A Wireless Charging Coil in Printed Circuit Board with Partially Split Conductors for Low Resistance

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***Abstract*— The paper proposed a PCB type coil with partially split conductors which have reduced resistance compared to a conventional PCB type coil. In order to design the proposed PCB type coil, a position where the resistance per unit length is relatively large in the conventional PCB type coil was analyzed by calculation. Then we analyzed total resistance of the PCB type coils according to the number of divided conductors by calculation. The PCB type coil with a proposed design was fabricated for measurement. Resistance of each coil was measured using a vector network analyzer. Experiment results show that the proposed PCB type coil has resistance reduced by 28% compared to the conventional PCB type coil. In addition, results of circuit simulation show that when the proposed PCB type coils are used to 15 W class wireless power transfer system, the efficiency increased by 5.2% compared to the conventional coils.**

Keywords—Wireless power transfer (WPT), Printed circuit board (PCB), Resistance, Litz structure, Power transfer efficiency

I. Introduction

Wireless power transfer (WPT) systems have attracted much attention and are being studied to be applied for various applications such as mobile applications, railway system and electric vehicle [1, 2]. Among them, studies for applying WPT system to mobile applications such as smart phones are being actively researched [3]. Therefore, the WPT system that can replace wired charging has already been commercialized for mobile applications.

Meanwhile, because of ease of manufacturing and good repeatability [4], a printed circuit board (PCB) has been proposed as a manufacturing method of coils for a WPT system for mobile applications [5]. However, the PCB type coil can have large resistance due to the skin effect and the proximity effect at frequency of several tens of kHz to several MHz. Because these frequencies are mainly adopted as operating frequency in the WPT system. To overcome this limitation, there is a previous research that applied the multi-conductor to the PCB type to reduce the resistance of the PCB type coil [6]. However, since this method requires an increase in the number of layers for a complicated coil shape, the manufacturing cost of the coil is increased as compared with a conventional PCB type coil.

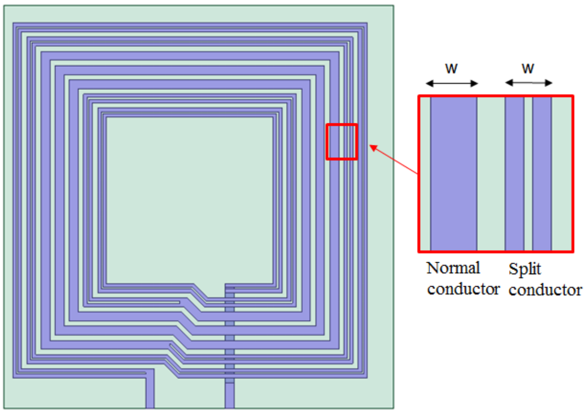

Fig. 1. The proposed PCB type coil with partially split conductors.

In this paper, we propose a PCB type coil with partially split conductors as shown in Fig. 1. In the PCB type coil with partially split conductors, only the necessary parts of the conductors are split in the conventional single-layer, single-conductor PCB type coil. Despite the fact that the amount of conductors did not increase but rather decreased, the proposed PCB type coil has lower resistance compared with the conventional single-layer, single-conductor PCB type coil.

Through the following sections, we determine which part of the conductor is to be divided, and how many pieces of the conductor are to be split. This is proved by calculation and simulation. Then, by measuring the resistance of the PCB type coil fabricated according to the proposed design, it is proved that the proposed PCB type coil has lower resistance than that of the conventional PCB type coil.

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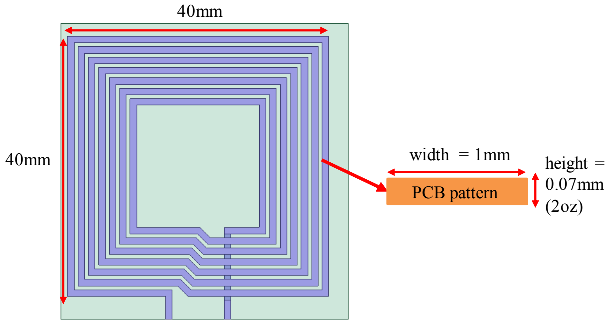

Fig. 2. A 15 W class PCB type coil for mobile applications.

TABLE I. DESIGN SPECIFICATIONS FOR 15 W CLASS PCB TYPE COILS

Component	Value
Target transfer power	15 [W]
Maximum current	2 [A]
Operating frequency	6.78 [MHz]
Number of turns	7 [turns]

II. DESIGN OF THE PROPOSED PCB TYPE COIL WITH PARTIALLY SPLIT CONDUCTORS

A. AC resistance of PCB type coils

The position of the conductor to be split must be determined first. The reason for having a high resistance despite the sufficient amount of conductors is that the current is biased toward a part of the conductor and flows unevenly. This is due to the effects of the skin effect and the proximity effect. Therefore, the resistance can be reduced by dividing the conductor of the large resistance in the PCB type coil.

For this, positions having large resistance per unit length must be determined by calculation. The frequency-dependent AC resistance can be expressed as (1) [4].

$$R_{ac} = R_{cond} + R_{prox} \tag{1}$$

In equation (1), R_{cond} is a model of loss caused by the influence of the inside of the conductor, and represents a conduction loss including a skin effect. Meanwhile, R_{prox} represent AC resistance increase due to the influence of the outside of the conductor, especially the proximity effect. R_{cond} per unit length and R_{prox} per unit length of a PCB type coil with rectangular conductor can be calculated from (2) and (3), respectively [4].

$$R_{cond\ rec\ u.l} = \frac{1}{wh\sigma}\Phi_{cond\ rec}\left(\frac{w}{\delta},\frac{h}{\delta}\right) \tag{2}$$

$$R_{prox\ rec\ u.l} = \frac{4\pi}{\sigma}\Phi_{prox\ rec}\left(\frac{w}{\delta},\frac{h}{\delta}\right)H^2 \tag{3}$$

In the equations (2) and (3), w and h are width and height of the PCB pattern as shown in Fig. 2, σ is the conductivity of the conductor, δ is skin depth at the operating frequency, H^2 is the squared amplitude of the varying magnetic field when the winding drives 1 A of current. $\Phi_{cond\ rec}$ and $\Phi_{prox\ rec}$ are functions including frequency and geometrical dependences [7].

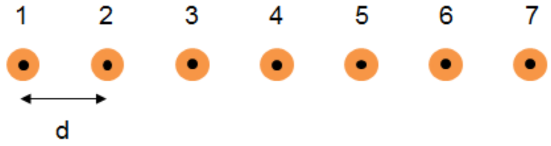

Fig. 3. Conductors of PCB type coil modeled as circular shape.

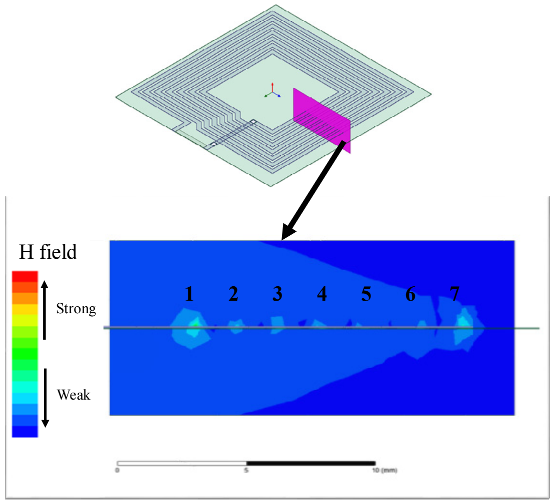

Fig. 4. The magnetic field intensity applied to each conductor verified by the magnetic field simulation.

B. Determine the position of the conductor to be divided

When the width, height of PCB pattern and operating frequency of WPT system are determined, the $R_{cond\ rec\ u.l}$ is determined according to (2). However, $R_{prox\ rec\ u.l}$ depends on the square of the external magnetic field according to (3). In other words, the resistance value per unit length is high in conductors where the external magnetic field intensity is strong. Therefore, the conductor of the PCB pattern with the strongest external magnetic field intensity need to be split.

In this paper, the design is based on the conventional PCB type coil with the design specifications as shown in Fig. 2, and Table I. In order to calculate the tendency of the magnetic field intensity applied to each conductor, it is assumed that all conductors are circular conductors. If this assumption is established, the calculation of the magnetic field can be simply calculated by Ampere's circuital law. Fig. 3 shows the circular conductor model of the PCB type coil patterns. Using the Ampere's circuital law, the magnetic field intensity applied to each conductor is calculated as shown in (4) to (7).

$$H_1 = H_7 = \frac{I}{2\pi}\sum_{k=1}^{6}\frac{1}{kd} \tag{4}$$

$$H_2 = H_6 = \frac{I}{2\pi}\left\{\left(\sum_{k=1}^{5}\frac{1}{kd}\right) - \frac{1}{d}\right\} \tag{5}$$

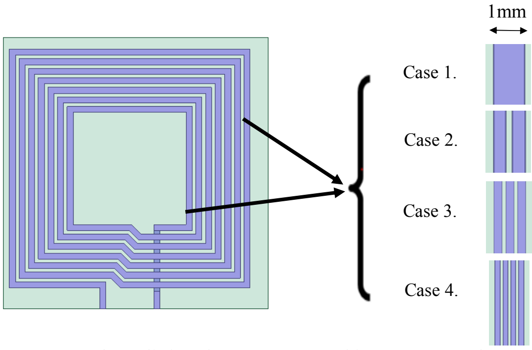

Fig. 5. Four cases for splitting the outermost and innermost conductors.

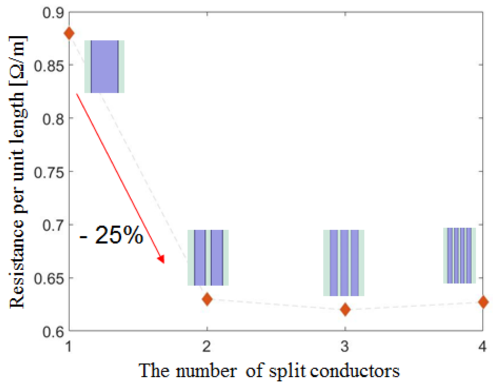

Fig. 6. Resistance per unit length according to the number of split conductors.

$$H_3=H_5=\frac{I}{2\pi}\{(\sum_{k=1}^{4}\frac{1}{kd})-(\frac{1}{d}+\frac{1}{2d})\} \quad (6)$$

$$H_4=\frac{I}{2\pi}\{(\sum_{k=1}^{3}\frac{1}{kd})-(\sum_{k=1}^{3}\frac{1}{kd})\}\simeq 0 \quad (7)$$

$$H_1=H_7>H_2=H_6>H_3=H_5>H_4\simeq 0 \quad (8)$$

In (4) to (7), H_1 to H_7 are the sum of the magnetic field intensity applied to the each conductor, I is the current flowing through the conductor of the PCB type coil and d is the equivalent spacing between the conductors. The comparison of these calculations is shown in (8). It shows that the magnetic field intensity applied to the innermost conductor and the outermost conductor is the strongest in the PCB type coil. The magnetic field intensity calculation through the assumption of the circular conductor was verified by magnetic field simulation. Fig. 4 shows the results of magnetic field simulation. Although the magnetic field intensity is not exactly zero at the center of the fourth conductor as calculated, it was confirmed that the magnetic field applied to the innermost conductor and the outermost conductor was the strongest, and the assumption was valid. Therefore, the position of the conductor of the PCB type coil to be split is determined as the innermost conductor and the outermost conductor.

C. Determine the number of pieces of conductor to split

Since we decided to split the outermost and innermost conductors, the number of pieces to be split should be determined. As shown in Fig. 5, there are four cases according to the number of split conductors and calculates the resistance per unit length of each case to select the case with the lowest resistance. When splitting the conductor, the width of the sum of the conductor pieces is fixed to 1 mm as shown in Fig. 5. The calculation of the resistance per unit length was carried out through equations (1) to (3) [4].

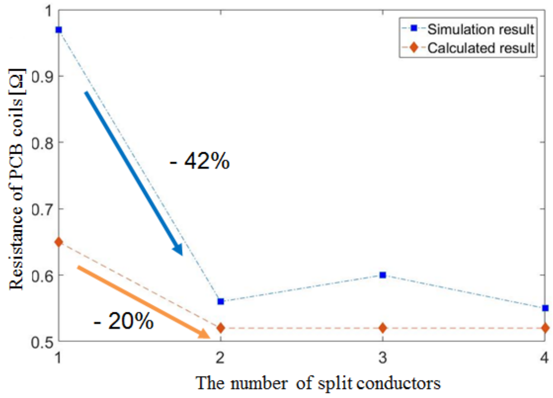

Fig. 7. Simulation and calculation results of total resistance of PCB type coils according to the number of split innermost and outermost conductors.

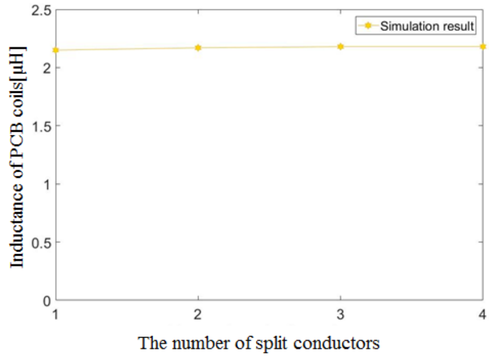

Fig. 8. The simulation results of inductance of PCB type coils according to the number of split innermost and outermost conductors.

Fig. 6 shows calculation results of resistance per unit length for each case. It was found that the resistance per unit length was reduced by 25% when the conductor was split into two pieces as compared with the conventional PCB type coil which was not with split conductors. In addition, when the conductor is divided into three pieces and four pieces, there is no significant difference compared to the case where the conductor is divided into two pieces.

Fig. 7 shows the total resistance of PCB type coils calculated through AC resistance calculation and extracted through magnetic field simulation in the cases of Fig. 5. The real value of the Z_{11} was extracted from the magnetic field simulation result, and the simulation was performed at the operating frequency of 6.78 MHz. The results show that total resistance is reduced when the outermost and innermost conductors is divided into two pieces in comparison with the conventional PCB type coil in which the conductors are not divided. These results are shown in both simulations and calculations. When the outermost and innermost conductors

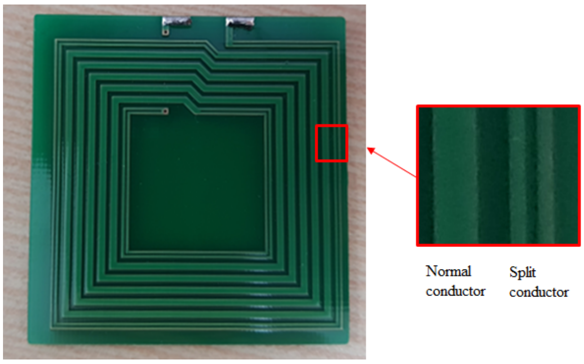

Fig. 9. A actual PCB type coil with the outermost conductor and the innermost conductor split into two pieces.

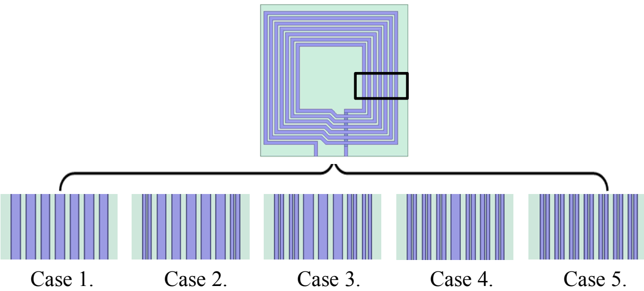

Fig. 10. Fabricated five cases of PCB type coils where the conductors are divided into two pieces from the outermost and innermost sides.

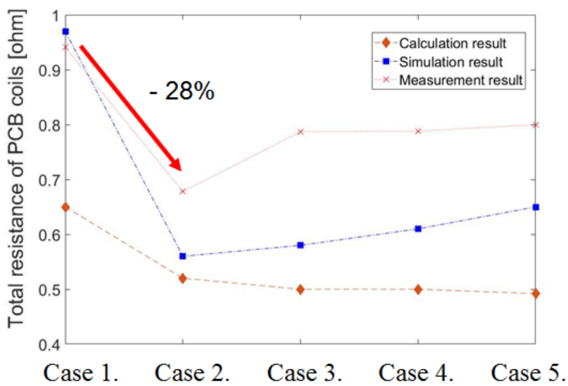

Fig. 11. The calculated, the simulated resistance, and the measured resistance for the cases in Fig. 10.

were divided into three or more pieces, the resistance did not decrease as compared with the case of dividing into two pieces. Fig. 8. shows the inductance of the PCB type coils for each case in Fig. 5, which shows that the inductance is almost constant despite the conductors are split. Through simulation and calculation results, the way to reduce resistance is to split the outermost and the innermost conductors into two pieces, respectively.

III. Verification Through Experiment and Simulation

A. *Comparison of measured resistance of PCB type coils with simulated and calculated resistance*

The fabricated PCB type coil with the outermost and innermost conductors split into two pieces, as determined in

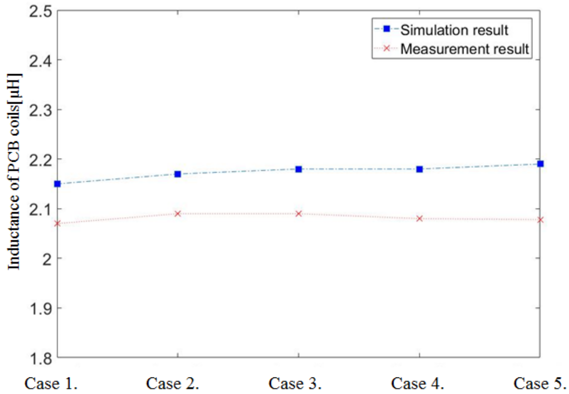

Fig. 12. The simulated inductance, and measured inductance for the cases in Fig. 10.

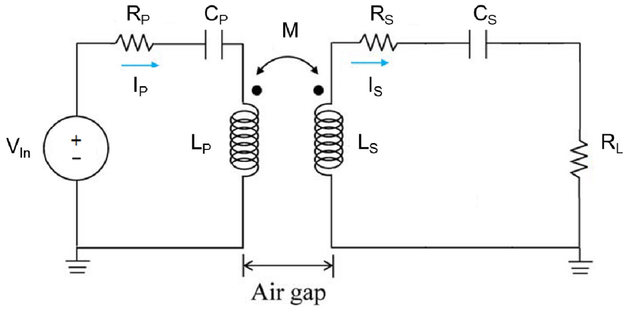

Fig. 13. Equivalent circuits of WPT simulation.

TABLE II. Circuit Simulation Conditions and Measured Mutual Inductance

Component	Value
Transferred power to the load	15 [W]
Operating frequency	6.78 [MHz]
Air gap	5 [mm]
Load (R_L)	4 [Ω]
Mutual inductance between conventional PCB type coils (measured)	1.05 [μH]
Mutual inductance between proposed PCB type coils (measured)	1.03 [μH]

Section Ⅱ, is shown in Fig. 9. In addition, five cases of coils are fabricated as shown in Fig. 10 to verify that the coil in Fig. 9 actually has lower resistance than other coils. For these five case coils, the AC resistance was calculated from equation (1) to (3) for the calculated results and the real value of Z_{11} was extracted through the magnetic field simulator for the simulation results. For the measurement results, the real value of Z_{11} was measured through a vector network analyzer (Agilent E5071C).

Fig. 11 shows the calculated resistance, the simulated resistance, and the measured resistance for the cases in Fig. 10. Fig. 11 shows that the resistance is smaller in the case of splitting the outermost and innermost conductors into two pieces than the conventional PCB type coil without splitting the conductors. In particular, in the case of the measured resistance, it is found that the resistance of proposed the PCB type coil in Fig. 9 is 28% lower than that of the conventional

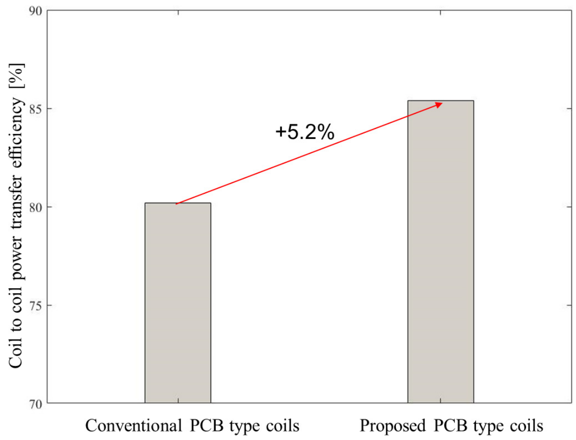

Fig. 14. Comparison of power transfer efficiency between the conventional PCB type coil and the proposed PCB type coil in 15 W WPT simulation.

PCB type coil without splitting the conductor. However, when the conductors in PCB type coils are split into more than two turns from the outer side and the inner side, there is little decrease in resistance or resistance is increased. Fig. 12 also shows that the inductance is almost constant if the conductor corresponding to each turn is divided into two pieces.

B. *Analysis of the PTE of WPT system applying the proposed coil by circuit simulation*

When the proposed PCB type coil with reduced resistance is applied to the WPT system for mobile applications, it is verified by circuit simulation how much the power transfer efficiency (PTE) is improved than that of the conventional PCB coil. The equivalent circuits for simulation setup is shown in Fig. 13. The PTE was calculated as shown in (9).

$$\text{PTE [\%]} = \frac{|\mathbf{I}_S|^2 R_L}{|\mathbf{I}_P|^2 R_P + |\mathbf{I}_S|^2 R_S + |\mathbf{I}_S|^2 R_L} \qquad (9)$$

Table II. shows the simulation conditions and the measured mutual inductance at 5 mm of air gap. Similar to the measured inductance, the difference between the proposed PCB type coil and the conventional PCB type coil inductance was less than 2 %.

Through circuit simulation, PTE of coil-to-coil was calculated when 15 W of power was delivered to a 4 ohm equivalent load. Fig. 14 shows that the PTE of the proposed PCB type coil is 5.2 % higher than that of the conventional PCB type coil. This is because the losses in the coils due to the resistance is reduced. The effectiveness of the proposed PCB type coil was verified by measuring the resistance and circuit simulation.

IV. Conclusion

The importance of WPT systems is becoming increasingly important in various fields. Particularly, researches on WPT system of mobile applications are being actively conducted, and many researches have been carried out to apply PCB type coils with advantages of ease of manufacturing and good repeatability to mobile applications. However, the resistance of the PCB type coil highly depends on the frequency. To overcome these limitations, we proposed the PCB type coil with partially split conductors. The proposed PCB type coil is designed through calculation and simulation and has a lower resistance than the conventional PCB type coil. The proposed PCB type coil was actually fabricated and was proved to have lower resistance than the conventional PCB type coils. In addition, circuit simulation proved that the loss is reduced due to the reduced resistance of the proposed PCB type coil and the PTE is increased.

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