A Novel Parallel Double Helix Loop Resonator for Magnetic Coupled Resonance Wireless Power Transfer

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Abstract— A novel parallel double helix loop resonator for magnetic coupled resonance wireless power transfer (WPT) is proposed in this paper. The various characteristics are investigated by using simulation and experiment. Compare to a same geometry size traditional structure helix loop resonator, the proposed resonator could reduce the resistance loss about 48% and improve the maximum power transfer efficiency about 8% within the strong coupled region. On the other hand, the coupling efficiency of proposed resonator used WPT system is also increased. Finally, for increase the power transfer efficiency at the region of outside of the strong coupled, a pair of matching loops are used to match the transmitting and receiving resonator to the optimal port impedance at varying distance and the measurement results shows the maximum power transfer efficiency that the system could achievable by using traditional structure helix loop resonator and parallel double helix loop resonator are 34% and 57% at the distance of 20 cm, respectively.

1. INTRODUCTION

Magnetic coupled resonance WPT technology is expected to the next generation wireless power charging system, because of its advantage of mid-range power transfer distance and high efficiency [1]. There are two most important performances of this technology always be focus on which are: long power transfer distance and high power transfer efficiency. To achieve this, it is necessary to improve the resonator quality factor and the coupling efficiency. The quality factor of resonator is proportional to the resonance frequency and self-inductance of the resonator and inversely proportional to the resonator resistance loss. Therefore, it is necessary to reduce the resistance loss in order to improve the resonator quality factor.

2. RESONATOR DESIGN

A traditional structure helix loop resonator is widely used and researched for magnetic resonance WPT system as shown in Fig. 1. It can be represented in terms of a simplified LCR equivalent lumped circuit element [2]. The L and C are the resonator self-inductance and self-capacitance which could make it resonant at the operation frequency of ω_0. R is the resistance loss including both radiation and conductivity loss.

From the fundamentals of an RLC circuit, when two inductors are connected so that the magnetic field of one affects the other which will occurs a mutual inductance L_m between them, and the mutual inductance increases or decreases the total inductance of circuit. When two inductors are connected in parallel with an aiding, the total inductance L_T becomes to (1). The mutual inductance can be calculated by using Equation (2) where k is the coupling efficiency between two inductors. From Equations (1) and (2), when the coupling efficiency between two parallel connected inductors is closely coupled where $k = 1$ and the inductance value of two inductors is the same

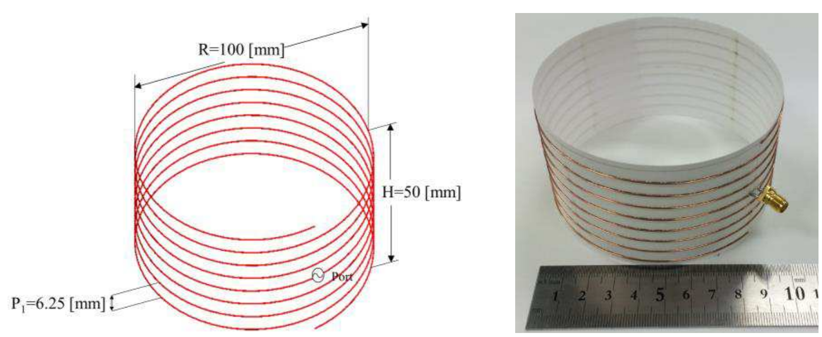

Figure 1: Traditional structure helix loop resonator configuration.

$L_1 = L_2 = L$, not only the mutual inductance between two inductors but also the circuit total inductance will equals to the value of inductor self-inductance. It means the circuit self-inductance will be not changed $L_T = L$. On the other hand, the total resistance loss of the circuit is reduced by a parallel connected resistance and it can be calculated by using Equation (3).

$$L_T = (L_1 + L_m)(L_2 + L_m)/(L_1 + L_m) + (L_2 + L_m) \tag{1}$$

$$L_m = k(L_1 L_2)^{(1/2)} \tag{2}$$

$$R_T = (R_1 R_2)/(R_1 + R_2) \tag{3}$$

Depend on this characteristic, a parallel double helix loop resonator is proposed as shown in Fig. 2, which has the same geometry size with the traditional structure helix loop that be proposed in this paper as shown in Fig. 1. Both of them are made by a 0.55 mm diameter copper wire. To maintain the resonator self-inductance, the currents on both helix loops of the parallel double helix resonator should be equal in magnitude. In this study, various structures have been analyzed and it is found out that when two same structure helix loops are coaxially parallel connected with 180 degree phase displacement in the same plane, the equal magnitude currents will be induced on each helix loop and occurs a highest mutual inductance between them.

At first, the input impedance of each resonator is calculated by using method of moment (MoM) and measured by a Vector Network Analyzer (VNA) under the condition that only one resonator exists. For the purpose of making the simulation and experiment results could have a great agreement with each other, the conductor conductivity loss should be considered in calculation, and it is assumed to $4e6$ S/m in this study Figs. 3(a) and (b) show the each resonator input impedance characteristic as a function of frequency, respectively. In the traditional structure helix loop resonator, the self-resonance frequency occurs at 44.24 MHz with 5.86 Ω resistance loos and the parallel double helix loop is resonated at the frequency of 39.25 MHz with 3.07 Ω resistance loss. It could confirm that, compare to the traditional structure the parallel double helix loop resonator decreases the resistance loss about 48%.

Table 1 lists the lumped parameters of traditional and parallel double helix loop structure

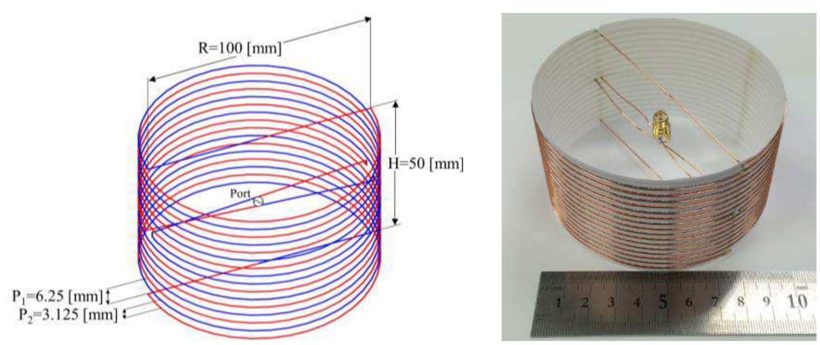

Figure 2: Parallel double helix loop resonator configuration.

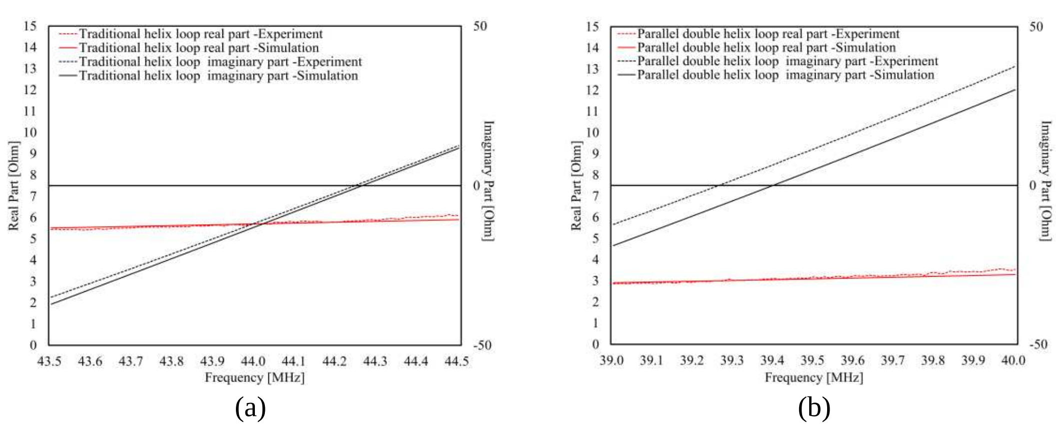

Figure 3: Resonator input impedance. (a) Traditional helix loop resonator. (b) Parallel double helix loop resonator.

Table 1: Lumped parameter of two resonators.

Parameter	Simulation		Experiment	
	Traditional helix loop	**Parallel double helix loop**	**Traditional helix loop**	**Parallel double helix loop**
Self-inductance [uH]	3.93	3.86	3.95	3.83
Self-capacitance [pF]	3.29	4.23	3.28	4.29
Resistance loss [Ω]	5.7	2.99	5.86	3.07
Resonance frequency [MHz]	44.26	39.39	44.24	39.25
Q	191	319.8	187.4	307.9

resonator, respectively. From experiment results, the proposed type resonator could maintain the self-inductance well. On the other hand, it should be noted that the resonator self-capacitance of parallel double helix loop also be increased and the reason can be assumed by the parallel connected self-capacitance of two helix loops. Nevertheless, because of the reduced resistance loss, compare to the traditional structure helix loop resonator the Q factor of proposed type resonator has been increased about 64.3%.

3. POWER TRANSFER CHARACTERISTICS

To analysis the power transfer characteristics of the system, the transmitting and receiving resonator are placed facing each other along their common axis as shown in Fig. 4 where a $\lambda/4$ sleeve balun is used for the network measurement and the port impedance is $50\,\Omega$. Fig. 5 shows the coupling efficiency calculation results comparison of traditional and parallel double helix loop used WPT system. From the result, the coupling efficiency of proposed resonator used condition is higher than the traditional type resonator used system at varying distance about 12% is confirmed. The reason can be considered by the stronger near magnetic field of parallel double helix loop resonator due to the alignment field by two helix loops and lower resistance loss.

The critical coupling $k_{critical}$ point is a very important factor for magnetic coupled resonance WPT system, which represents the maximum power transfer efficiency that the system could achievable at the furthest possible operation distance [2]. When the coupling efficiency k between transmitting and receiving resonator is greater than critical coupling point $k > k_{critical}$, the system is at the strong coupled region and the maximum power transfer efficiency resonance frequency is split at two points, the even mode ω_e and odd mode ω_o. Conversely, when $k < k_{critical}$, the system is sad to be under-coupled, the split two maximum efficiency resonance frequencies will converge to the resonator operation frequency point ω_0 and amount of power will dramatically fall off with the distance. Hence, if a frequency tracing system is used, which could automatically adjust to provide the maximum power transfer efficiency at varying distance, the power transfer efficiency characteristic as a function of distance will be shown in Fig. 6. The experimentally demonstrates that the maximum power transfer efficiency of parallel double helix loop resonator is 87% and traditional

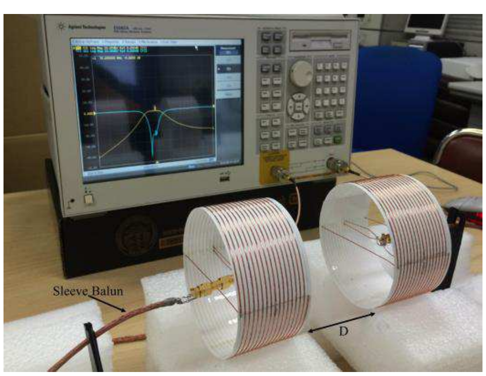

Figure 4: The wireless power transfer efficiency measurement setup.

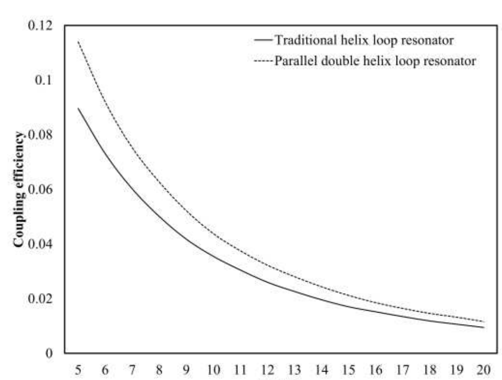

Figure 5: The coupling efficiency comparison of two type resonators used WPT system.

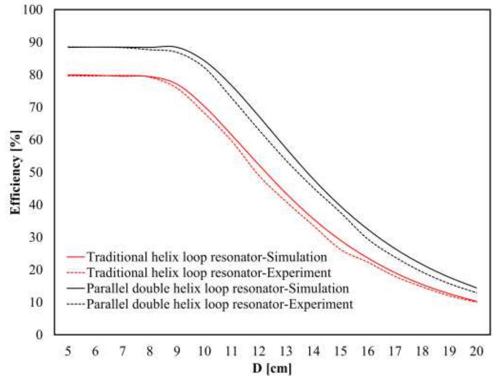

Figure 6: The power transfer efficiency comparison of two type resonators used WPT system when the system could automatically tuning the highest power transfer efficiency resonance frequency.

structure helix loop resonator is 79% within the strong coupled region, respectively.

4. IMPEDANCE MATCHING

In the magnetic coupled resonance WPT system, the optimal port impedance of resonator vary dramatically with the power transfer distance between transmitting and receiving resonator, because it is a function of the mutual inductance and is given by Equation (4) [3]. The L_m is the mutual inductance between transmitting and receiving resonator, R is the resistance loss of single resonator. From this equation, it is found out as the mutual inductance decreases, the optimal port impedance is closed to the resonator resistance loss. Equation (5) represents the maximum power transfer efficiency that the system could achievable when the resonator is matched to the optimal port impedance at varying power transfer distance.

$$Z_{opt} = \left\{R^2 + (\omega_0 L_m)^2\right\}^{(1/2)} \tag{4}$$

$$\eta_{opt}(\omega) = (\omega_0 L_m)^2 / (Z_{opt} + R)^2 \tag{5}$$

Thus for improve the power transfer efficiency at the region of under-coupled, match the resonator to optimal port impedance is a very efficiency method. Direct match the port impedance is very difficult to realize. Hence, a inductive coupling by using matching loop is chosen to match both of the transmitting and receiving resonator as shown in Fig. 7 [4]. The matching loop radius is 45 [mm] and the 50 Ohms feed port is directly connected to it.

After the matching loop size is fixed, the port impedance at the matching loop can be converted into the optimal impedance of the resonator by adjusting the separation between matching loop and resonator at different power transfer distance. Fig. 8 shows the power transfer efficiency comparison of two type resonators used WPT system after the resonator is matched by the matching loop.

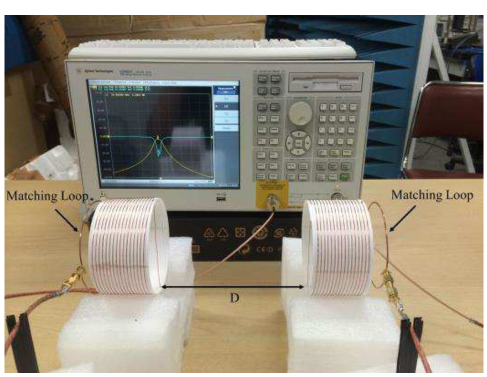

Figure 7: Power transfer efficiency measurement setup by using matching loop.

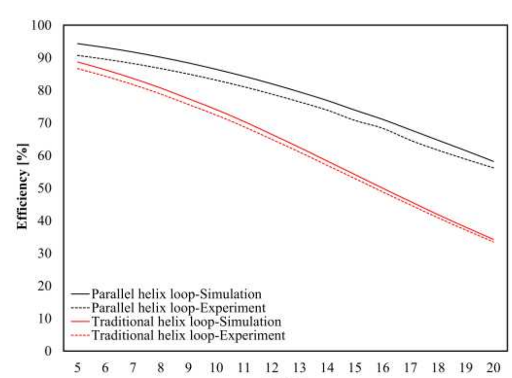

Figure 8: The power transfer efficiency comparison of two type resonators used system by using matching loop.

From the measurement result, the traditional structure helix loop resonator used system could only achieve to 34% but the parallel helix loop resonator could achieve to 57% at the transfer distance of 20 cm.

5. CONCLUSION

A novel parallel double helix loop resonator for magnetic coupled resonance WPT is proposed and investigated by using simulation and experiment in this paper. The experimentally demonstrates that the quality factor of proposed resonator is greater than a same geometry size traditional structure helix loop resonator about 64.3% and the maximum power transfer efficiency at the strong coupled region of parallel double helix loop resonator and traditional structure helix loop resonator used WPT system are 87% and 79%, respectively. On the other hand, due to the stronger near magnetic field and lower resistance loss, the coupling efficiency of parallel double helix loop resonator used WPT system is also increased. After a pair of matching loops are used to match the resonator to the optimal port impedance, the measurement results shows that the maximum power transfer efficiency of parallel double helix loop resonator used WPT system could achieve to 57% at the distance of 20 cm and compare to the traditional structure helix loop resonator used WPT system, the efficiency has been improved about 23% is confirmed.

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