well known that a magnetic core inserted into the coil is able to increase the magnetic coupling. This section presents a quantitative analysis on the total coupling as well as its electric and magnetic coupling components on such solenoidal resonators.

The basic Solenoidal Resonator (SR) structure in this study has a coil connected by a lumped capacitor. The loaded capacitor is used in order to obtain the expected resonator frequency easily. Figure 6 shows the simulated result of resonant frequency as a function of the permeability of the magnetic core. Similar to the dielectric material, a magnetic matter inserted in a solenoidal coil changes the resonant frequency. The frequency decreases with the permeability increasing because the effective inductance increases in the solenoidal resonator.

The coupling coefficient changes when a magnetic core is inserted in the solenoidal coil. In the next analysis, we investigate 3 types of solenoidal resonators (SR), as shown in the Figure 7. SR1 is a solenoidal coil without magnetic material. SR2 is a resonator by inserting a magnetic material in SR1,

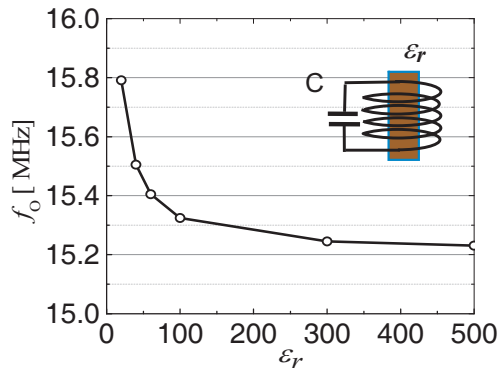


Figure 6. Resonant frequency of a solenoidal coil as a function of the permeability of magnetic core inserted in the coil. Coil radius $R = 15.5$ mm, Turn number $T = 5$, Pitch $p = 2$ mm, C is kept at 56.1 pF.

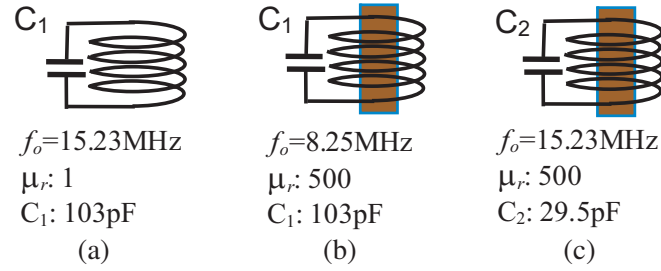


Figure 7. The structure of 3 kinds of solenoidal resonators (SR). Coils in 3 kinds of resonators have the same structure. Radius of coil $R = 25$ mm. Pitch of coil $p = 10$ mm. Turn $T = 5$. (a) SR1, (b) SR2, (c) SR3.

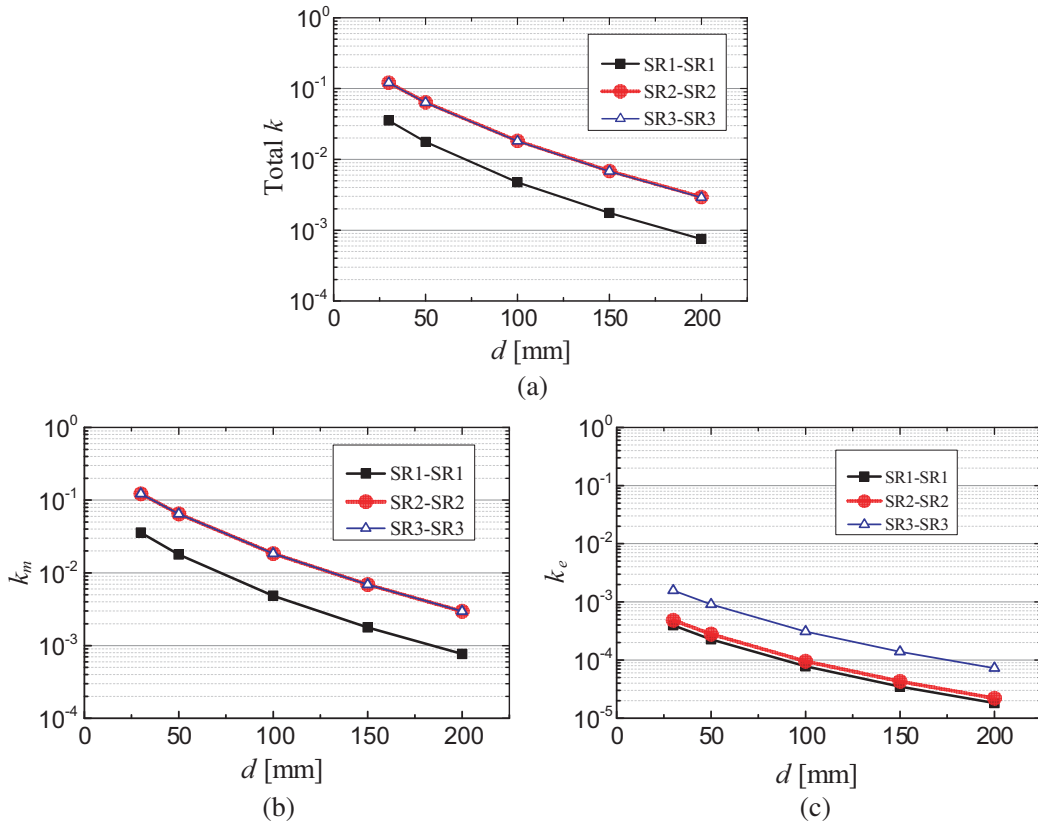


Figure 8. k , k_m and k_e with respect to the distance between the resonators for 3 kinds solenoidal resonators.

thus the resonator frequency changes from 15.23 M to 8.25 MHz. SR3 is a resonator of 15.23 MHz by adjusting the capacitor value in SR2 being 29.5 pF.

The calculated results of k , k_m , k_e for SR1, SR2 and SR3 are summarized in Figure 8. In general, k_e is very small for the solenoidal resonators. k_e is smaller than two percent of k_m . k of SR2 and k of SR3 are both larger than that of SR1, because they have the inserted magnetic materials. k_m increases from 0.03 to 0.12 at $d = 30$ mm when a magnetic core is inserted. It is interesting that k of SR2 is almost same with that of SR3. The reason can be found from the separated k_m and k_e by the perturbation method. k_m of SR2 and SR3 are almost the same because they have the same coil and the same inserted magnetic core. The lumped capacitor in SR2 is different to that in SR3, however the capacitors have little effect on the total k because the electric coupling is very weak.

5. CONCLUSIONS

In this paper, we give a quantitative analysis on coupling coefficient for WPT systems including dielectric or magnetic materials. The analyzed data is useful to understand the coupling in a WPT system quantitatively, although some physical phenomena are well known. The coupling investigation includes not only the total coupling coefficient, but also the electric and magnetic coupling components. The transmitting and receiving elements under study are spiral and solenoidal resonators.

Firstly, this paper gives an analysis on the spiral resonators with a dielectric material. The results show that a dielectric material does not affect the magnetic coupling component k_m . It is also shown that a dielectric material has little effect on the electric coupling components when the resonators are in a far distance. However, electric coupling becomes fairly strong when the resonators are arranged close. For the spiral resonators in this study, k_e can be as large as half of k_m . Hence the total coupling will be influenced by a dielectric material inserted in the WPT system. A loaded capacitor can enclose the electric field within the resonator. The coupling between the resonators loaded with capacitors is therefore immune to the dielectric material.

Secondly the paper gives an analysis on the solenoidal resonators with a magnetic material. The results show that electric coupling is fairly weak, and the effect of k_e on the total coupling can be ignored. Magnetic coupling components k_m is markedly affected by a magnetic material. For the solenoidal resonators in this study, an inserted core can improve the total coupling coefficient 4 times as large as that of the resonators without an iron core.

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