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Influences of Coil Radius on Effective Transfer Distance in WPT System

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ABSTRACT The improvement of effective transfer distance is significant for wireless power transfer (WPT) via coupled magnetic resonances, with coil radius being the most important influencing factor. To study the relationship between effective transfer distance and coil radius, a model of WPT is established at first. Based on analyses of circuit and magnetic field, the influencing factors for effective transfer distance are obtained. Second, the models of WPT are constructed using software COMSOL, and the influences of Tx and Rx coil radius on the effective transfer distance are studied in detail. In addition, they are not proportional and the coil impedance is the most important factor. On this basis, a coil design method is proposed. Finally, an experiment device was built, and experimental results were well consistent with the theoretical analysis, showing the rationality and effectiveness of the proposed method.

INDEX TERMS Coil radius, Distance characteristics, Effective transfer distance, Wireless power transfer

I. INTRODUCTION

Wireless power transfer (WPT) is a contactless power transfer (CPT) technique, which uses space soft medium to convert electricity into other forms of energy, thus realizing the wireless transfer of electric energy after being transmitted for a distance without direct contact [1]-[3]. WPT has wide application prospects in many fields, because it is free of constraints on wires and makes the access of electric energy flexible, safe and convenient [4]-[7].

In 2007, a research team at MIT firstly proposed the technique of WPT via coupled magnetic resonances, which has advantages of long power transfer distance, large transfer power, and high spatial freedom [8], [9]. However, there exists a serious problem, i.e., the transfer power and power transfer efficiency (PTE) of the WPT system will drop sharply with the increase in transfer distance [10], [11]. To study the distance characteristics of WPT, the critical point at which the load received power decreases with the increase in the distance between coils is defined. The distance between the Tx coil and the critical point is called effective transfer distance, which is represented as the working range of WPT via coupled magnetic resonances.

At present, several methods to improve the effective transfer distance without changing the coil structure have been introduced. An essential principle of WPT system about the superposition of the two evanescent fields was proposed, showing that transfer distance could be improved by mediating the evanescent fields [12]. A parity–time symmetric circuit incorporating a nonlinear gain saturation element was presented to make sure that the remaining transfer efficiency was consistent [13]. However, the implementation conditions of the above methods are relatively strict and difficult to implement in practical engineering applications.

Besides, there are a few methods on design and optimization of coils were proposed to solve the problem. Two additional intermediate coils were adopted to increase the effective magnetizing impedance [14]. And multi-coil system which have more than three coils between the primary and secondary side provide a higher coupling coefficient [15]. A small coil was added to the Tx coil to achieve high quality factor and uniform magnetic field distribution [16]. The above methods are about increasing the number of resonant coils, whereas these ways also make the WPT system more complicated and manufacturing cost goes higher. Therefore, previous design and optimization methods may not suitable for the compact WPT systems in the MHz.

Moreover, the design of coil radius also can influence on transfer distance. The average radius was adopted in refs [17]-[19]. The effects of inductive parameters and nearby electromagnetic fields on coils with two different radii were analyzed [17]. The Q-factors of coils were derived and analyzed for enhancing the transfer distance [18]. The effects of coil radius and transfer distance on transfer efficiency, magnetic and electric field distributions were also investigated [19]. The outside radius was considered in [20], [21]. The Tx and Rx coils of different radius were researched for avoiding the magnetic over-coupling [20]. The self-inductance, impedance, quality factor and coupling coefficient at different coil radii were calculated at a fixed transfer distance of 10 cm [21]. Refs [17], [19] and [21] studied the coil radius, nevertheless, most of the research only focused on the resonant frequency of kHz rather than MHz. The symmetrical structure was deeply studied [20]. Moreover, the coil radius of the WPT via coupled magnetic resonances system varied within a small range and with a short transfer distance, the efficiency was 96% at 5 cm [16] and 75% at 3 cm [18]. Note that the resonant frequency of WPT via coupled magnetic resonances is MHz, when a large changing rate of coil radius exists, the design and matching of coil parameters, modeling simulation, and experimental research will be relatively difficult.

The main contributions of this paper are as follows:

1) We describe the simulation model that study the influence of Tx/Rx coil radius on the effective transfer distance at 6.78MHz and present that they are not proportional. This is different from the assumptions commonly found in the existing literature.
2) We change the resonant frequency and load, and the law of effective transfer distance changing with coil radius also exists. And the essential cause of this law is explained.

The purpose of this paper is to illustrate the influence of Tx/Rx coil radius on effective transfer distance and to increase the effective transfer distance by improving coil structure. The rest of this paper is as follows. An equivalent model of an WPT system is constructed at first, and it is calculated based on the theoretical analysis of high-frequency circuit and magnetic field. At 6.78 MHz, multiphysics simulation software COMSOL is used to study the comprehensive influences of coil radius (from 5cm to 25cm) on the effective transfer distance, both symmetrical and asymmetrical structures are considered, based on which the radius is further optimized at a fixed distance. Finally, an experimental platform was built to verify simulation results

II. ANALYSIS OF EFFECTIVE TRANSFER DISTANCE

The key parts of a WPT system via coupled magnetic resonances are a power transmitting device and a receiving device. In this paper, the coil structure with a planar spiral coil is taken as an example, as shown in Fig. 1(a). According to the equivalent principle of high-frequency circuit, an equivalent circuit model is shown in Fig. 1(b).

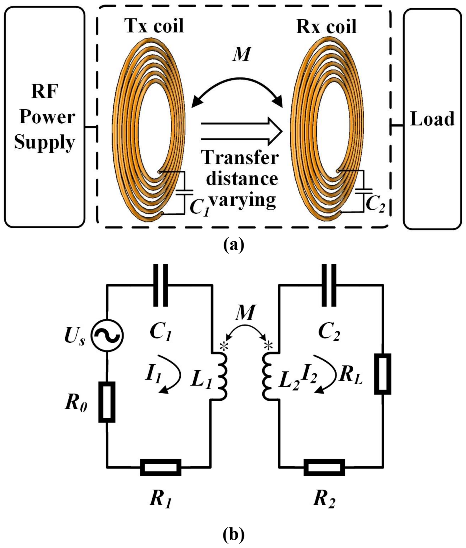


FIGURE 1. (a) Schematic and (b) Equivalent circuit of WPT system

The transmitting device is composed of a Tx coil and an equivalent capacitance C_1: the Tx coil is modeled by self-inductance L_1, parasitic resistance R_1, parasitic capacitance, while C_1 includes a parasitic capacitance and a tuning capacitor. The receiving device includes an Rx coil and an equivalent capacitance C_2: the Rx coil is modeled by self-inductance L_2, parasitic resistance R_2, parasitic capacitance, while C_2 includes parasitic capacitance and a tuning capacitor. The Tx coil is connected to a source with the peak voltage Us and a source resistance R_0, while the Rx coil is connected to a load resistance R_L. When the system is in resonance, the impedance of each coil will be pure resistance, thus the load received power and system efficiency can be expressed as:

$$P_L = \frac{U_S{}^2 R_L (\omega M)^2}{[(R_0+R_1)(R_2+R_L)+(\omega M)^2]^2} \tag{1}$$

$$\eta = \frac{R_L(\omega M)^2}{[(R_0+R_1)(R_2+R_L)+(\omega M)^2](R_2+R_L)} \tag{2}$$

where M is the mutual inductance between Tx and Rx coils. Note both two coils have the same resonant frequency, i.e., ω. According to (1) and (2), η can be regarded as a function of M. Moreover, $\frac{\mathrm{d}\eta}{\mathrm{d}M}$ is always positive, i.e., the system efficiency increases with the increasing mutual inductance between Tx and Rx coils. In actual engineering, the received power is often required to reach a maximum value, so P_L can be treated as a function in which M is considered as a variable. When $\frac{\mathrm{d}P_L}{\mathrm{d}M} = 0$, the following expression can be obtained:

$$M = \frac{\sqrt{(R_0+R_1)\cdot(R_2+R_L)}}{\omega} \tag{3}$$

The value of M obtained from (3) maximizes the received power of load, at which the critical coupling point is reached. Meanwhile, the distance between two coils is exactly the effective transfer distance. For two coaxial coils of radii r_i and r_j, at a center-to-center distance d_{ij}, the mutual inductance M_{ij} can be calculated as[22][23]:

$$M_{ij}=\frac{2\mu_0}{k}\sqrt{r_i r_j}\left[\left(1-\frac{k^2}{2}\right)K(k)-E(k)\right] \tag{4}$$

with

$$k=2\sqrt{\frac{r_i r_j}{(r_i+r_j)^2+d_{ij}^{\,2}}} \tag{5}$$

where $K(k)$ and $E(k)$ are the complete elliptic integrals of the first and second kinds, respectively. The mutual inductance M between Tx and Rx coils with turns N_1, and N_2 can be represented as：

$$M=\sum_{i=1}^{N_1}\sum_{j=1}^{N2}M_{ij} \tag{6}$$

Formulas (4)–(6) indicate that the radii of Tx and Rx coils largely determine the value of M. With the combination of formula (3), the relationship between the transfer distance and radius can be obtained, in which R_1, R_2, ω and R_L also should be taken into account. Then, the location of the critical coupling point will be changed with M. Based on the above analysis, the effective transfer distance is affected by multiple coil parameters. In this case, the degree of coupling between the above coil parameters is more serious. When the coil winds tightly while the frequency, R_L and turns are constant, the magnetic field intensity and the location of critical coupling point are mainly affected by the coil radius (i.e., Tx coil radius r_1 and Rx coil radius r_2). Therefore, the comprehensive optimization objective of the WPT system can be expressed as max $d(r_1, r_2)$.

III. SIMULATION ANALYSIS

In general, WPT systems can be classified into symmetric and asymmetric types. In this paper, a symmetry system is used at first to study the effects of different coil radii. Then, an asymmetric system is used to study the effects when the Tx or Rx coil radius changes separately. A simulation model of the symmetric coupling system is established, as shown in Fig. 2, with a Tx coil on the right side, and an Rx coil on the left. By means of a tuning unit, the resonant frequency of coils are tuned at 6.78 MHz. From the simulation results, it can be seen that the wireless transfer channel of electric energy is established, and the electric energy is received successfully.

Compared with [19] and [24], the simulation models constructed in this paper set the outermost air domain as a "perfect matching layer" to simulate the experimental environment in which electromagnetic waves can propagate infinity. Meanwhile, the asymmetric coil structures are fully considered, and the magnetic field distribution around the two coils is visually represented by the section and magnetic induction line.

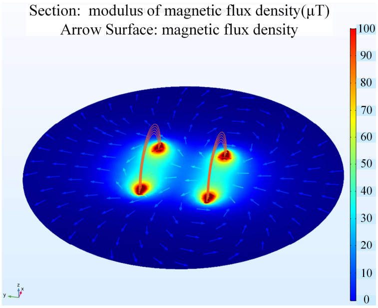
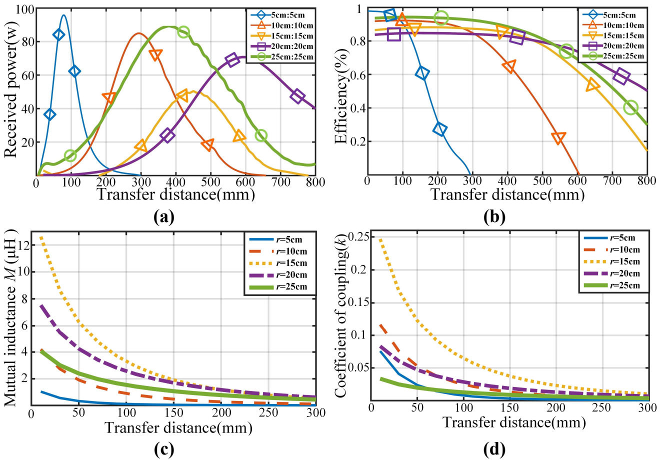


FIGURE 2. Simulation model of WPT system

In this model, only the coil radius is treated as a variable, while the other coil parameters are kept constant, e.g., the wire diameter is set as 1.06 mm, the number of turns is 10, and the excitation power supply adopts an AC constant voltage source at an effective value of 100 V. In addition, the internal resistance of excitation power supply is 50 Ω. To reduce the influence of distributed capacitance on the turns of the coil, the coil winding pattern is tight and the model of the WPT system can adopt different coil radii by varying the inner diameter of the coil. The input impedance of the system has the same trend as the frequency splitting of the WPT system [24]. Therefore, when the system's input impedance is equal to a certain value, the WPT system will reach the critical coupling point. According to [24]-[26] and the maximum power transfer theorem, the real part of the system's input impedance is equal to that of the internal impedance under the excitation power supply; the imaginary part of system input impedance is 0, which is the necessary condition for realizing the maximum transfer power.

A. INFLUENCE OF COIL RADIUS

The simulation model in Fig.2. By using the "Parametric scanning" in COMSOL on the transfer distance, the load received power, PTE, mutual inductance and coefficient of coupling are obtained. When the coil radius adopts different values, the simulation results are also different, as shown in Fig. 3. Five sets of WPT system reach the same resonant frequency (6.78 MHz) under load of 50 Ω.



(a) (b)

(c) (d)

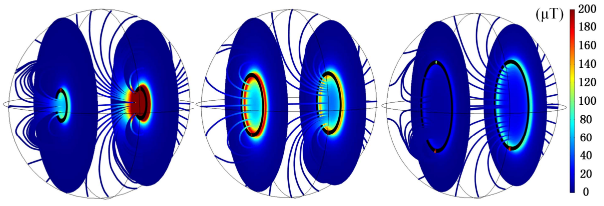
FIGURE 3. Simulation results of (a) Received power, (b) PTE, (c) M, and (d) k

As shown in Fig. 3(a), when the coil radii are 5, 10, 15, 20, and 25 cm, respectively, the maximum load received powers (at the critical coupling point) corresponding to the effective transfer distance are 7, 29, 44, 60, and 38 cm, respectively. As the coil radius grows, the effective transfer distance increases to its maximum and then gradually decrease.

As shown in Fig. 3(b), when the effective transfer distances of different coil radii are 7, 29, 44, 60, and 38 cm, respectively, the corresponding PTEs of the WPT system are 96.54%, 85.86%, 82.87%, 73.23% and 89.74%, respectively. The PTE of each WPT system decreases with the increasing transfer distance, and when the effective transfer distance is exceeded, the PTE decreases obviously.

As the distance increases, the mutual inductance (*M*) and the coefficient of coupling (*k*) of the WPT system with different coil radii also decrease, as shown in Fig 3(c) and (d). With the increasing transfer distance, the values of *M* and *k* of each WPT system decrease rapidly, and the values with radii of 5 and 25 cm are smaller. The values of *M* and *k* with radius of 15 cm are larger before the transfer distance exceeds 20 cm.

To illustrate the problem more clearly, the magnetic field intensity and magnetic induction lines of different WPT systems are compared, as shown in Fig. 4. Note the system frequency, excitation voltage, and load are set to the same values, and the transfer distance is 55 cm.



(a) (b) (c)

FIGURE 4. **Simulation results for WPT systems with different radii (a) $r_1=r_2=10$ cm, (b) $r_1=r_2=20$ cm, and (c) $r_1=r_2=30$ cm**

It can be seen that the magnetic field intensity of the Rx coil in Fig. 4(b) is stronger than those in 4(a) and (c). Therefore, the system with coil radius of 20 cm is more efficient. More magnetic induction lines pass through the Rx coil in Fig. 4(b) than in (a) and (c). If the coil radius is too small, more magnetic induction lines will form a loop near the Tx coil, thus increasing the magnetic flux leakage. If the coil radius is too large, the distribution of magnetic induction lines will become sparse and the magnetic field intensity will be reduced accordingly. In summary, it can be inferred that a too small or too large coil radius can reduce the effect on the WPT system.

B. INFLUENCE OF T$_X$ RADIUS

Based on the simulation model in Fig.2, the influence of Tx coil radius on the effective transfer distance is studied, as shown in Fig. 5. The radii of the Tx coil are 5, 10, 15, 20, and 25 cm, respectively, and the corresponding radii of the Rx coil are 10, 15, and 20 cm, respectively. All the WPT systems reach the same resonant frequency (i.e., 6.78 MHz) under load of 50 Ω.

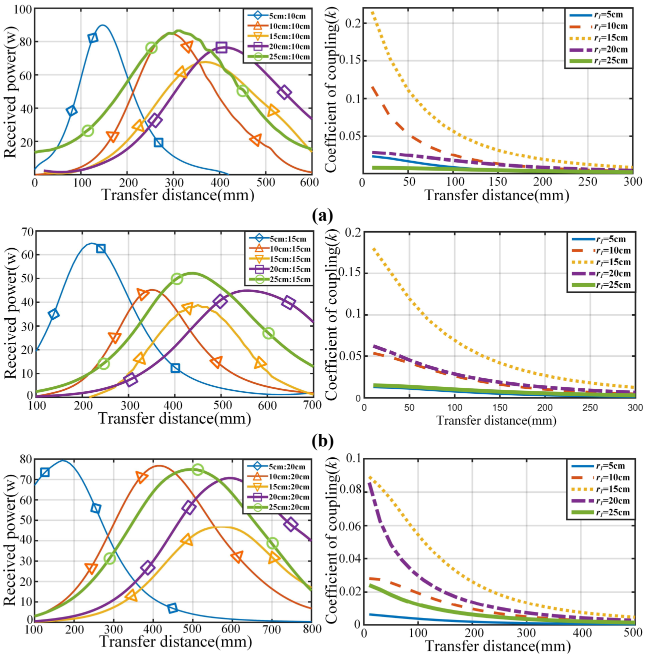


FIGURE 5. **Distance characteristics with different Rx coils: (a) r_2=10 cm, (b) r_2=15 cm, and (c) r_2=20 cm**

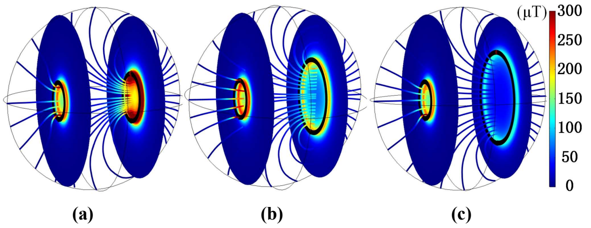
The effective transfer distances corresponding to cases in Fig.5 are listed in Table.1.

TABLE 1. **Effective transfer distances in Fig.5 (unit: cm)**

	r_2=10 cm	r_2=15 cm	r_2=20 cm
r_1=5 cm	15	21	18
r_1=10 cm	29	36	41
r_1=15 cm	37	44	54
r_1=20 cm	40	55	61
r_1=25 cm	29	43	49

From the above analysis, it can be seen that when the radius of the Tx coil increases, the effective transfer distance will increase to its maximum first and then gradually decrease. If there is a great difference of radius between Tx and Rx coils, the effective transfer distances will be relatively closer. Therefore, when the radius of the Tx coil is fixed, there exists a values of Rx coil radius that can maximize the effective transfer distance.

Here, the radius of Rx coil is set to 10 cm, the radii of the Tx coil are set to 15, 20, and 25 cm, respectively, and the transfer distance is set to 42 cm. The magnetic field intensity and magnetic induction lines of different WPT systems as shown in Fig 6.



(a) (b) (c)

FIGURE 6. **Simulation results for WPT systems with different Tx coils: (a) r_1=15 cm, (b) r_1=20 cm, and (c) r_1=25 cm**

The magnetic field intensity of the Rx coil shown in Fig. 6(b) is stronger than those in (a) and (c). Therefore, the system with the Tx coil radius of 20 cm is more efficient than those with 10 and 30 cm. More magnetic induction lines pass through the Rx coil in Fig 6(b) than in (a) and 6(c), indicating that a larger size of the Tx coil is not beneficial for the WPT system.

C. INFLUENCE OF R_X RADIUS

Based on the simulation model in Fig.2, the influence of Rx coil radius on effective transfer distance is studied, as shown in Fig. 7. All the WPT system reach the same resonant frequency (i.e., 6.78 MHz) under load of 50 Ω.

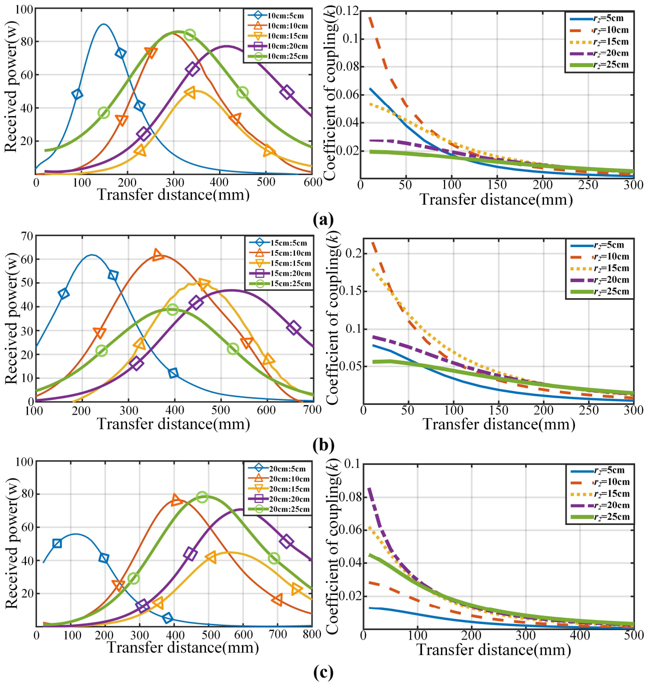


FIGURE 7. **Distance characteristics with different Tx coils: (a) r_1=10 cm, (b) r_1=15 cm, and (c) r_1=20 cm**

The effective transfer distances corresponding to cases in Fig.7 are listed in Table.2.

TABLE 2. **Effective transfer distances in Fig.7 (unit: cm)**

	r_1=10 cm	r_1=15 cm	r_1=20 cm
r_2=5 cm	14	21	13
r_2=10 cm	29	37	40
r_2=15 cm	36	44	55
r_2=20 cm	41	54	60
r_2=25 cm	31	38	49

The radius of Tx coil is set to 10 cm, the radii of the Rx coil are set to 15, 20, and 25 cm, respectively, and the transfer distance is set as 42 cm. The magnetic field intensity and magnetic induction lines of different WPT systems are compared, as shown in Fig. 8.

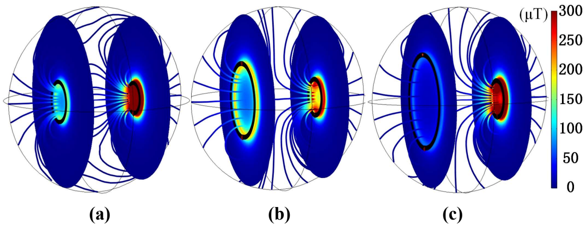


FIGURE 8. **Simulation results for WPT system with different Rx coils: (a) r_2=15 cm, (b) r_2=20 cm, and (c) r_2=25 cm**

From Fig. 8, it can be seen that the system with the Rx coil radius of 20 cm is more efficient, and a larger Rx coil is not beneficial for the WPT system.

D. INFLUENCES OF RESONANT FREQUENCY AND LOAD

In the actual engineering of WPT systems, the resonant frequency and load are always changing. Based on the simulation model in Fig.2, resonant frequency is changed to 2.78 and 10.78 MHz (R_L=50 Ω), and load is set to 25 Ω and 75 Ω (f=6.78 MHz). By changing the radius of the Tx and Rx coils simultaneously, the results are obtained, as shown in Fig 9.

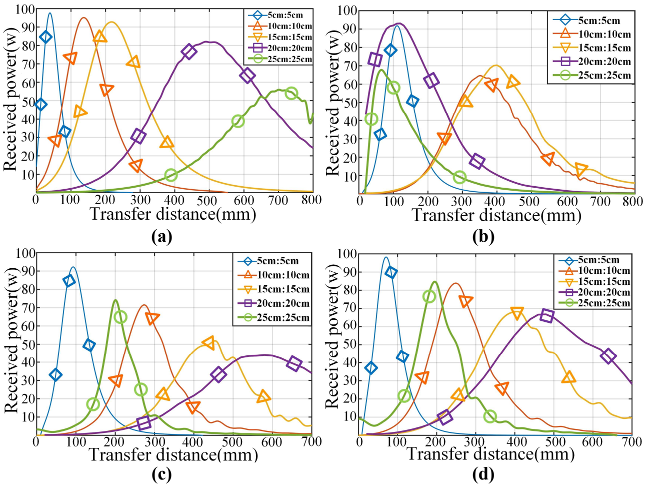


FIGURE 9. **Distance characteristics with different resonant frequencies and loads: (a) f=2.78 MHz, (b) f=10.78 MHz, (c) R_L=25 Ω, and (d) R_L=75 Ω**

The effective transfer distances corresponding to cases in Fig.9 are listed in Table.3.

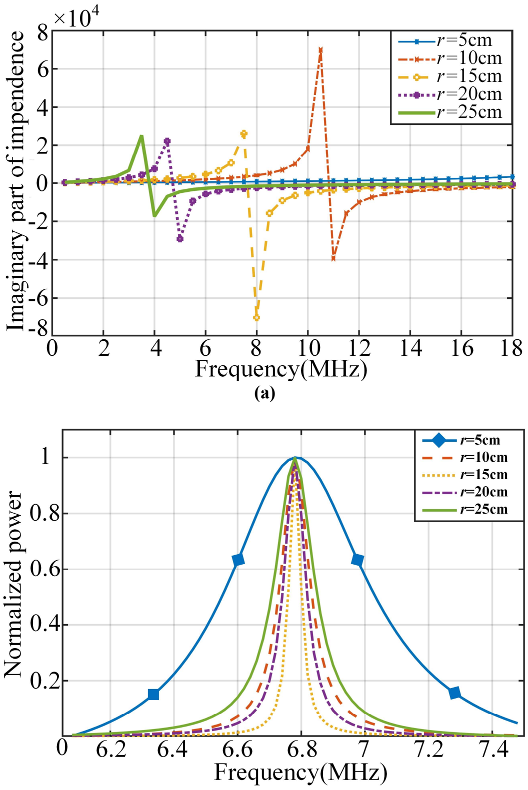
TABLE 3. **Effective transfer distances in Fig.9 (unit: cm)**

	f=2.78MHz	f=10.78MHz	R_L =25Ω	R_L =75Ω
r=5 cm	4	11	10	8
r=10 cm	14	35	28	24
r=15 cm	22	39	46	40
r=20 cm	49	12	57	46
r=25 cm	70	7	20	20

According to the above analysis, except the case in Fig 9(a), the effective transfer distance of WPT system does not always increase with the growth in coil radius. When the resonant frequency is changed (to 2.78 and 10.78 MHz), the radius that makes the effective transfer distances reach its maximum are 25 and 15 cm, respectively, instead of 20 cm.

However, when the load is changed from 50 to 25 and 75 Ω, the coil radius that maximizes the effective transfer distance is still 20 cm. It is found that by reducing the resonant frequency, we can avoid the situation in which the effective transfer distance decreases with the growth in coil radius, and a larger coil radius does not have a satisfying transfer effect when the resonant frequency is higher. The change in load also affects the effective transfer distance, but does not change the radius of the coil that maximizes the effective transfer distance.

To further verify the above conclusions, the frequency sweep of coils with a radius of 5, 10, 15, 20 and 25 cm are accomplished. The imaginary part of the coil impedance (without tuning) and normalized power (with tuning) are shown in Fig. 10.



(a)

(b)

FIGURE 10. **Frequency characteristics of different coils: (a) Imaginary part of the coil impedance, and (b) Normalized power**

When the imaginary part of coil impedance changes from positive to negative, the frequency of abrupt point is approximatively the resonant frequency of the coil. After tuning a single coil at 6.78MHz, the sharpness of curve of normalized power indicates quality factor of coil, the sharper curve means the higher quality factor.

In Fig. 10, when r=15cm, the f_{self} (self-resonant frequency of coil) is very close to 6.78 MHz and the quality factor is the highest; when r=20cm, the f_{self} is slightly lower than 6.78 MHz and the quality factor ranks the second; for coils with other radii, the f_{self} are far away from 6.78 MHz. Together with the Fig. 3(a), the WPT systems with radius of 15 and 20 cm achieve a longer effective transfer distance.

When the resonant frequency of the WPT system is set to 2.78 and 10.78 MHz respectively, combining Tab. 3 with Fig. 10(a), the f_{self} of coil with radius 25cm is close to 2.78 MHz, after tuning, the WPT system has the longest transfer distance. Meanwhile, the f_{self} with radius of 10 and 15 cm are close to 10.78 MHz, there are longer effective transfer distance too.

Therefore, the f_{self} is closer to the resonant frequency of the WPT system which means the higher quality factor of coil and the longer effective transfer distance. However, if the quality factor is too high, many problems will exist, such as difficulty in tuning, higher requirements for electronic devices, sensitivity of received power and PTE with respect to changes in resonant frequency and transfer distance. Based on the above analyses, it is necessary to choose an appropriate value to strike a balance between the implementation of the system work, cost, robustness and higher quality factor. Therefore, it is important to design a reasonable coil radius to improve the transfer performance of the system.

All the coils in above WPT system are tuned by a Series-Series compensation topology. The equivalent impedance of coil has no imaginary part, and it has the lowest impedance and the largest current. Moreover, the compensational capacitance of the Tx coil is independent of magnetic coupling and resistive load. In addition, the WPT system has a better stability. But in some applications, the parallel compensation topology is more suitable.

E. DESIGN METHOD FOR COILS

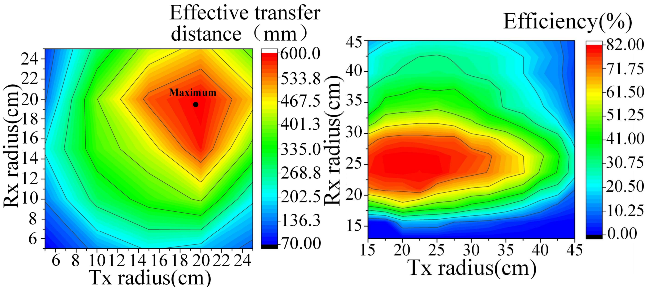
In actual engineering, system parameters such as transfer power, efficiency, frequency, and load should be determined in advance. The design method for coils is described as follows.

(1) On the basis of the given parameters, the effective transfer distance corresponding to different Tx and Rx coils are calculated through simulations, as shown in Fig.11(a).

(2) According to the given parameters (i.e., transfer power of 100 W, and distance of 30 cm), the efficiency of WPT system with different Tx and Rx coils are simulated, as shown in Fig. 11(b).

(3) As shown in Fig.11(a), if the maximum of effective transfer distance does not meet the system's requirement, the Tx and Rx coil radii can be determined by the maximum point. Otherwise, the coil radius can be determined by the efficiency and constraints on the coil size, as shown in Fig. 11(a) and (b).

(4) According to the determined coil radius, a coil experiment will be designed to verify whether the power, efficiency and distance meet the actual requirements.



(a) (b)

FIGURE 11. **Equivalent curves of system characteristics: (a)Effective transfer distance, and (b) Efficiency of WPT system**

IV. EXPERIMENTAL RESULTS

An experimental platform of WPT via coupled magnetic resonances was built on the basis of simulations, as shown in Fig.12.

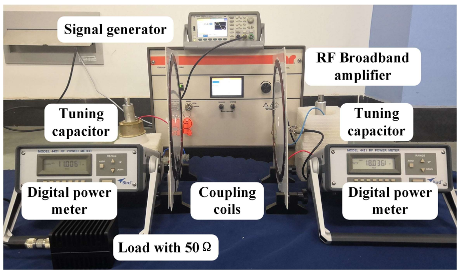


FIGURE 12. **Experimental platform**

In Figure 12, the signal generator was connected to the RF Broadband amplifier (with internal resistance of 50 Ω) to provide high frequency power for the WPT system. The coils in the experiment were connected to a vacuum adjustable capacitor for tuning. The receiving power was measured by a BIRD high-precision power meter. The parameters of coils used in the experiment are listed in Table. 4.

TABLE 4. **Parameters of coil with different radii**

Radius/cm	Inductance/μH	Resistance/mΩ
5	9.90	20.43
7.5	16.58	27.97
10	23.50	34.50
12.5	30.95	45.39
15	39.23	60.21
17.5	48.72	87.70
20	57.80	113.62
22.5	68.38	132.29
25	79.54	159.84

At first, the Tx and Rx coils were placed coaxially and levelly. The WPT system was tuned under coupling. Then, the distance was controlled to grow step by step, and the distance point that maximized the received power was determined. Finally, the vector analyzer network was connected to verify whether the real part of the system's input impedance was 50 Ω and the imaginary part was 0 at this distance point, thereby determining the effective transfer distance. When the WPT system had a symmetrical structure, the coil radius ranging from 5 to 25 cm was selected to verify the way the coil radius influenced the effective transfer distance. Note that the resonance frequency of the WPT system and load in each group of experiments were kept unchanged. The experimental and simulation results are shown in Fig.13.

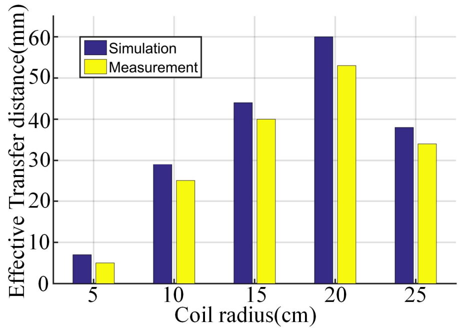


FIGURE 13. **Effective transfer distance for symmetric coils**

From Fig. 13, it can be seen that as the coil radius increases, the effective transfer distance increases to its maximum (53 cm) when the coil radius is 20 cm, and then it gradually decreases. When the WPT system had an asymmetric structure, the experimental data are shown in Fig. 14, where the system's resonant frequency and load were kept constant.

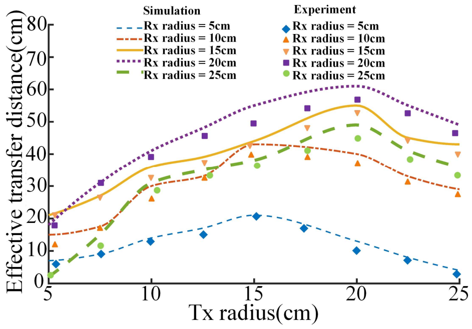


FIGURE 14. **Effective transfer distance curves for asymmetric coils**

From Fig. 14, it can be seen that the positions of maximum effective transfer distance are mostly backward, while the position of the maximum point moves relatively forward when the radius of the Rx coil is smaller. Therefore, by appropriately increasing the coil radius, we can improve the effective transfer distance.

Based on the simulation in Fig. 4, the magnetic field of Rx coils were measured by 3D visualization electromagnetic field measuring device in Fig.15. In the process of setting up the experimental platform, the center frequency of spectrum analyzer (AARONIA, NF-5035S) was 6.78 MHz, resolution band-width(RBW) was 30KHz and sampling time(SpTime) was 500 ms, after the parameter setting was completed, it was fixed on the aluminum tube of the test bench.

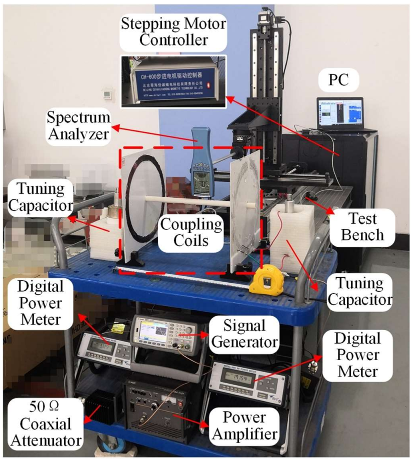


FIGURE 15. **3D visualization electromagnetic field measuring device**

Then the stepping motor which was controlled in the PC using the software to drive the movement of joystick, and the modulus of magnetic flux density between the two coils were measure. The simulation and experimental results were shown in Figure 16.

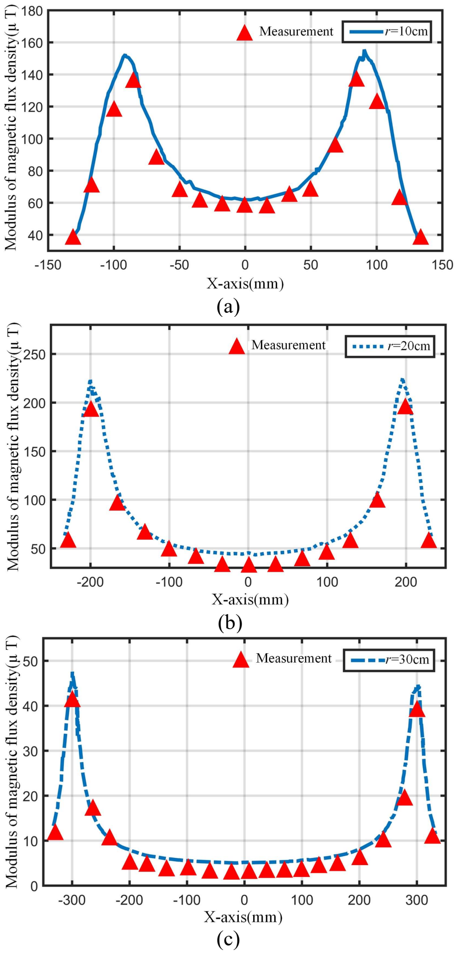


FIGURE 16. **Experimental results: (a)r=10cm, (b)r=20cm and (c)r=30cm**

From Fig. 16, the magnetic field around the coil with a radius of 20cm is the strongest, the coil with a radius of 10cm is the second, and the coil with a radius of 30 cm is the lowest. The magnetic induction lines which in the center of coil with a radius of 10cm are more concentrated, so the magnetic field at center is stronger.

V. CONCLUSION

In this paper, the influences of coil radius on the effective transfer distance are studied, and a general expression for effective transfer distance is obtained. The main results are as follows.

- In the case of certain resonant frequency and load, as the coil radius on one or both sides of the WPT system grows, the effective transfer distance first increases to its maximum and then gradually decreases; a too small or too large coil radius will affect the effect on the WPT system. A proper adjustment of resonant frequency and load can change this phenomenon.
- The basic reason of the effective transfer distance is the coil impedance. When the self-resonant frequency of coil is near the resonant frequency of the WPT system, the quality factor of the coil is higher, and the far effective transfer distance can be reached. But the quality factor is too high, many problems will exist.
- By increasing the radius of the Tx (Rx) coil appropriately, we can improve the effective transfer distance; however, the increase in radius is constrained in a limited range. Once the effective transfer distance of the WPT system is determined, the coil radius with the combination of best aspect ratio can be determined using the coil design method proposed in this paper.

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