PAPER

Effects of Lossy Mediums for Resonator-Coupled Type Wireless Power Transfer System using Conventional Single- and Dual-Spiral Resonators

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SUMMARY To realize a stable and efficient wireless power transfer (WPT) system that can be used in any environment, it is necessary to inspect the influence of environmental interference along the power transmission path of the WPT system. In this paper, attempts have been made to reduce the influence of the medium with a dielectric and conductive loss on the WPT system using spiral resonators for resonator-coupled type wireless power transfer (RC-WPT) system. An important element of the RC-WPT system is the resonators because they improve resonant characteristics by changing the shape or combination of spiral resonators to confine the electric field that mainly causes electrical loss in the system as much as possible inside the resonator. We proposed a novel dual-spiral resonator as a candidate and compared the basic characteristics of the RC-WPT system with conventional single-spiral and dual-spiral resonators. The parametric values of the spiral resonators, such as the quality factors and the coupling coefficients between resonators with and without a lossy medium in the power transmission path, were examined. For the lossy mediums, pure water or tap water filled with acryl bases was used. The maximum transmission efficiency of the RC-WPT system was then observed by tuning the matching condition of the system. Following that, the transmission efficiency of the system with and without lossy medium was investigated. These inspections revealed that the performance of the RC-WPT system with the lossy medium using the modified shape spiral resonator, which is the dual-spiral resonator proposed in our laboratory, outperformed the system using the conventional single-spiral resonator.

key words: *electromagnetic coupling, wireless power transfer, lossy mediums, power transmission efficiency, spiral resonator*

1. Introduction

To realize a stable and efficient wireless power transfer (WPT) system that can be used in any environment, it is necessary to inspect the influence of environmental interference along the power transmission path of the WPT system. Until now, many electric appliances have used WPT systems that use electromagnetic induction, such as the Qi system [1], [2], but their power transmission distance is much shorter, and they are sensitive to positioning misalignment between transmission (Tx) and receiving (Rx) units. Furthermore, the power transmission efficiency of the electromagnetic induction type WPT system through a lossy medium is quite low for practical application. Therefore, a resonator-coupled type WPT (RC-WPT) system, which can transmit electric energy over a mid-range distance without power cable using electromagnetic near-field coupling between the resonators installed in Tx and Rx units, was proposed [3], [4]. In this system, if a magnetic field is used for field coupling, electric energy can transmit wirelessly through materials such as walls [5], water [6], and so on. Furthermore, the performance of the RC-WPT system is stable against the positioning tolerance between Tx and Rx units [7]. This has resulted in significant developments in power supply for electric appliances, electric vehicles [8], small robots [9], mobile devices [10], and medical devices [11]–[13].

Here, the electric loss of the materials is caused by acting on the electric fields rather than the magnetic fields. Therefore, planar spiral coil type resonators were used as resonators in our RC-WPT system to prevent the influences of the lossy medium and ensure that the coupling between magnetic fields is dominant. According to [14], the planar spiral coil is one of the most suitable resonators for the WPT system because of its compact size and low transfer loss. Until now, the conventional single-spiral has been used in the RC-WPT system. However, when the lossy mediums are adjacent to the system, the leaked electric fields around the resonator act on the loss and reduce the transmission efficiency [15]–[18]. To improve the efficiency, we proposed a coplanar type dual-spiral resonator [19], in which the electric fields tend to lie on the spiral surface, and the capacitive component is increased. Furthermore, the electric field is tightly confined inside the dual-spiral resonator effectively.

In this paper, the performance of an RC-WPT systems with conventional single-spiral and the proposed dual-spiral resonators was compared under the same resonant frequency and outer diameter of the resonators. The performance of the RC-WPT system using dual-spiral resonators was presented and compared with the system using conventional single-spiral resonators based on experimental results for cases that lossy mediums existed around the Tx and Rx units.

This paper supplements and extends the two International Conference Proceedings [20], [21] with the additional experimental data and further discussions.

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2. Configuration Setup for RC-WPT System

The schematic structure of the RC-WPT system treated in this paper is presented in Fig. 1. The system consists of Tx and Rx units. Each unit has a pair of loop coil and a spiral resonator. In the RC-WPT system, the electric power induced from port 1 is converted to electromagnetic energy stored in the resonator in the Tx unit through the loop coil. The adjacent resonator with the same resonant frequency in the Rx unit is excited by the electromagnetic field formed by the resonator in the Tx unit. The electromagnetic energy of the resonator in the Rx unit is converted to electric power through the loop coil and output to port 2 [22]–[25]. The coupling electromagnetic field between the Tx and Rx units is mainly magnetic because the spiral resonator is a coil type. Here, the distance between the spiral resonator and loop coil is a [cm], and the distance between the spiral resonators is d [cm]. The loop coils in Tx and Rx units are connected to a vector network analyzer (VNA), which serves as the system's power supplier and receiver. Additionally, the setup for the RC-WPT system with lossy mediums is shown in Fig. 1(b).

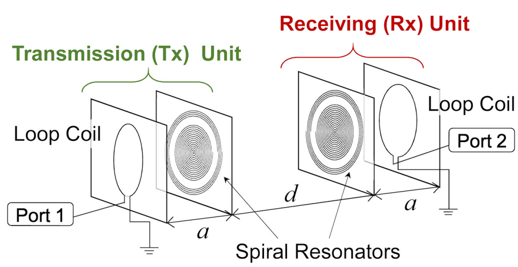
On styrofoam boards, the loop coils are made with 1.0 mmϕ copper wire. As a result, conventional single-spiral and proposed dual-spiral resonators were built on 2 mm thick polyethylene boards with a spiral-shaped groove of 1.2 mm width and 1.0 mm depth, and the polyethylene boards are now referred to as "spiral guides" [19]. The 1.0 mmϕ copper wire is embedded to fit into the groove of the spiral guide. The single-spiral resonator has a 1.0 cm pitched spiral-shaped groove, while the dual-spiral resonator has a 0.5 cm pitched spiral-shaped groove.

The shape of the two kinds of spiral resonators treated in this paper, the single-spiral resonator and dual-spiral resonator, as shown in Fig. 2. To ensure a fair comparison of the performance of the RC-WPT system with these resonators under the influence of lossy mediums, their outer diameters, D_1 and D_3, and also their resonant frequency, f, were set to be the same in this paper.

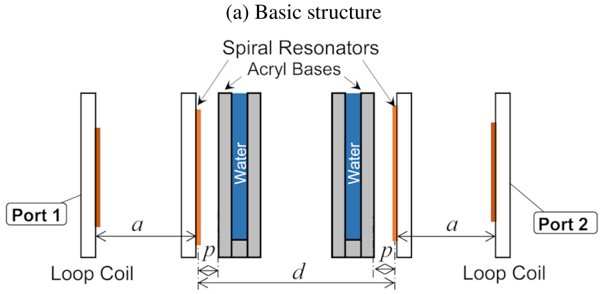
The dual-spiral resonator is designed as an appropriate combination of the outer edgewise and inner conventional spiral resonators which have the same resonant frequency [19], [26] on the same plane. First, the outer diameter of edgewise spiral resonator, D_3, and the wire spacing, s_2, are determined. The length of the Cu wire winding is then related to the resonant frequencies of the isolated edgewise spiral and the conventional single-spiral resonator on the spiral guide. Subsequently, the resonant frequency of the spiral resonators combined on the same spiral guide is measured using the resonant frequency of the isolated spiral resonator as a parameter. Further, the resonant frequency and winding length of the Cu wire of each isolated spiral resonator are determined at the desired resonant frequency of the combined spiral resonator. By winding the Cu wire of the inner and outer spiral resonators as defined above, the separation x [cm] between the inner and outer spiral resonators and the diameter of each spiral resonator are decided [19], [20].

When the wire spacing of the conventional single-spiral resonator, s_1, is set to 1.0 cm and the resonant frequency f = 10.0 MHz, the diameter D_1 is fixed at 37.2 cm. As D_3 is set to D_1, D_3 is automatically decided as 37.2 cm. To set the resonant frequency of the dual-spiral resonator as f = 10.0 MHz, the wire spacing, s_2, should be narrower than that of conventional single-spiral resonator, s_1. We therefore set s_2, to 0.5 cm. The resonant frequency of 10.0 MHz was chosen due to the size of the experimental facility and the proximity of bands is the ISM band.

Under these conditions, when the separation between the inner and outer resonators, x, of the dual-spiral resonator is set as 3.5 cm, the resonant frequency of each resonators is 11.4 MHz, and D_2 = 24.4 cm in this paper. Since the dual-spiral resonator is a type of coupled-resonator, it has two modes: odd mode and even mode [27]. In our study, the lowest resonant point mode, f_1 = 10.0 MHz, is referred to as *mode 1*, and the other resonant point, f_2 = 13.4 MHz, is referred to as *mode 2*. The resonant frequency of *mode 1* is set to the same value as that of the conventional single-spiral

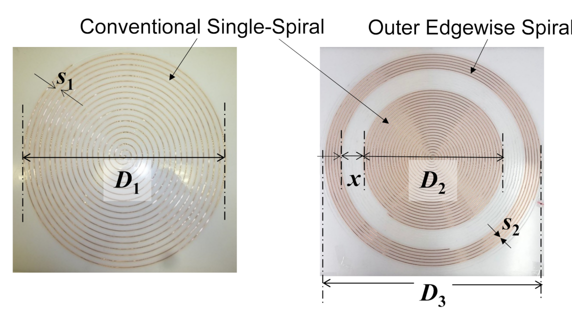


(a) Basic structure



(b) Setup of lossy mediums

Fig. 1 Schematic setup for RC-WPT system.



(a) Single-Spiral Resonator (b) Dual-Spiral Resonator

Fig. 2 Structural parameters of fabricated spiral resonators.

resonator because *mode 1* is used for RC-WPT in this paper owing to its good stability and better performance.

The conductive and dielectric loss in the lossy medium are caused by the electric field. Furthermore, a spiral resonator with a capacitor exhibits higher Q_u than a simple spiral resonator with no capacitor when wet object is adjacent to the resonator [28]. Here, the electric energy is stored inside the capacitor itself, indicating that reducing the electric field leakage from the resonator might realize an insensitive system against lossy objects. Although the simple spiral resonator with a capacitor and the dual-spiral resonator have the same mechanism of the loss reduction, our dual-spiral resonator has no lumped elements such as the capacitors; instead, the separation x between the resonators provides the capacitance component of the dual-spiral resonator, which is to be increase such that the electric field vector of the resonator lies in the spiral surface and the electric energy is confined in the resonator [20], [21]. Therefore, the RC-WPT system with dual-spiral resonators is expected to be less sensitive to lossy medium than the RC-WPT system with conventional single-spiral resonators.

The performance of the RC-WPT system depends on the quality factors and coupling coefficients between resonators [4]. Thus, the measured results for typical quality factors, the unloaded Q, Q_u, and the coupling coefficients, k, using single-spiral, and dual-spiral resonators, will be presented in the following section.

3. Measurement of Fundamental Parameters

3.1 Measurement of Q Factor

To determine the resonator's performance, the unloaded Q, Q_u, which is proportional to the inverse of the dissipated loss in the resonator through one cycle, should be investigated. The measurement setup for the Q factor of the resonator with a water-filled acryl base as the lossy medium is shown in Fig. 3. In the Q factor measurement, one set of loop coil and resonators was used. The measurement was conducted using S-parameters, S_{11}. The detailed measurement procedure is detailed in Refs. [15] and [29]. The Q factor without lossy medium can be determined by removing the acryl base. By this setup, the external Q, Q_e, and Q_u can be measured simultaneously; however, the results for Q_u are presented in this section.

The measured Q_u without lossy medium for each spiral resonator as a function of a is shown in Fig. 4. Here, the circle marks represent the Q_u for the single-spiral resonator, while the solid and hollowed square marks represent the Q_u for *modes 1* and *2* of the dual-spiral resonator, respectively.

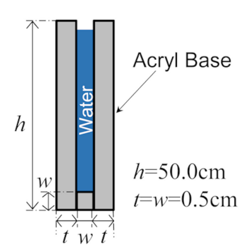
Based on the measured results, the Q_u for *mode 1* of the dual-spiral resonator is slightly higher than that of the single-spiral resonator. As a exceeds 15.0 cm, the Q_u of the dual-spiral resonator asymptotes to 870 whereas that of the single-spiral resonator asymptotes to 750. When a is up to 9.0 cm, Q_u for *mode 2* shows the same characteristic; however, as a exceeds 9.0 cm, Q_u for *mode 2* decreases and cannot be measured in the range of a >12.0 cm. Therefore, our investigation for the dual-spiral resonator has been limited to *mode 1* because the operation mechanism of *mode 2* has yet to be determined.

Furthermore, Q_u of the resonator with the lossy medium is examined to check the characteristics of the spiral resonator when lossy mediums are placed close together. Another parameter of this measurement is the distance between the spiral resonator and acryl base, p, as shown in Fig. 3(b). When p is short, it means the lossy medium is close to the Tx or Rx units.

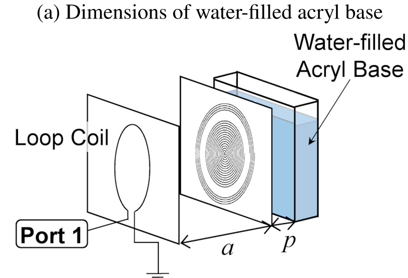
In this paper, tap or pure water-filled acryl bases are used as a lossy medium along the transmission path. The acryl bases are kinds of lossy mediums with dielectric loss that also serve as water containers. In this experiment, the conductivity of the tap water is approximately 223 μS/cm, whereas the conductivity of pure water is negligibly less than 0.1 μS/cm. Additionally, water is a dielectric material with a large permittivity. The tap water contains dissolved ionic salts, whereas the pure water has been filtered and processed to remove impurities. Therefore, when electric energy is transmitted through a tap or pure water in the RC-WPT system, the tap water will dissipate the extremely large electric energy more than the pure water.

Figure 5 (a) and (b) show the measured results of Q_u for the single-spiral and dual-spiral resonators when the lossy medium is closed to the system, p = 1.0 cm, with the hollowed marks, and those for p = 7.0 cm with the solid marks. In these figures, the Q_u without a lossy medium in Fig. 4 is also presented for comparison. In each result, the triangle marks represent the Q_u without lossy medium, whereas the diamond and circle marks represent the Q_u with pure water-filled acryl base and tap water-filled acryl base, respectively.

From these results, when the water-filled acryl bases are closed to the resonator, the Q_u significantly decreased than the case without the lossy medium. It was revealed



(a) Dimensions of water-filled acryl base



(b) Measurement Setup for Q factors

Fig. 3 Measurement setup for Q factors of RC-WPT system with lossy medium.

that the lossy medium around the resonator affects the deteriorating properties of the spiral resonators. Conversely, when the lossy medium was placed 7.0 cm from the resonator, the Q_u was obviously increased. Furthermore, when pure or tap water-filled acryl base is inserted into the system, the Q_u using a dual-spiral resonator is larger than that using a single-spiral resonator. It can be inferred that the electric field leaked out from the dual-spiral resonator is smaller than those of the single-spiral resonator. Since Q_u is the inverse of the loss consumed within the resonator, the resonator with a higher Q_u indicates a lower loss resonator. Therefore, when a lossy medium exists around the resonators, the dual-spiral resonator has a lower loss than the single-spiral resonator.

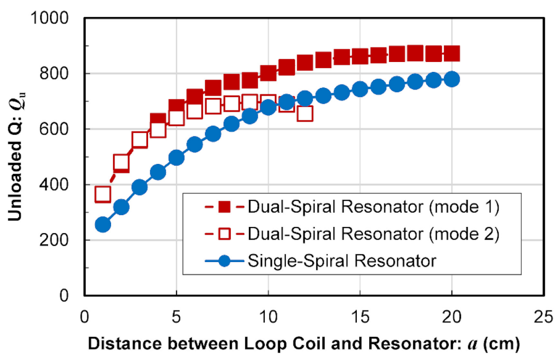
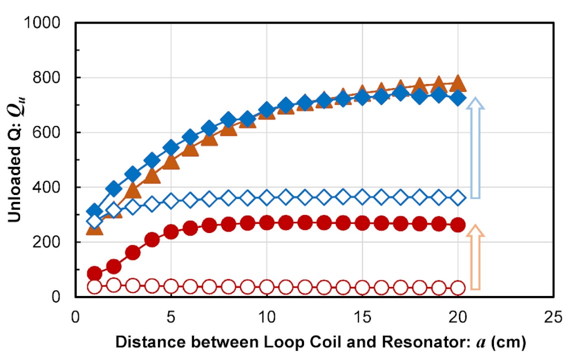
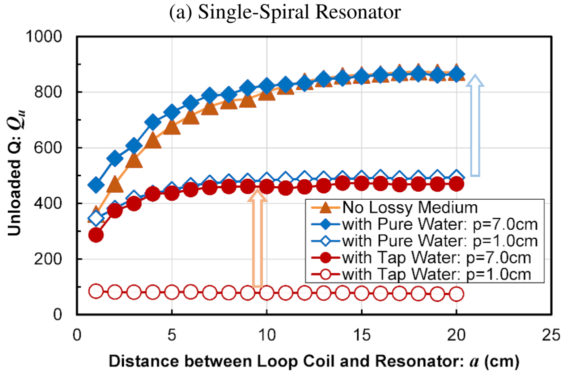


Fig. 4 Measured Q_u for the single- and dual-spiral resonators without lossy medium.



(a) Single-Spiral Resonator

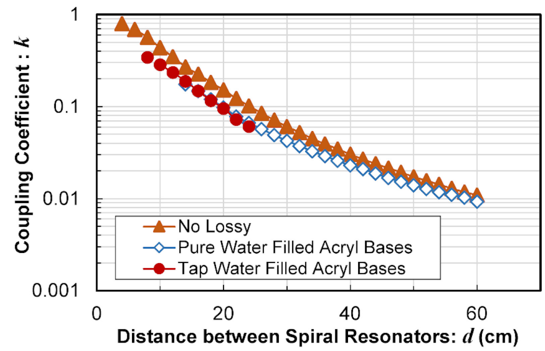


(b) Dual-Spiral Resonator (*mode 1*)

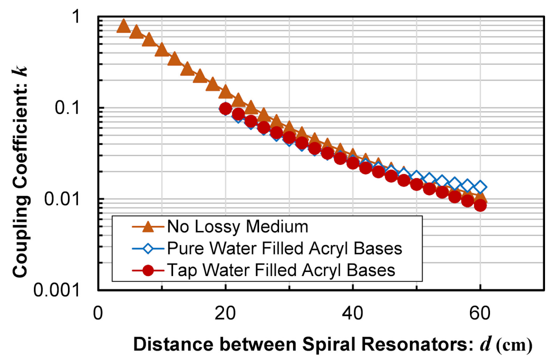
Fig. 5 Measured Q_u with lossy medium where p = 1.0 and 7.0 cm. The symbol legends are depicted in (b).

3.2 Measurement of Coupling Coefficient

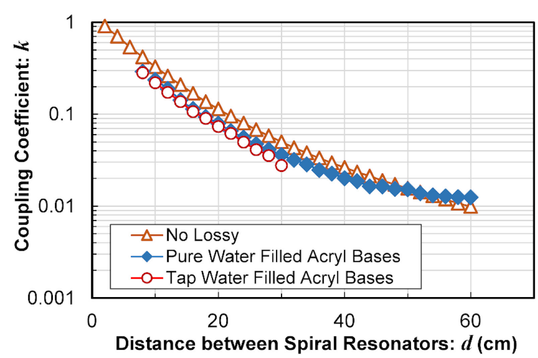
In the cases that p = 1.0 and 7.0 cm, the coupling coefficients



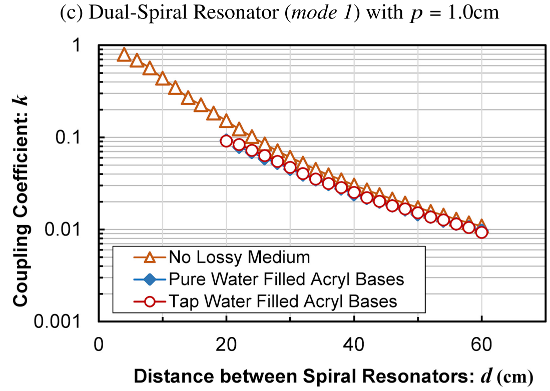
(a) Single-Spiral Resonator with p = 1.0cm



(b) Single-Spiral Resonator with p = 7.0cm



(c) Dual-Spiral Resonator (*mode 1*) with p = 1.0cm



(d) Dual-Spiral Resonator (*mode 1*) with p = 7.0cm

Fig. 6 Measured k for RC-WPT system with lossy mediums.

for the RC-WPT system with lossy mediums were examined in the measurement setup as shown in Fig. 1 (b).

The measurement was conducted using S-parameters, S_{12}. The measurement procedure is detailed in Refs. [15] and [29]. In the measurement, the distance between the loop coil and spiral resonator, a, is fixed at 15.0 cm for each unit because the Q_u for single-spiral and *mode 1* of dual-spiral resonators are asymptote to a constant in the range of a greater than 15.0 cm [30]–[32]. In this situation, the influence of the external parts has been prevented, and the pure coupling coefficients between the resonators can be measured. In the case that the single-spiral and the dual-spiral resonators are used in the RC-WPT system, the measured coupling coefficients, k, between resonators as a function of d with the lossy medium is presented in Fig. 6. The coupling coefficients for each resonator were shown to be the lowest when using tap water-fill acryl bases, and this was only observed over short distances d. Although the coupling coefficients for the system without lossy medium are slightly higher than those with tap water-filled acryl bases and also pure water-filled acryl bases, each measured curve presented almost the same tendency, and the differences were smaller than those of Q_u (see Fig. 5).

4. Power Transmission Efficiency with Lossy Mediums

The power transmission efficiency of the RC-WPT system can be evaluated after the quality factors and coupling coefficients are examined. The measurement setup for the power transmission efficiency of the RC-WPT system with the lossy medium is shown in Fig. 1(b).

Here, the equivalent circuit of the RC-WPT system can be expressed by 2-stage Band Pass Filter (BPF) circuit [33], [34]. According to the design theory of BPF circuit, the system matching condition should be satisfied to obtain the maximum transmission efficiency for each RC-WPT system. The external Q, Q_e, can be measured simultaneously with Q_u and the inverse of Q_e defines the external k, ($k_e = 1/Q_e$) [32]. Then, the system matching condition for our RC-WPT system can be established when k_e as a function of a equals the coupling coefficient, k, as a function of d. Therefore, the sets of a and d satisfying the system matching conditions would be obtained from the relation, $k = k_e$ [15], [32].

The theoretical value of transmission loss L on the system matching condition can be obtained using the BPF design theory expressed as follows [4],

$$L = \frac{8.686}{kQ_u} \quad \text{dB} \tag{1}$$

where it is assumed that Q_u of two spiral resonators used in the RC-WPT system has the same resonant frequency. Here, the constant in the denominator of Eq. (1) depends on the shape of the system's equivalent circuit. Therefore, this equation holds in the case of a system with no lossy mediums on the power transmission path; however, the fact that the transmission loss is proportional to the inverse of the product of kQ_u would hold in the case of a system with lossy mediums.

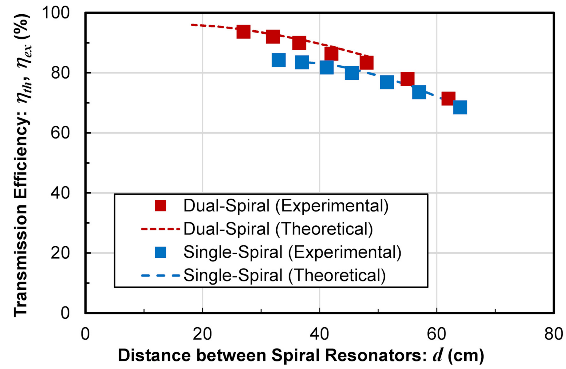


Fig. 7 Power transmission efficiency of RC-WPT system without lossy mediums.

Hence, using the k and Q_u shown in the previous section, the theoretical value of transmission efficiency, η_{th}, can be obtained from the transmission loss in Eq. (1) using the following equation,

$$\eta_{th} = 10^{-\frac{L}{10}} \times 100 \quad \%. \tag{2}$$

Using system-specific transmission loss, L, the η_{th} is the transmission efficiency excluding the lossy medium along the power transmission path. In the practical measurements, to get the maximum power transmission efficiency, some adjustments for d would be required.

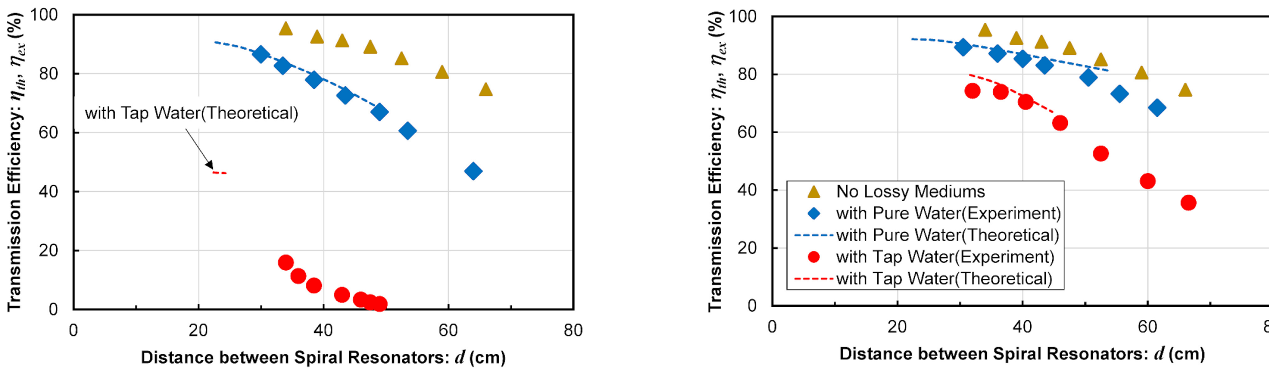
To obtain the experimental value of the transmission efficiency, η_{ex}, the input port 1 and output port 2 of the RC-WPT system are connected to vector network analyzer (VNA), and the S-parameters S_{11} and S_{21} are measured [33], [34]. Using the measured S-parameters, η_{ex} can be estimated by the following equation,

$$\eta_{ex} = \frac{10^{\frac{|S_{21}|}{10}}}{1 - 10^{\frac{|S_{11}|}{10}}} \times 100 \quad \%. \tag{3}$$

η_{ex} is the power transmission efficiency between the resonators in Tx and Rx units as the effect of reflection from the input port is removed using the formula of the denominator.

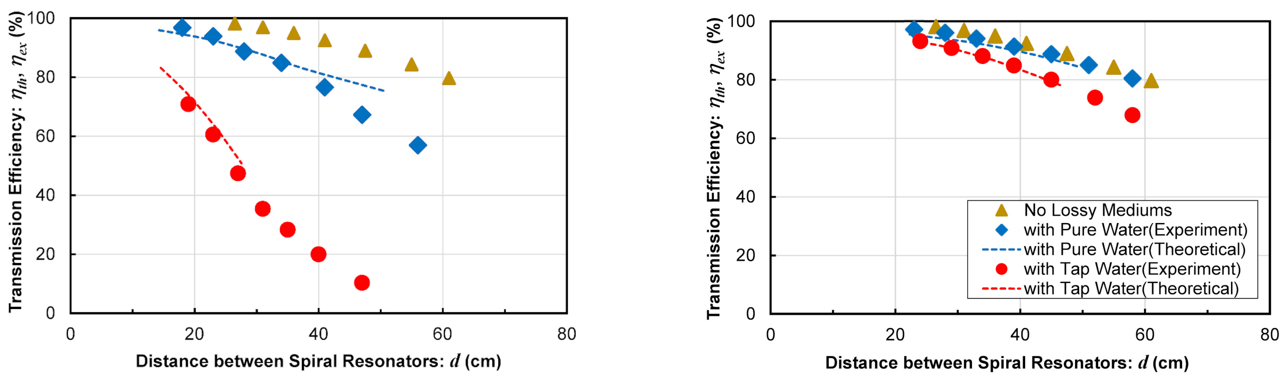
Figure 7 shows the comparison of the measurement result between the theoretical and experimental value of transmission efficiency without a lossy medium in the RC-WPT system. Based on this result, the theoretical and experimental efficiency values of the RC-WPT system show good agreement between them. Furthermore, as the distance d increases, the transmission efficiency of the system decreases. However, the dual-spiral resonator has a higher transmission efficiency and the range of distance d where the transmission efficiency is larger than 60% is wider than those of the single-spiral resonator. These results show that when there are no lossy mediums inside the system, the dual-spiral resonator effectively confined the electric field compared to the single-spiral resonator.

Furthermore, the transmission efficiency of the RC-



(a) p = 1.0cm (b) p = 7.0cm

Fig. 8 Measured power transmission efficiency of RC-WPT system with Single-Spiral Resonators through lossy mediums. The symbol legends are depicted in (b).



(a) p = 1.0cm (b) p = 7.0cm

Fig. 9 Measured power transmission efficiency of RC-WPT system with Dual-Spiral Resonators through lossy mediums. The symbol legends are depicted in (b).

WPT system with the lossy medium is examined. The measured results where the separation between the spiral resonator and acryl base, p, are fixed at 1.0 and 7.0 cm, are presented in Fig. 8 for the system with single-spiral resonators and Fig. 9 for the system with dual-spiral resonators. The transmission efficiency without a lossy medium in Fig. 7 is also presented in the same figure for comparison. Here, the triangle marks represent the transmission efficiency for the system without lossy mediums. Meanwhile, the diamond and circle marks indicate the measured experimental results in the systems with a pure water-filled acryl base and a tap water-filled acryl base, respectively, and the dashed lines are the theoretical results estimated by Eq. (2). The experimental and theoretical results follow similar trends excepting in the case of tap water-filled acryl bases at p = 1.0 cm (Fig. 8 (a)). In the RC-WPT system with the single-spiral resonators adjacent to tap water-filled acryl bases, the transmission efficiency was drastically reduced and the theoretical system matching conditions were satisfied only at a few points.

From the results in Figs. 8 and 9, the transmission efficiency of the RC-WPT system with lossy mediums with the single-spiral and dual-spiral resonators is lower than that of the system with no lossy medium. As previously stated, the acryl base is only a dielectric material, whereas tap and pure waters are dielectric and conductive loss material with high permittivity. Here, if water-filled acryl bases are inserted into the system, the effect of dielectric and conductive loss will be dissipated from the water as well as dielectric loss from acryl bases. Thus, the electric fields leaked from the spiral resonators would be attenuated because of the dielectric and conductive loss [28], [33], [34]. These decays cause a decrease in the electromagnetic energy and transmitted electric power.

Furthermore, when a lossy medium is inserted in the RC-WPT system, the transmission efficiency of the system with tap water-filled acryl bases is lower than that with pure water-filled acryl bases. The decrease in this transmission efficiency would be caused by the high conductivity of tap water. Therefore, the tap water-filled acryl base has the lowest transmission efficiency of the RC-WPT system compared to other lossy mediums.

From the results in Fig. 8, when p = 1.0 and 7.0 cm, the transmission efficiency for the conventional single-spiral with pure or tap water-filled acryl base is far less than the transmission efficiency without lossy medium inside the RC-WPT system. However, using the dual-spiral in Fig. 9, the transmission efficiency for the system with pure or tap water-filled acryl base using the dual-spiral resonator has improved compared with that using single-spiral resonator. Additionally, the transmission efficiency for the system with dual-spiral resonator approaches to that without lossy medium. These results show that when a lossy medium is introduced in the system, the dual-spiral resonator has a smaller decreased rate of transmission efficiency than that of the single-spiral resonator. Furthermore, when the distance p is the same, the dual-spiral resonator has higher transmission efficiency of the system and wide range of distance d where the transmission efficiency is larger than 60%. Judging from the measurement results of Q_u and k in Sect. 3, by inserting the lossy medium adjacent to the resonator, Q_u decreases due to the strong influence of that object, but the k does not change. From Eq. (1), the transmission loss of the RC-WPT system is proportional to the inverse of the product kQ_u. These facts tell us that the insertion of lossy mediums would affect to the properties of resonator, especially in Q_u, and lead to a decrease in the transmission efficiency of the entire RC-WPT system.

Here, the dual-spiral resonator effectively confines the electric field compared to single-spiral resonators. Since the influence of the lossy medium is caused by the interaction between the electric field and lossy medium, the spiral resonator, which is the dual-spiral resonator, would be the most effective way to establish a strong resistance for the RC-WPT system against the lossy medium. To confirm these statements, we should investigate the modes of spiral resonators more in detail using an electromagnetic simulator.

5. Conclusions

In this paper, the performance of the RC-WPT system with and without lossy mediums in the power transmission path was examined under conditions of the same resonant frequency and outer diameter of resonators between the conventional single-spiral and proposed dual-spiral resonators. From the measured results, when mediums comprising dielectrics with conductive loss are installed along the power transmission path, the power transmission efficiency of RC-WPT system using conventional single-spiral resonators is decayed. However, the system using the proposed dual-spiral resonators improves the decay of power transmission efficiency. Therefore, it is confirmed that the system with dual-spiral resonators is less sensitive to a lossy medium than the system with single-spiral resonators. In other words, the influence of lossy mediums can affect the properties of the spiral resonators, and thereby decrease the transmission efficiency of the entire RC-WPT system. The degradation effect is smaller in the dual-spiral resonator than in the conventional single-spiral resonator.

In future work, the investigation of the performance of the RC-WPT system under the influence of saltwater-filled acryl base and the modal properties of *mode 2* of dual-spiral resonator should be conducted in detail.

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