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Fundamental Characteristics of Some Modified Shape Spiral-Resonators Used for Resonator-Coupled Type Wireless Power Transfer System

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1 Introduction

Magnetically Resonator-Coupled type Wireless power transfer (RC-WPT) system is one of the promising ways the next generation which connects the power supply and the electrical appliances without regulation of the layout of household goods. From this reason, authors have studied the RC-WPT system using the spiral coils resonator due to its compactness.

In this RC-WPT system, a spiral resonator is the most important component for transferring electrical energy. To understand the installation of practical electrical appliances, the influence of obstacles with loss toward the resonators or system itself should be considered. So the dual-spiral resonators which have the robustness to electrical lossy objects around the resonator was proposed [1]. Here, the dual-spiral resonator has two modes due to its structure, however, only one mode with low resonant frequency is investigated [2]. For this reason, as a first step, the characteristics of two modes for the dual-spiral resonator would be examined in detail.

In addition, although another type of novel spiral resonator with a grounded-loop has only one mode, it is expected to improve the performance of the RC-WPT system has been proposed in this paper and the fundamental properties of this novel spiral resonator with grounded-loop would be presented, the characteristics of this resonator were also examined and finally to compared these two resonators.

2 Resonator-Coupled type WPT System

In general, this paper discusses the differences of the RC-WPT system that uses two types of spiral resonators. The fundamental structure of the RC-WPT system that uses the dual-spiral resonators is shown in Fig.1. This system has constructed with the set of loop-coil and spiral resonator in each input and output (I/O) units. To study the properties of the system and the resonator, the I/O ports were connected to the Vector Network Analyzer (VNA) and the S-parameters were measured.

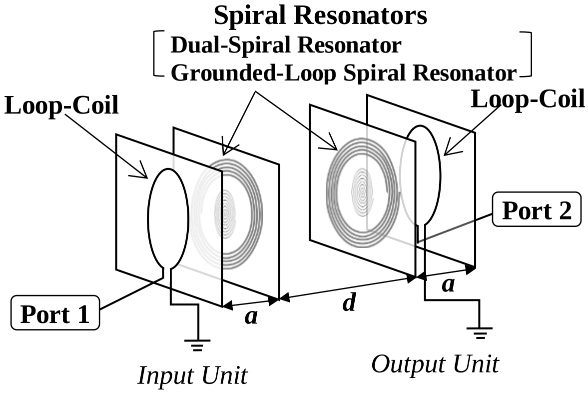


Fig.1 Schematic setup of RC-WPT system

The loop-coil in each I/O unit with the diameter 17.5 cm was fabricated by using 1.0 mmϕ *Cu* wire on the styrene foam boards. On the contrary, the spiral resonator was fabricated by using the 2.0 mm thickness Polyethylene (PE) boards on which 5.0 mm pitched spiral-shaped groove with the width of 1.2 mm was drawn and the 1.0 mmϕ *Cu* wire was embedded into that groove. In the case of the dual-spiral resonator, the two spirals with different shapes, the conventional and edge-wise shape, on the same PE board is shown in Fig.2 where the separation between the two spirals is x [cm].

Here, the conduction losses and dielectric losses are mainly caused by the electric fields. The dual-spiral resonator has a gap between the two resonators, the electric field of its eigen-mode tends to lie on the surface of the spiral, and the electric field is confined to the resonator itself. For this reason, the RC-WPT system with the dual-spiral resonators is expected to show the robustness against the lossy objects located on the power transmission path of the RC-WPT system.

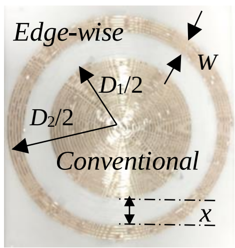


Fig.2 Dual-Spiral Resonator

In the fabrication process, the diameter of conventional spiral was set as $D_1 = 24.2$ cm and the winding turns were 26 times. For the edge-wise spiral, its outer diameter was set as $D_2 = 38.7$ cm, the width of winding region $W = 3.0$ cm

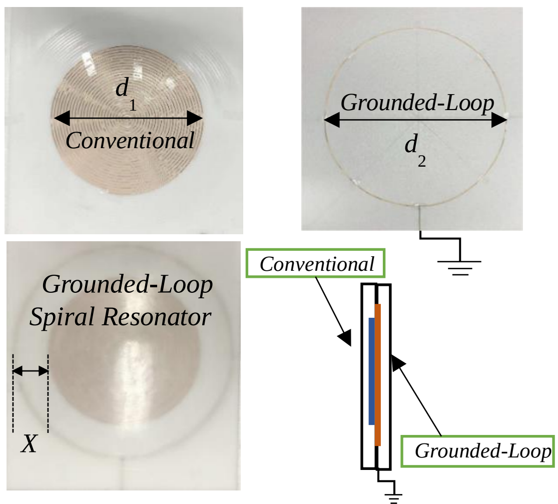
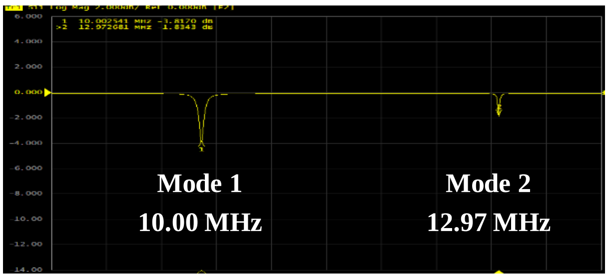


Fig.3 Schematic setup for grounded-loop spiral resonator

and winding turns were 6 times. Then, the separation between the two spirals was x = 5.0 cm. In this case, the resonant frequency of both isolated two spiral resonators are the same at 11.24 MHz. Combining these two kinds of spiral resonators, the dual-spiral resonator was constructed.

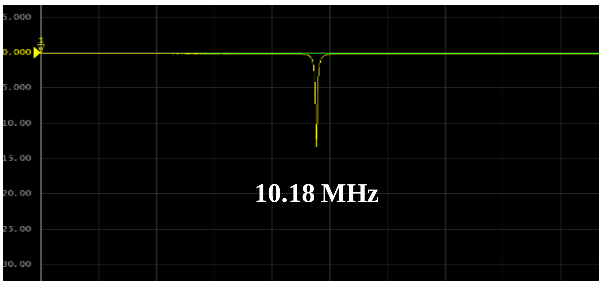
As another type of spiral resonator called grounded-loop spiral resonator was proposed with the conventional spiral resonator and the grounded-loop is shown in Fig.3. A conventional spiral resonator was fabricated on the same PE board that was used in the dual-spiral resonator, a grounded-loop was fabricated on the other styrene foam board. The two boards were overlapped face to face so that the resonator and grounded-loop side of the *Cu* wire were put together.

In order to compare the two different types of resonators, the resonant frequency of the conventional spiral resonator was set as 10.00 MHz, same with Mode 1 of the dual-spiral resonator. To satisfy this condition, the diameter of spiral resonator in this novel type was set as d_1 = 26.0 cm, the winding turns and direction were 26 times and clockwise, respectively. The grounded-loop was designed the diameter d_2 = 37.2 cm in this paper, the separation between the conventional resonator and the grounded-loop was X = 5.6 cm.



←Low frequency **High frequency→**

(***a***) Dual-Spiral Resonator.



←Low frequency **High frequency→**

(b) Grounded-Loop Spiral Resonator

Fig.3 Resonance of fabricated two types of Spiral Resonators

The observed result of S_{11} by using the loop-coil and the VNA with the dual-spiral resonator is shown in Fig.3 (a). It is clear that the dual-spiral resonator has two resonant modes, since that is what a coupled resonator with two different kinds of resonators. The resonant mode at a lower resonant frequency was called Mode 1 and the other, Mode 2, respectively. With the above dimensional parameters, the resonant frequency of the Mode 1 is 10.00 MHz and that of the Mode 2 is 12.97 MHz.

Another result of S_{11} by using the loop-coil and the VNA with the grounded-loop spiral resonator is shown in Fig.3 (b). Since this type of resonator is a combination of resonator and grounded line, only one resonant mode can be observed and the resonant frequency is 10.18 MHz.

The performance of the RC-WPT system depends on the quality factors of resonator and the coupling efficiency between resonators [2], [3]. Thus, in the next section, the measured results for typical quality factors, the unloaded Q, Q_u, the external Q, Q_e, and the coupling efficiency were shown, finally to measure the transmission efficiency for the two types of spiral resonators.

3 Measured Results

First of all, unloaded Q, Q_u, which is the inverse of energy loss of resonator and measured by changing the distance between the loop coil and the resonator, a, need to be found. Fig.4 (a) shows the measured Q_u for the grounded-loop spiral resonator and each modes of the dual-spiral resonator. From this result, for a < 7 cm, the Q_u of both modes increases as a increases, the grounded-loop spiral resonator and the Mode 1 of the dual-spiral resonator shows almost the same characteristics. When a is longer than 5 cm, the value of Q_u by using the the grounded-loop spiral resonator is higher than that of the Mode 1.

However, when the a is larger than 14 cm, the Q_u for grounded-loop spiral resonator and Mode 1 of dual-spiral resonator becomes stable, but the Q_u for Mode 2 of the dual-spiral resonator decreased as the distance a is longer than 7 cm and cannot be measured after a = 12 cm.

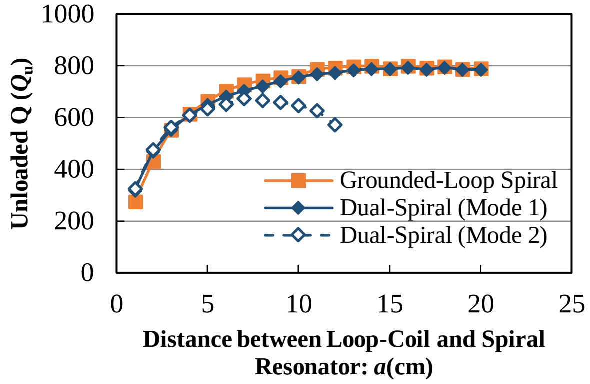
After that, the external Q, Q_e, which indicates the index for the inverse of the loss dissipated by the coupling between the resonator and the external circuit was measured. To make it easier to understand, the k_e was defined as following

$$k_e = \frac{1}{Q_e}. \tag{1}$$

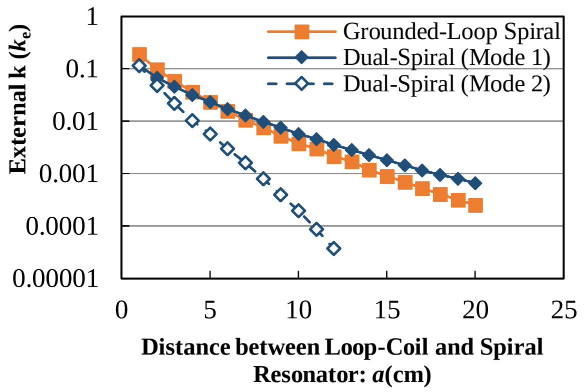
representing the strength of the coupling between the loop coil and resonator. The values of measured k_e were presented in Fig.4 (b). From these result, we can see when the distance a is increse,the k_e for both of two types spiral resonators are decrease. However, when a is less than 6 cm, the k_e for the grounded-loop spiral resonator is slightly higher than other modes of the dual-spiral rensonator.

In addition, Fig.4 (c) shows the measured coupling coefficient, k, between the two types of resonators in the RC-WPT system as a function of the distance between the resonators themselves, d. It can be seen clearly that the values of k decrease as the distance d increase. The value of the grounded-loop spiral resonator shows shortest distance of d and cannot be measured after d = 44 cm. Totally, the Mode 1 has the highest value of k, followed by the RC-WPT system that uses the grounded-loop spiral resonator. However, the Mode 2 gives the lowest value of k.

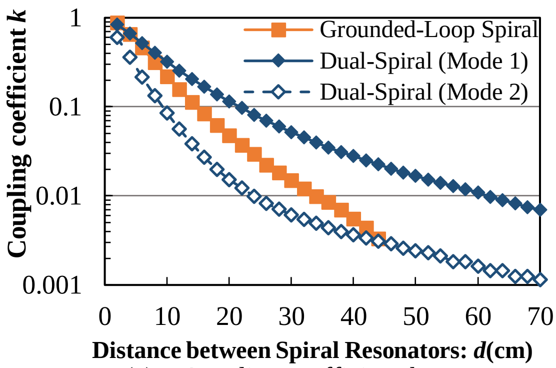
To measure transmission efficiency, the matching conditions of the RC-WPT system are estimated when the choice of the set of a and d when the k_e is equal to k [4].



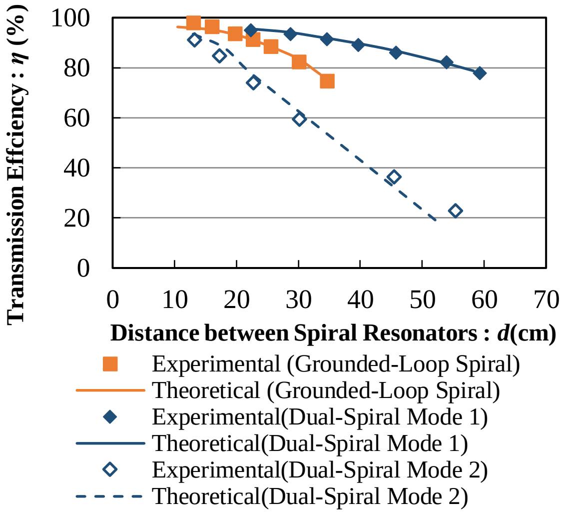
(*a*) Unloaded Q (Q_u)



(b) External k (k_e)



(c) Coupling coefficient *k*



(d) Power transmission efficiency

Fig .4 Measured with the Grounded-Loop Spiral Resonator and the Dual-Spiral Resonator

Table 1 Theoretical values of the Power Transmission Efficiency

	Dual-Spiral Resonator				Grounded-Loop Spiral Resonator	
	Mode 1		Mode 2			
a [cm]	*d* [cm]	*η* [%]	*d* [cm]	*η* [%]	*d* [cm]	*η* [%]
1.0	22.0	95.57	13.0	93.45	13.50	93.30
2.0	28.20	94.25	18.0	87.98	17.80	92.72
3.0	33.0	92.41	22.0	78.53	19.0	92.37
4.0	39.0	89.97	30.0	62.65	23.0	89.58
5.0	45.0	87.10	40.50	42.10	27.0	85.81
6.0	52.20	82.81	52.30	18.76	30.50	80.86
7.0	58.30	78.73			34.30	74.38

Table 2 Experimental values of the Power Transmission Efficiency

	Dual-Spiral Resonator				Grounded-Loop Spiral Resonator	
	Mode 1		Mode 2			
a [cm]	*d* [cm]	*η* [%]	*d* [cm]	*η* [%]	*d* [cm]	*η* [%]
1.0	22.30	95.02	13.20	91.27	13.0	98.17
2.0	28.70	93.46	17.20	84.81	16.0	96.46
3.0	34.60	91.37	22.70	74.07	19.70	93.81
4.0	39.60	89.08	30.10	59.51	22.60	91.38
5.0	45.70	85.95	45.40	36.48	25.50	88.49
6.0	53.90	82.17	55.30	22.97	30.0	82.49
7.0	59.30	77.91			34.60	74.76

If the set of *a* and *d* satisfied the matching condition, the RC-WPT system will show the maximum power transmission efficiency.

Based on the results of Figs.4 (b) and (c), with the sets of *a* and *d* at which k_e=k and some fine tunings, the measured result of the transmission efficiency is presented in Table.1, Table.2 and Fig.4 (d), together with the theoretical value obtained by using the method presented in Refs. [2] and [3].

From these results, it is clearly that for the Mode 1 of dual-spiral resonator, as the spiral distance *d* increases, the value of transmission efficiency gradually decreases. For the Mode 2, the value of transmission efficiency also decreases as the *d* increases, but it drops much quickly and ends at 55.3 cm with the value of transmission efficiency at 22.97 %. In addition, the theoretical value and the experimental efficiency value with two Modes are almost the same.

On the other hand, for the grounded-loop spiral resonator, the value of transmission efficiency also decreases as distance *d* increases. Table.2 has clearly shown that the value of transmission efficiency for the grounded-loop spiral resonator is higher than the other two when a < 7 cm, however when the distance a is same, the distance d is shorter than the Mode 1 of the dual-spiral resonator.

4 Conclusions

In this paper, the dual-spiral resonator and the grounded-loop spiral resonator were proposed, the fundamental property and measured the power transmission efficiency of the RC-WPT system with both were presented. According to these results, we can conclude that when using the dual-spiral resonator, the power transmission efficiency of Mode 1 with the RC-WPT system is higher than Mode 2. Furthermore, under the condition of being set to the almost same frequency at 10 MHz, with same distance a , the power transmission efficiency of the grounded-loop spiral resonator are higher than that of the dual-spiral resonator, but the distance d is shorter than that of the two Modes. That means the grounded-loop spiral resonator is more suitable to using a short-range power transfer than the dual-spiral resonator.

However, higher level of precision precise in the frequency of spiral resonators should be reached to analyze the characteristics. Since the ultimate goal of this research is to achieve the comparison of two types resonators at the same 10.0 MHz frequency, we will continue to conduct this research by turning the grounded-loop spiral resonator become 10.0 MHz as well in the near future work. For the dual-spiral resonator, the law of frequency change will desire to be discover by changing the separation between the two spiral resonators. Finally, we will commit to achieve the understanding in the comparison for the RC-WPT system by using the Mode 2 of the dual-spiral resonator and the grounded-loop spiral resonator due to the lossy materials.

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