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Fundamental Study on Paired-Spiral Resonators with Different Winding Directions Combination Used for Resonator-Coupled Type Wireless Power Transfer System

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1 Introduction

Wireless Power Transmission system transfers electrical power in the form of electromagnetic fields so that setting layout of the electric appliances woud be free [1]. Recently, Resonator-Coupled type Wireless Power Transmission (RC-WPT) [2] system which is one of Wireless Power Transform ways has been payed much attention.

The spiral resonator is the most important element in the RC-WPT system. To improve the property of RC-WPT system, we have modified the spiral resonator into paired-spiral type resonators [3], [4].

In the Ref. [5], WPT system using the paired-spiral resonator composed of the two conventional spiral resonator with the same winding directions has been investigated with non-uniform resonant frequency. In this paper, the properties of the paired-spiral resonator composed of the two conventional spiral resonator with the opposite winding directions with uniform resonant frequency have been presented in this paper, and compared with those in Ref. [5]. By accomplishing these studies, the modification and the optimization of the paired-spiral resonator would be able to carry out. It is expected that the smaller the gap between spirals in paired-spiral resonators has better performance.

2 Definition and Principle used in RC-WPT System with Paired-Spiral Resonator

Fig.1 shows the schematic constructions of RC-WPT system using the paired-spiral resonators [5]. As shown in this figure, the distance between resonators of transmitting and receiving unit is defined as *d* and that between loop coil and resonator is *a*. Here, paired-spiral resonators consisted with the same conventional spiral resonators which are adjacent to each other with the separation *s* also shown in Fig.1.

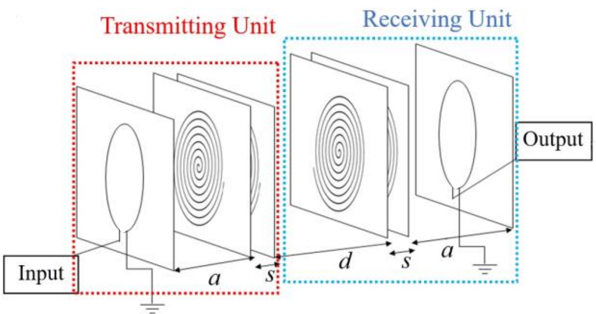

Fig.1 Structure of RC-WPT system using paired-spiral resonators.

According to Ref. [5], the spiral resonators used in this paper are the same. With wire spacing of the resonators *p*=0.5cm, four spiral resonators were made. According to Fig.1, by looking from input to output sides, each spiral resonators are labeled as Sp1, Sp2, Sp3 and Sp4 and they have almost the same structure parameter. Its outlook is as shown in Fig.2.

Fig.2 Spiral Resonator

In this paper, the efficiency of WPT system with different winding directions combination of the resonators are examined. Fig.3 shows two types of winding directions. Based on the figure, by looking from loop coil of each unit, if the winding direction of the spiral resonator is clockwise, that spiral resonator is labeled as positive, “P”. On the other hand, if the winding direction of the spiral resonator is anticlockwise, that spiral resonator is labeled as negative, “N”. The definition is applied at both transmitting and receiving unit of WPT system.

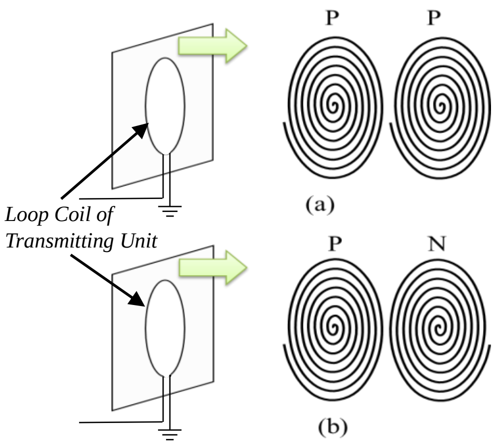

Fig.3 Example setup for paired-spiral resonators with PP or PN winding direction

By using this principle, several combination types of RC-WPT system can be made. However, in this paper, only two types of combination were conducted. From left to the right order of WPT system as shown in Fig.1, the combination of the resonators conducted are PP-PP and PP-NN. The first two letters are the winding direction of Sp1 and Sp2 by looking from loop coil of transmitting unit while the third and fourth letters are the winding direction of Sp3 and Sp4 by looking from loop coil of receiving unit.

In the case of single spiral resonators, only one resonator is needed at each transmitting and receiving side. Thus, Sp1 is placed at the transmitting unit, while Sp2 is placed at receiving unit. The experiment for single spiral resonator was conducted with winding direction P.

In this paper, the experiment is conduct when the resonant frequency of the spiral resonators are fixed at 10MHz and the length of all four spirals is maintained to be same. For single spiral resonator, it can achieve 10MHz simply by cutting the wire length to 10.845cm. In the case for paired-spiral resonator, two resonant frequency are existed. This can be referred in Fig.4, where it shows the resonant frequencies for paired-spiral resonator when all the wire length are 10.845cm.

Fig.4 Resonant frequency of paired-spiral with PP winding direction when s=4cm

As shown in figure above, two modes appeared [5]; the mode with lower frequency, mode 1, is considered as even mode, while the other one is mode 2 which would be odd mode [5]. The resonant frequency which is needed to be maintained at 10MHz is mode 1. Besides, when the separation s is changed, the resonant frequency of the spiral resonator will be changed too. Hence, to keep the resonant frequency maintained at 10MHz, the length of the spiral resonators must be modified with condition of the length of spiral resonators are the same. Table 1 shows the length of the resonators for each parameter distance s to keep resonant frequency at 10MHz.

Table 1 Wire length of paired-spiral resonators for each parameter s when resonant frequency at 10MHz

Separation s [cm]	Length of wire [m]
2.0	10.085
4.0	10.110
6.0	10.190

In Fig.4, the data was taken when the paired-spiral resonators of PP winding direction is set with distance a=20cm and s=4cm. Based on the graph, before tuning mode 1 to 10MHz, the resonant frequency of mode 1 is 9.33MHz while mode 2 is 11.26MHz.

In case for PN winding direction combination, the resonant frequency of mode 1 is much lower than that of PP combination before tuning to 10MHz. While mode 2 of PN combination has much higher resonant frequency than mode 2 of PP combination. In case for single spiral resonator, only one resonant frequency appeared at 10MHz, this means single mode operation.

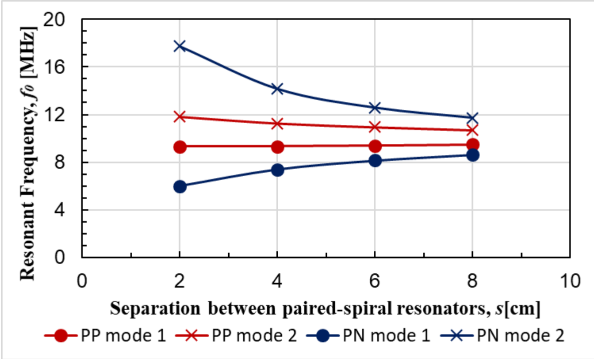

Fig.5 Resonant frequency f_0 for resonators with PP and PN winding direction when a=14cm

The difference in resonant frequency of mode 1 and 2 for PP and PN paired-spiral resonators is summarized in Fig.5. According to the graph, the gap between mode 1 and 2 of resonant frequencies for PN winding direction is wider than that of PP.

3 Measurement Methods

The experiments were conducted by using Vector Network Analyzer (VNA) to analyze the transmission system. Three (3) elements were measured in this paper. The elements are simplified as follow [2];

1) Finding the **quality factors (Q factors)** of the resonators
2) Finding the **coupling coefficient, k** of the system
3) Determine the **transmission efficiency, η** of the system

i) Q Factors

The Q factor indicates the inverse of the energy loss relative to the amount of energy stored within the resonator per unit time. The higher the Q factor, the lower the rate of energy loss.

During experiment, two types of Q factor are examined. Unloaded Q, Q_u. indicates Q factor due to intrinsic loss for resonator, while Q factor due to coupling or radiating loss of resonator is called external Q, Q_e.

The measurement setup for this experiment is as shown in Fig.3, but instead of connect to the power source, the loop coil is connected to VNA port 1. Thus, the graph of reflection coefficient S_{11} were observed within the range $2 \leq a \leq 20$cm. The observed values are inserted into equation (1) and (2), which will be substituted into equation (3) in order to obtain unloaded Q, Q_u and external Q, Q_e.

$$Q_L = \frac{f_0}{f_2 - f_1} \tag{1}$$

$$\beta_e = \begin{cases} \dfrac{1-10^{-\frac{L_0}{20}}}{1+10^{-\frac{L_0}{20}}} & (0 < \beta_e < 1) \\[2ex] \dfrac{1+10^{-\frac{L_0}{20}}}{1-10^{-\frac{L_0}{20}}} & (\beta_e \geq 1) \end{cases} \tag{2}$$

$$Q_u = Q_L(1+\beta_e), Q_e = \left(1+\frac{1}{\beta_e}\right) \quad (3)$$

Besides, external k, k_e can be defined as the inversion of external Q, Q_e, [5] which represents the coupling strength between the loop coil and spiral resonators [2], [3].

$$k_e = 1 / Q_e, \quad (4)$$

ii) Coupling Coefficient

Coupling coefficient, k is the bonding strength between transmitting unit and receiving unit of RC-WPT system. It is the second major method before obtaining the wireless power transmission efficiency, which is decided by the Q factor of the resonators and the coupling efficiency between them [2].

The measurement setup for this method is as shown in Fig.1.The graph of forward gain S_{21} is observed within range $2 \leq d \leq 60$cm. The peak frequencies, f_1 and f_2 from every range are inserted into the equation (5) in order to obtain result for k.

$$k = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2} \quad (5)$$

iii) Transmission Efficiency

Transmission efficiency for the system can be determined with two methods. First is called the theoretical transmission efficiency, while the other is experimental transmission efficiency.

In order to obtain theoretical transmission efficiency, the matching condition between k_e and k must be observed from both of previous result. The matching conditions of the RC-WPT system are estimated when the choice of the set of a and d when the k_e is equal to k [2], [3]. Then, the efficiency is calculated using equation (6)

$$\eta = 10^{-\frac{L}{10}} \times 100 \quad [\%] \quad (6)$$

whereas equation (7) is used to calculate the experimental value of transmission efficiency.

$$\eta = \frac{S^{\frac{|S_{21}|}{10}}}{1 - 10^{\frac{|S_{11}|}{10}}} \times 100 \quad [\%] \quad (7)$$

4 Experiment Flow with Measurement Result

Various procedures have been conducted to complete this research paper, thus it is important to understand the flow of the research experiment. Since there are too many experiments and data results to write this paper, it has been decided to finish this paper in the following order;

i) Comparing Q factors between paired-spiral with winding direction combination of PP and NN.
ii) Comparing transmission efficiency of WPT system that uses paired-spiral resonator combination between PP-PP and PP-NN.
iii) Comparing Q factors of paired-spiral resonators PP-NN combination with different *s*-parameters.
iv) Comparing coupling coefficient k for the WPT system for PP-NN combination between different ***s***-parameter.
v) Comparing transmission efficiency for the WPT system between different distance ***s***-parameter.

The experiment regarding PN-PN and PN-NP were initially conducted. However, after determine the power transmission efficiency for each combinations, both of them have very low efficiency. Thus, further investigation has been changed to PP-PP and PP-NN combinations.

It can be considered that mode 1 is the effective mode and for that reason, the following investigation of paired-spiral resonator is limited to that of mode 1. All data collected regarding mode 2 is neglected due to unstable and very low [4].

i) Q Factors for Paired-Spiral Resonator with winding direction PP and NN

Fig.6 shows the value of unloaded Q when paired-spiral resonator is set with PP or NN winding direction.

Based on the graph, it can be seen clearly that when

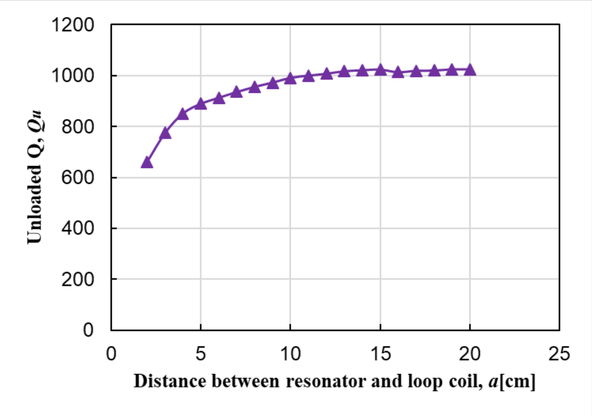

Fig.6 Q_u of paired-spiral with same winding direction (PP or NN)

the distance a becomes longer, the value of Q_u increases. It can be concluded that when the resonators which used at the first two combination is same direction, the amount energy loss is almost the same.

Furthermore, this result also proves that in order to find the coupling coefficient for the system that uses paired-spiral resonator, it is enough to just compare between the system that uses combination PP-PP and PP-NN. Initially, it has been planned to compare between PP-PP, NN-NN, PP-NN, and NN-PP. However, result in Fig.6 shows that the system with combination PP-PP is the same that of NN-NN, while PP-NN is the same that of NN-PP. Thus, in the next step, only the system with PP-PP and PP-NN were included in this paper.

ii) Transmission Efficiency of WPT System for Combination PP-PP and PP-NN

Fig.7 shows the power transfer energy efficiency with winding direction combination of PP-PP and PP-NN. According to the figure, the efficiency of WPT system for both PP-PP and PP-NN combination is almost the same. However, at distance about *d*=40cm, the efficiency of PP-NN is slightly higher than that of PP-PP. Based on this results, it has been decided to use PP-NN combination to examine the power transfer efficiency with different separation *s*-parameters.

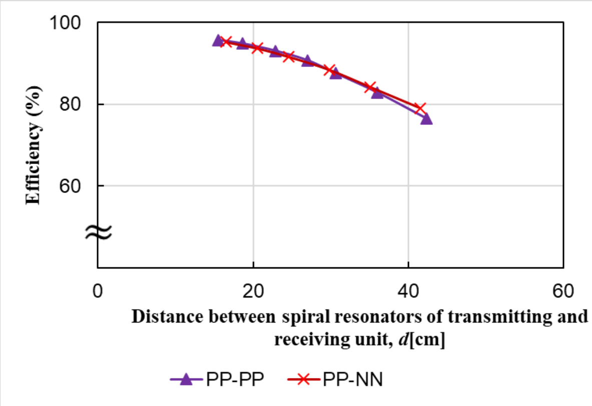

Fig.7 Experimental value of power transfer energy for PP-PP and PP-NN combination when *s*=2cm

Since the efficiency of PP-NN is higher than that of PP-PP for almost overall distance *d*, the data for difference *s*-parameters is only conducted with combination PP-NN to find the Q factor, coupling coefficient *k* and power transfer energy of WPT system.

iii) Q factors for Paired-Spiral Resonator

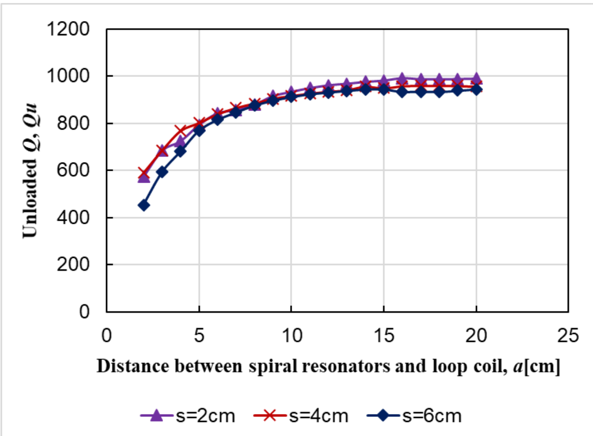

Fig.8 Q_u of paired-spiral PP winding direction for mode 1

Fig.8 shows the value of Q_u of paired-spiral with combination PP for mode 1 when the separation *s* is altered. As can be seen, the value of *Qu* increases as the separation *s* changed. Nonetheless, the value of Q_u is the highest when distance *a* is from 15cm to 20cm. Paired-spiral for *s*=2cm has the highest values of Q_u, while the paired spiral for *s*=6cm has the lowest values of Q_u. These indicate that when the separation between spirals in paired-spiral resonator *s* is shorter, the energy loss within the system is lower due to higher value of Q_u. Furthermore, When distance *a* is less than 5cm, the energy loss for paired-spiral with *s*=6cm is lower than other combination with a quite big margin compared to when *a*>5cm.

Fig.9 is the value of k_e when *s*-parameter is changed which correspondent with the value of Q_u of Fig.8. As the distance *a* increases, the value of k_e decreases. However, the results show that when *s*=4cm, the value of k_e is the lowest.

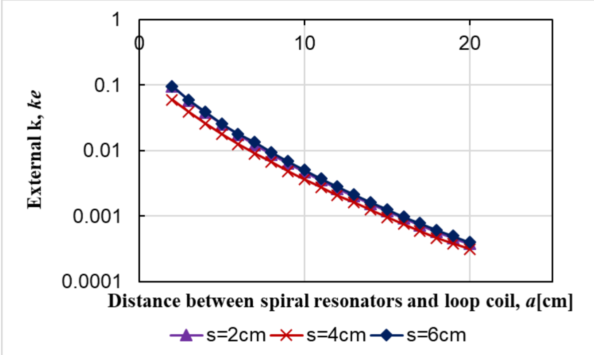

Fig.9 k_e of paired-spiral PP winding direction for mode 1

iv) Coupling Coefficient *k* for WPT System using Paired-Spiral Resonator

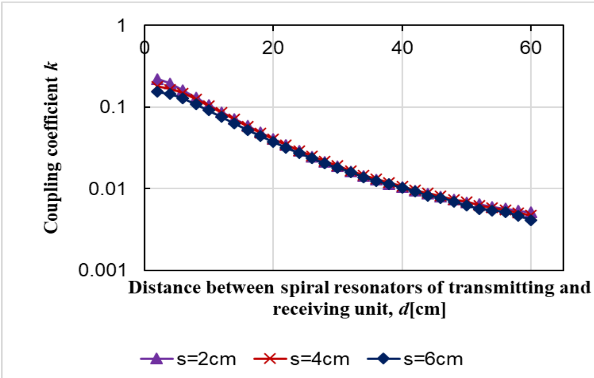

Fig.10 Coupling coefficient *k* of paired-spiral PP-NN winding direction combination

Fig.10 shows the coupling coefficient *k* of paired-spiral with PP-NN winding direction combination. From the results, the data for *k* is almost same for all 3 parameter of *s*. In addition, the graph descends as the distance *d* increases. The value of *k* is slightly higher when *s*=2cm especially when distance *d* is 2cm and 4cm. The value of *k* is lower at some degree.

v) Transmission Efficiency for WPT System using Paired-Spiral Resonator

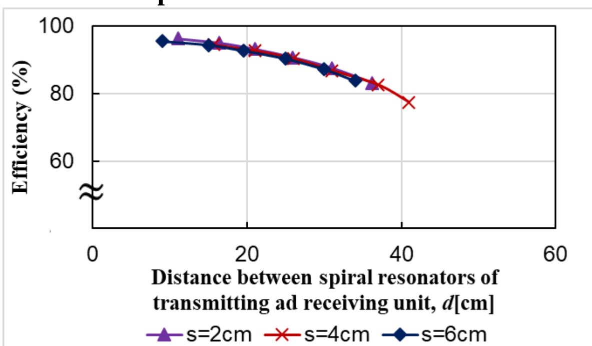

Fig.11 Theoretical value of power transfer energy for paired-spiral PP-NN winding direction combination

Fig.11 shows the theoretical value of power transfer energy efficiency for paired-spiral PP-NN combination. Fig.12 and Table 2 are the experimental values of the efficiency with the same parameter. Based on theoretical results, the efficiency almost has no different for all 3 *s*-parameters. However, the efficiency for experimental results when *s*=4cm is lower than that of *s*=2cm and *s*=6cm.

Table 2 Experimental values of the power transmission efficiency WPT system

	Paired-spiral PP-NN combination					
	s=2cm		*s*=4cm		*s*=6cm	
a [cm]	*d* [cm]	η [%]	*d* [cm]	η [%]	*d* [cm]	η [%]
2.0	16.5	95.21	18.4	89.77	19.2	94.37
3.0	20.5	93.68	23.0	86.72	23.5	92.52
4.0	24.6	91.58	28.0	84.41	28.0	87.21
5.0	29.8	88.41	34.0	79.66	33.3	82.37
6.0	35.1	84.16	40.0	72.56	40.0	79.62
7.0	41.5	79.00	48.0	63.46	48.0	70.21

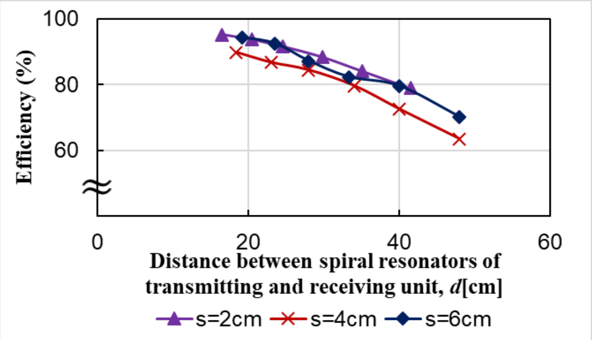

Fig.12 Experimental value of power transfer energy for paired-spiral PP-NN winding direction combination

It can be seen that the system that uses paired-spiral resonator with separation *s*=2cm has highest transmission efficiency compared to others. It can be referred in Table 2, when the distance *d* is about 30cm, the system that uses paired-spiral resonator with *s*=2cm provides about 88% transmission efficiency compared to the system which uses *s*=4cm and *s*=6cm.

On top of that, as the distance *d* increases, the transmission efficiency for the system that uses *s*=6cm are quite as good as that of *s*=2cm. When the distance *d*=40cm, both paired-spiral resonators have about 79% transmission efficiency. It can be assumed that the larger the distance *d*, the system that uses bigger separation *s* has better transmission efficiency compared to the smaller one.

5 Conclusions

In this paper, we proposed the winding direction combination of the spiral resonators and presented the fundamental property of paired-spiral resonators. However, the data and results collected is limited to resonant frequency for 10MHz.

As conclusion, by referring to Fig.5 of resonant frequency, the difference in value of resonant frequency of mode 1 and 2 for PN winding direction is bigger and wider than that of PP. After that, by referring to Fig.6, the value of Q_u when the paired-spiral resonators are placed with PP direction or opposite NN direction does not change. Next, according to Fig.7, PP-NN combination has higher transmission efficiency than that of PP-PP when separation *s*=2cm. Therefore, the comparison regarding difference in separation *s* used PP-NN combination only. Regarding Q factor and coupling coefficient from Fig.8 and Fig.10, paired-spiral with *s*=2cm has dominant performance compared to other *s*-parameters. Based on the obtained results from Fig.12 and Table 2, it can be summarized that by using paired-spiral resonator with PP-NN winding direction combination, the smaller the separation *s* is suitable for short range of WPT system. Meanwhile, long range of WPT system is suitable when longer separation *s* is used.

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