Effects of Coil Locations on Wireless Power Transfer via Magnetic Resonance Coupling

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Abstract — The coil locations have strong impacts on efficiency, resonant frequency and bandwidth in the wireless power transfer (WPT) system with four coil resonators, which is a popular configuration for mid-range WPT via magnetic resonance coupling. Herein, effects of coil location parameters, such as the distances between neighboring coils, are investigated by virtue of full-wave electromagnetic solution and validated by measurements. Three operational regions can be defined in terms of the distances between neighboring coils: over coupling, strong coupling and under coupling. It is shown that the distance between the receiving coil and the load coil has significant impact on the power transfer efficiency whereas the distance between the driving coil and the transmitting coil may merely affect the bandwidth and the resonant frequency in the strong coupling regime. In addition, the distance between the transmitting coil and the receiving coil can have strong impact on both the bandwidth and the resonant frequency. Design guidelines for optimal coil locations, by which the highest transfer efficiency or the longest transfer distance can be achieved, are also discussed.

Index Terms — Magnetic resonance coupling, power transfer distance, wireless power transfer.

I. INTRODUCTION

In recent years, wireless power transfer (WPT) has been drawing a great deal of attention. The WPT technology allows elimination of unsightly, unwieldy and costly power cords and eases anxiety of running out of battery power. The WPT systems have found applications in portable electronic products (e.g., cellular phones, tablet computers), wireless sensor networks (e.g., wireless body sensor networks), implantable medical devices, etc.

Traditionally, the WPT technology has been classified into two types: radio frequency (RF) radiation and inductive coupling in low frequency (LF) bands. RF radiation, which is widely employed for exchanging data and information, can transfer only a small amount of power (e.g., a few milliwatts) because a majority of power is lost into free space [1]. The RF radiation generated by high directional antennas is usually used for WPT [2], such as applications in space solar power station [3]. It can transfer high power over long distances, but requires uninterrupted line-of-sight, which may be harmful to human bodies. On the other hand, the LF-band inductive coupling can transfer power with high efficiency. The LF-band WPT is a mature technology (e.g., it has been widely used in electric toothbrush). Recently, an industry consortium has been formed to standardize this technology for charging mobile devices [4]. However, the LF-band WPT usually transfers power only over a very short range (e.g., a few centimeters).

The recent progress in the WPT technology based on magnetic resonance coupling in high-frequency (HF) bands has opened up a new paradigm for mid-range power transfer [5]. Since then, studies on various aspects of the WPT via magnetic resonance coupling have been conducted [6-19]. The WPT via magnetic resonance coupling has also been extended into various applications [20-25], such as machinery rat [20], underwater robots [21], electric vehicles [22], LED TV [23], medical implants [24], wireless sensor networks [25], etc.

The coil locations have strong impact on efficiency and resonant frequency of the WPT systems using magnetic resonance coupling. So far, however, they are not studied in-depth. In most previous studies, the coil locations of the WPT systems using magnetic resonance coupling are set either without any explanation or simply as equally spaced. There are only a few studies that discussed the coil location effects. In [7], a simple guideline for selecting the optimum repeater locations and numbers were provided. In the case of two repeaters, for example, only two simple rules have been stated: i) the distances of every two coils are equal; ii) the distance between the transmitter and the repeater is equal to the
distance between the repeater and the receiver. In [10], the relation between resonant frequency and distance was discussed by simply assuming that the total distance is fixed and the equal space is adopted. In [26], the effects of coil inductance and placement have been analyzed.

In this work, effects of the coil locations of the four-coil WPT system via magnetic resonance coupling are studied in-depth by virtue of full-wave electromagnetic solution and validated by measurements. In particular, the dependences of the power transfer efficiency, the resonant frequency and the bandwidth on important location parameters are carefully examined. Some important observations on effects of the coil locations are drawn based on theoretical studies, which are also verified by experiments. Design guidelines for optimal coil locations are presented for the WPT system, to which the highest transfer efficiency or the longest transfer distance can be achieved.

II. SYSTEM MODEL

Consider a four-coil WPT system via magnetic resonance coupling, which is a popular configuration for mid-range WPT via magnetic resonance coupling [5]. This WPT system is composed of four coils: driving coil, transmitting coil, receiving coil and load coil, as shown in Fig. 1. The driving coil (D) is a single loop (i.e., one turn) and connects to the voltage source. The transmitting coil (T) and receiving coil (R) are helix coils. The load coil (L) is also a single loop and connects to the load. The four-coil configuration can reduce the influence of the source and the load, and hence improve the efficiency of the WPT system.

![Fig. 1. Schematic of four-coil WPT system.](image)

The four coils are resonant and contactless with each other. The distances (i.e., separations) between the driving and transmitting coils, between the transmitting and receiving coils and between the receiving and load coils are, respectively, denoted as $d_{12}$, $d_{23}$ and $d_{34}$. The radius of the four coils, the height of the transmitting and receiving coils and the cross-sectional radius of the conductor coil wires are denoted as $r$, $h$ and $a$ respectively.

Two types of system models for the WPT system via magnetic resonance coupling are shown in Fig. 2. Panel (a) shows the widely used equivalent circuit model for circuit analysis in the previous published literature, whereas panel (b) illustrates a more accurate model by virtue of full-wave electromagnetic theory.

In panel (a), the driving, transmitting, receiving and load coils are numbered as coils 1, 2, 3 and 4 respectively, $M_{ij}$ $(i, j = 1, 2, 3, 4)$ denotes the mutual inductance between coil $i$ and coil $j$ (and $M_{ji} = M_{ij}$), $V_s$ is an excitation voltage source with an internal resistance denoted as $R_s$. The circuit elements $C_i$, $L_i$, and $R_i$ $(i = 1, 2, 3, 4)$ represent the parasitic capacitance, self-inductance, and resistance of coil $i$ respectively, $R_L$ is the load resistance connected to coil 4, and the current in coil $i$ is denoted as $I_i$ $(i = 1, 2, 3, 4)$.

![Fig. 2. System models of the WPT system. (a) Equivalent circuit model; (b) two-port S-parameter model.](image)

In panel (b), the WPT system is treated as an integrated (or tightly coupled) unit that is fully characterized as a two-port scattering parameter matrix (i.e., S-parameters) network, in which the transmitting port is denoted as port 1 and the receiving port is denoted as port 2. The S-parameter matrix can be obtained from the full-wave electromagnetic solution. The driving coil is excited by ac excitation voltage source $V_s$ with internal resistance $R_s$, while the load coil is connected to the load resistance $R_L$.

Instead of the equivalent circuit model, the more accurate two-port S-parameter model is adopted to study the WPT system by virtue of the full-wave electromagnetic solution. Based on the S-parameters, the power transfer efficiency of the WPT system can be evaluated as:

$$\eta = \frac{P_o}{P_i} = \frac{|S_{21}|^2 (1 - |\Gamma_L|^2)}{|1 - S_{22} \Gamma_L|^2 (1 - |\Gamma_o|^2)},$$

(1)
where $\Gamma_L$ is the reflection coefficient at the load $Z_L = R_L$, and $\Gamma_0$ is the reflection coefficient at port 1. They can be calculated as:

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0}, \quad (2)$$

$$\Gamma_{in} = S_{11} + \frac{S_{12} S_{21} \Gamma_L}{1 - S_{22} \Gamma_L}, \quad (3)$$

where $S_{11}$, $S_{21}$, $S_{12}$ and $S_{22}$ are the S-parameters, as shown in Fig. 2 (b). If mismatching at the port 1 is omitted, the maximum transfer efficiency can be achieved when the load meets the following matching condition:

$$\Gamma_l = S_{22}^{-1}(f). \quad (4)$$

In the following section, the S-parameters are computed by using the full-wave electromagnetic solution in reference to a characteristic impedance $Z_0 = 50 \, \Omega$.

### III. EFFECTS OF COIL LOCATIONS

In this section, analysis on coil locations of the WPT system via magnetic resonance coupling, as shown in Fig. 1, is presented by virtue of the full-wave electromagnetic solution. The full-wave electro-magnetic solution is obtained by a commercial full-wave electromagnetic simulation tool, called FEKO. The four coils are made of Cu. The geometrical and physical parameters are listed in Table 1.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_1$</td>
<td>Radius of driving coil</td>
<td>30</td>
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</tr>
<tr>
<td>$r_2$</td>
<td>Radius of transmitting coil</td>
<td>30</td>
<td>cm</td>
</tr>
<tr>
<td>$r_3$</td>
<td>Radius of receiving coil</td>
<td>30</td>
<td>cm</td>
</tr>
<tr>
<td>$r_4$</td>
<td>Radius of load coil</td>
<td>30</td>
<td>cm</td>
</tr>
<tr>
<td>$a$</td>
<td>Cross-sectional radius of coil</td>
<td>0.3</td>
<td>cm</td>
</tr>
<tr>
<td>$h$</td>
<td>Height of the transmitting coil</td>
<td>20</td>
<td>cm</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of turns of the transmitting coil and the receiving coil</td>
<td>5.25</td>
<td>turn</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Internal resistance of voltage source</td>
<td>50</td>
<td>ohm</td>
</tr>
<tr>
<td>$R_l$</td>
<td>Load resistance</td>
<td>550</td>
<td>ohm</td>
</tr>
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</table>

The distance parameters include $d_{12}$, $d_{23}$ and $d_{34}$. The total transfer distance between the driving coil and the load coil is defined as:

$$d = d_{12} + d_{23} + d_{34}. \quad (5)$$

Note that the heights of the transmitting coil and the receiving coil are not included in the total transfer distance.

Electromagnetic simulations are performed by FEKO to study effects of coils locations (i.e., distances between pairs of adjacent coils) in terms of the power transfer efficiency, the resonant frequency and the bandwidth. Note that, in the WPT system via magnetic resonance coupling, the input power has little impact on the power transfer efficiency as theoretically expected since this WPT system is linear and the input power has been factored out from the power transfer efficiency as shown in its definition (1).

### A. Effects of variable $d_{34}$ with fixed $d_{12}$ and fixed $d_{23}$

In this subsection, effects of $d_{34}$ on efficiency of the WPT system via magnetic resonance coupling are studied. It is assumed that $d_{34}$ varies from 5 cm to 60 cm with a step size of 5 cm, whereas $d_{12}$ is fixed at 15 cm and $d_{23}$ is fixed at 150 cm. The efficiency versus $d_{34}$ is plotted in Fig. 3, while the efficiency versus the frequency is depicted in Fig. 4.
efficiency is. When $d_{34}$ is between 10 cm and 20 cm, the efficiency is almost flattened within a small range from 82.07% to 84.51%. When $d_{34}$ is beyond 20 cm, the efficiency diminishes dramatically.

The efficiency is the highest around the frequency of 10.42 MHz regardless the value of $d_{34}$. When the operating frequency shifts roughly 1.5% from 10.42 MHz (such as 10.30 MHz and 10.60 MHz), the efficiency decreases dramatically as shown in Fig. 3. The highest efficiency can be obtained as 85.51% when $d_{34}$ is 15 cm and the operating frequency is 10.42 MHz.

From Fig. 4, one can observe that when $d_{34}$ is shorter than 10 cm, the bandwidth is wide but the efficiency is not very high. For example, when $d_{34}$ is 5 cm, the bandwidth is 0.174 MHz and the highest efficiency is only 74.97%.

When $d_{34}$ is between 10 cm and 20 cm, the bandwidth becomes narrower, but the highest efficiency is always above 80%. For example, when $d_{34}$ is 10 cm, 15 cm and 20 cm, the bandwidth is 0.144 MHz, 0.114 MHz and 0.090 MHz respectively, whereas the efficiency can be as high as 82.07%, 84.51% and 83.49% respectively.

When $d_{34}$ is longer than 20 cm, the bandwidth is still narrow and the efficiency becomes lower. For example, when $d_{34}$ is 30 cm, the bandwidth is 0.042 MHz and the highest efficiency is 73.24%. When $d_{34}$ is 60 cm, the highest efficiency is now as low as 23.49%.

From Fig. 4, one can see that the resonant frequency is 10.408 MHz when $d_{34}$ is 5 cm. The resonant frequency stays almost constant at 10.42 MHz for all $d_{34}$ from 10 cm to 60 cm.

B. Effects of variable $d_{23}$ with fixed $d_{12}$ and fixed $d_{34}$

Effects of $d_{23}$ on efficiency of the WPT system via magnetic resonance coupling are studied in this subsection. It is assumed that $d_{23}$ varies from 20 cm to 300 cm with a step size of 20 cm, whereas $d_{12}$ and $d_{34}$ are fixed at 15 cm. The efficiency versus $d_{23}$ is plotted in Fig. 5, while the efficiency versus the frequency is depicted in Fig. 6.

From Fig. 5, one can see that when $d_{23}$ increases from 20 cm to 300 cm, the power transfer efficiency increases at beginning, then becomes saturated, and finally decreases considerably. When $d_{23}$ is shorter than 40 cm, the closer the transmitting and receiving coils are, the lower the efficiency is. When $d_{23}$ is between 40 cm and 120 cm, the efficiency is almost flattened within a small range from 89.69% to 92.23%. When $d_{23}$ is beyond 120 cm, the efficiency diminishes dramatically.

The efficiency is the highest at the frequency of 10.455 MHz for most values of $d_{23}$. When the operating frequency shifts roughly 1.5% from 10.455 MHz (such as 10.30 MHz and 10.60 MHz), the efficiency decreases dramatically as shown in Fig. 5. The highest efficiency can be obtained as 92.23% when $d_{23}$ is 60 cm and the operating frequency is 10.455 MHz.

From Fig. 6, one can see that when $d_{23}$ is within 40 cm, the bandwidth is very wide but the efficiency still has some room to improve. For example, when $d_{23}$ is 20 cm, the bandwidth is wider than 0.3 MHz while the highest efficiency is 84.28%.

When $d_{23}$ is between 40 cm and 120 cm, the bandwidth becomes narrower, but the highest efficiency is always above 85%. For example, when $d_{23}$ is 80 cm and 120 cm, the bandwidth is 0.2 MHz and 0.065 MHz respectively, whereas the efficiency can be as high as 92.15% and 89.69% respectively.

When $d_{23}$ is longer than 120 cm, the bandwidth is still narrow and the efficiency becomes much lower. For example, when $d_{23}$ is 140 cm, the bandwidth is 0.025 MHz and the highest efficiency is 86.68%. When $d_{23}$ is 300 cm, the highest efficiency is now as low as 23.82%.

From Fig. 6, one can observe that the resonant frequency is 10.31 MHz when $d_{23}$ is 20 cm. The resonant frequency decreases when $d_{23}$ increases from 40 cm to 120 cm. For example, the resonant frequency is 10.50 MHz, 10.43 MHz and 10.42 MHz when $d_{23}$ is 40 cm, 80 cm and 120 cm respectively. The resonant frequency stays almost constant at 10.42 MHz for all $d_{23}$ beyond 120 cm.

By comparing Fig. 5 to Fig. 3, one can see that the efficiency keeps high for a relatively large range of $d_{23}$.
That is, the distance $d_{12}$ between the transmitting and receiving coils has a wide range of the strong coupling state. Therefore, the distance $d_{12}$ can be used for expanding the total transmission distance.

C. Effects of variable $d_{12}$ with fixed $d_{23}$ and fixed $d_{34}$

Effects of $d_{12}$ on efficiency of the WPT system via magnetic resonance coupling are studied in this subsection. It is assumed that $d_{12}$ varies from 5 cm to 240 cm, whereas $d_{23}$ is fixed at 150 cm and $d_{34}$ is fixed at 15 cm. The efficiency versus $d_{12}$ is plotted in Fig. 7, while the efficiency versus the frequency is depicted in Fig. 8.

From Fig. 7, one can observe that when $d_{12}$ increases from 5 cm to 240 cm, the power transfer efficiency is stable at beginning and then rapidly decreases. When $d_{12}$ is shorter than 60 cm, the efficiency varies slightly from 84.14% to 84.51%. When $d_{12}$ is beyond 60 cm, the efficiency diminishes dramatically.

![Fig. 7. Efficiency versus $d_{12}$ (with fixed $d_{23}$ and fixed $d_{34}$).](image)

The efficiency is the highest at the frequency of 10.42 MHz regardless the value of $d_{12}$. When the operating frequency shifts roughly 1.5% from 10.42 MHz (such as 10.300 MHz and 10.600 MHz), the efficiency decreases dramatically as shown in Fig. 8. The highest efficiency can be obtained as 84.51% when $d_{12}$ is 15 cm and the operating frequency is 10.42 MHz.

From Fig. 8, one can observe that when $d_{12}$ is within 60 cm, the bandwidth decreases slightly along with increasing $d_{12}$, but the highest efficiency is nearly constant. For example, when $d_{12}$ is 5 cm and 60 cm, the bandwidth is 0.114 MHz and 0.096 MHz while the highest efficiency is 84.51% and 84.14% respectively.

When $d_{12}$ is longer than 60 cm, the bandwidth becomes narrower and the efficiency becomes much lower. For example, when $d_{12}$ is 140 cm, the bandwidth is 0.042 MHz and the highest efficiency is 67.73%. When $d_{12}$ is 240 cm, the highest efficiency is now down to 20.38%.

From Fig. 8, one can see that the resonant frequency stays almost constant at 10.42 MHz for all $d_{12}$ from 5 cm to 100 cm. The resonant frequency slightly decreases when $d_{12}$ gets longer than 100 cm. For example, when $d_{12}$ is 120 cm and 240 cm, the resonant frequency is 10.408 MHz and 10.396 MHz respectively.

By comparing Fig. 7 to Fig. 3, it is found that the distance $d_{12}$ between the driving and transmitting coils has a wide range of the strong coupling state, which is very beneficial for expanding the total transmission distance via increasing $d_{12}$.

D. Effects under fixed total transfer distance

Location effects on efficiency of the WPT system via magnetic resonance coupling are studied under a fixed total transfer distance $d$ in this subsection. It is assumed that $d$ is fixed at 200 cm, whereas $d_{12}$ and $d_{23}$ are always equal and vary from 10 cm to 70 cm with a step size of 10 cm. Correspondingly, $d_{23} = d – 2d_{12}$ varies from 180 cm to 60 cm with a step size of 20 cm. The efficiency versus $d_{12}$ (i.e., $d_{34}$) is plotted in Fig. 9, while the efficiency versus the frequency is depicted in Fig. 10.

From Fig. 9, one can observe that when $d_{12}$ and $d_{34}$ increase from 10 cm to 70 cm (i.e., $d_{23}$ decreases from 180 cm to 60 cm), the power transfer efficiency increases at beginning and then decreases. From Fig. 9, one can observe that when $d_{12}$ and $d_{34}$ are shorter than 20 cm (i.e., $d_{23}$ is longer than 160 cm), the closer the driving (receiving) and transmitting (load) coils are, the lower the efficiency is. Frequency splitting occurs when the distance between the driving (receiving) and transmitting (load) coils becomes too small and thus leads to lower efficiency. When $d_{12}$ and $d_{34}$ are longer than 20 cm, the efficiency diminishes dramatically.

The efficiency is the highest at the frequency of 10.42 MHz regardless the values of $d_{12}$, $d_{23}$ and $d_{34}$. When the operating frequency shifts roughly 1.5% from 10.42 MHz (such as 10.300 MHz and 10.600 MHz), the efficiency decreases dramatically as shown in Fig. 9. The highest efficiency can be obtained as 81.68% when $d_{12}$ and $d_{34}$ are 20 cm (i.e., $d_{23}$ is 160 cm) and the operating frequency is at the resonant frequency (i.e., 10.42 MHz).
Fig. 9. Efficiency versus $d_{12}$ (with $d_{23} = d - 2d_{12}$, $d_{34} = d_{12}$ and fixed $d$).

Fig. 10. Efficiency versus frequency (with $d_{23} = d - 2d_{12}$, $d_{34} = d_{12}$ and fixed $d$).

From Fig. 10, one can observe that when $d_{12}$ and $d_{34}$ are within 10 cm (i.e., $d_{23}$ is beyond 180 cm), the bandwidth is relatively wide although the efficiency is not very high. For example, when $d_{12}$ and $d_{34}$ are 10 cm (i.e., $d_{23}$ is 180 cm), the bandwidth is 0.06 MHz while the highest efficiency is only 68.48%.

When $d_{12}$ and $d_{34}$ increase from 20 cm to 50 cm (i.e., $d_{23}$ decreases from 160 cm to 100 cm), the bandwidth becomes narrower and the efficiency becomes lower. When $d_{12}$ and $d_{34}$ are longer than 60 cm (i.e., $d_{23}$ is shorter than 80 cm), the frequency splitting occurs and the efficiency is very low.

**E. Discussions**

Based on the preceding subsections, it is evident that the locations of four coils have strong impact on the efficiency, the resonant frequency and the bandwidth of the WPT system via magnetic resonance coupling. Some interesting observations can be drawn as follows.

The operation of the WPT system via magnetic resonance coupling can be divided into three regions in terms of the distance between each pair of two coils: over coupling, strong coupling and under coupling. The system is in the over coupling state if two coils (e.g., driving and transmitting coils, transmitting and receiving coils, or receiving and load coils) are too close to each other. When the system is in the over coupling state, the power transfer efficiency is usually low due to frequency splitting. The closer the two coils are, the lower the efficiency is. In addition, the resonant frequency may shift to a lower frequency when the system is in over coupling.

The system is in the under coupling state if two coils are too far away. When the system is in the under coupling state, the power transfer efficiency decreases along with increasing distance due to weakened coupling.

The system is in the strong coupling state if two coils are at a suitable distance. The power transfer efficiency achieves the highest and keeps almost constant regardless the distance variation within a certain range. However, the efficiency can decrease dramatically if the operating frequency deviates too far from the resonance frequency.

By adjusting locations of four coils, the WPT system via magnetic resonance coupling can be made to operate in different states. The system operates in the strong coupling state if the following conditions are satisfied: $\frac{r}{4} \leq d_{12} \leq \frac{r}{2}$, $\frac{r}{4} \leq d_{23} \leq 4r$ and $\frac{r}{4} \leq d_{34} \leq \frac{r}{2}$ (where $r$ is the coil radius).

The distances $d_{12}$, $d_{23}$ and $d_{34}$ have different impacts on the efficiency of the WPT system via magnetic resonance coupling. The distance $d_{34}$ between the receiving and load coils has more significant impact on the efficiency than the distance $d_{12}$ between the driving and transmitting coils. This is because the load coil is connected to the load. The variation of $d_{34}$ changes the load impedance and therefore affects the power transfer efficiency.

In the strong coupling state, the bandwidth is usually broadened and the resonant frequency shifts to a lower frequency. Interestingly, the distance $d_{12}$ between the driving and transmitting coils has a wide range of the strong coupling state. Consequentially, the efficiency does not change much with the variation of $d_{12}$ in the strong coupling state (as shown in Fig. 7), which is very beneficial for expanding the total transmission distance via increasing $d_{12}$.

The distance $d_{23}$ between the transmitting and receiving coils has a wide range of the strong coupling state too. However, it has strong impact on the bandwidth and the resonant frequency of the WPT system via magnetic resonance coupling. Therefore, one may expect some small adjustment on the resonant frequency when the distance $d_{23}$ is used for expanding the total transmission distance yet maintaining high efficiency.

There exists an optimal set of coil locations for the WPT system via magnetic resonance coupling under the assumption of a fixed total transfer distance. When the highest efficiency is the objective, the locations of four coils should be assigned according to the following...
guideline: $d_{12} \approx d_{34} \approx 0.5r$ and $d_{23} \approx 2r$ (where $r$ is the coil radius).

If the longest transfer distance is the objective under a fixed efficiency, one should hold $d_{34}$ at the upper limit of the strong coupling region (e.g., $d_{34} \approx \frac{2}{3} r$), and then stretch $d_{12}$ and $d_{23}$ as much as possible over their strong coupling regions (e.g., $d_{12}$ and $d_{23}$ can be, respectively, as large as two and four times of the coil radius) until the efficiency hits the targeted value.

Note that, although the results obtained for the specific coil radii 30 cm, the basic concept of this work is useful and can be a good guide for other radii. For a larger system, such as a “domino” system, which has coils more than four, similar analysis can be conducted and similar design guidelines are expected. The relay coils can be inserted between the transmitting coil and the receiving coil. The effects of these coil locations on WPT systems are similar to the effect of $d_{23}$.

IV. PRACTICAL VERIFICATION

Experiments have been carried out to verify the theoretical studies by using a four coil WPT system via magnetic resonance coupling, as shown in Fig. 11. The geometrical and physical parameters of the system are the same as those listed in Table 1. Compensating capacitors are added to the driving, transmitting, receiving and load coils to make them resonant at the frequency of 10.42 MHz. The related parameters are listed in Table 2.

![Fig. 11. Photograph of the WPT system for experiments.](image)

Table 2: Parameters of four coils

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
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<tbody>
<tr>
<td>Inductance of driving coil (µH)</td>
<td>1.7661</td>
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<tr>
<td>Capacitance of driving coil (pF)</td>
<td>132.1</td>
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<tr>
<td>Inductance of transmitting coil (µH)</td>
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<td>Capacitance of transmitting coil (pF)</td>
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<tr>
<td>Inductance of receiving coil (µH)</td>
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<td>Capacitance of receiving coil (pF)</td>
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<tr>
<td>Inductance of load coil (µH)</td>
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<tr>
<td>Capacitance of load coil (pF)</td>
<td>132.1</td>
</tr>
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</table>

The measurements are done by a network analyzer so that the frequency responses (both magnitude and phase) can be measured easily and accurately. The driving and load coils are connected to the ports of the network analyzer through SMA cables and connectors.

The measured S-parameter is then converted into the system efficiency.

In order to check the validity of the analysis in the preceding sections, several experiments are conducted for various location combinations as shown in Table 3. The experiments for both the highest efficiency and the longest transfer distance are performed. The measured results and simulated results are compared in Fig. 12.

![Fig. 12. Comparison of measurements and simulation results.](image)

**Table 3: Location combinations of four coils**

<table>
<thead>
<tr>
<th>$d$ (cm)</th>
<th>$d_{12}$ (cm)</th>
<th>$d_{23}$ (cm)</th>
<th>$d_{34}$ (cm)</th>
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<td>75</td>
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<tr>
<td>260</td>
<td>80</td>
<td>160</td>
<td>20</td>
</tr>
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</table>

From Fig. 12, one can observe the highest efficiency is obtained at $d_{12} = 10$ cm, $d_{23} = 55$ cm and $d_{34} = 10$ cm. The highest efficiency is 95.29%. The longest transfer distance is obtained at $d_{12} = 80$ cm, $d_{23} = 160$ cm and $d_{34} = 20$ cm in which the efficiency is slightly higher than 80%. The longest transfer distance $d$ is about 260 cm for a given efficiency of 80%. The measurements agree very well with the simulation results, as shown in Fig. 12.

V. CONCLUSION

Effects of coil locations of the four-coil wireless power transfer (WPT) system via magnetic resonance coupling were studied in-depth here. The location parameters of four coils, including the distance $d_{12}$ between the driving and transmitting coils, the distance $d_{23}$ between the transmitting and receiving coils, and the distance $d_{34}$ between the receiving and load coils, have been used as design variables. It was found that all these three location parameters have impact on the efficiency, the resonant frequency and the bandwidth of the WPT system.
system via magnetic resonance coupling.

The operation of the WPT system via magnetic resonance coupling can be divided into three regions in terms of the distance between each pair of two adjacent coils: over coupling, strong coupling and under coupling. Different operating states can be achieved by adjusting locations of four coils.

The distances $d_{12}$, $d_{23}$ and $d_{34}$ have different kinds of impact on the efficiency of the WPT system via magnetic resonance coupling. The distance $d_{34}$ has more significant impact on the efficiency than the distance $d_{12}$. Interestingly, the distance $d_{12}$ has a wide range of the strong coupling state. The efficiency does not change much along with variation of $d_{12}$ in the strong coupling state. The distance $d_{23}$ has also a wide range of the strong coupling state. However, it has strong impact on the bandwidth and the resonant frequency of the WPT system via magnetic resonance coupling. Finally, design guidelines for optimal coil locations have been presented for the WPT system, to which the highest transfer efficiency or the longest transfer distance can be achieved.

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