Proposal of Ferrite-less and Capacitor-less 85 kHz Four-Layer Coil for Stationary Wireless Power Transfer

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***Abstract*—In recent years, there have been many studies on wireless power transfer. In particular, it is expected to be applied to electric vehicles, such as stationary and dynamic wireless power transfer. However, power transfer coils for electric vehicles are high cost due to the use of resonant capacitors and ferrites. In previous research, self-resonant coils without ferrite core and capacitors have been proposed to reduce the cost. However, there is not yet a self-resonant coil for electric vehicles that complies with the coil size and power class of international standards. In this paper, we propose a four-layer ferrite-less and capacitor-less coil with self-resonance in the 85 kHz band. As a result of the power transmission experiment, even without ferrites and capacitors, 5.8 kW power in conversion value was obtained with an efficiency of over 90% at a 250 mm air gap.**

Keywords—wireless power transfer, electric vehicle, stationary wireless power transfer, open-end coil, self-resonant coil

I. INTRODUCTION

The development of Wireless Power Transfer (WPT) technology has led to active research on Dynamic Wireless Power Transfer (DWPT) and Stationary Wireless Power Transfer (SWPT), which is expected to solve the problems such as high cost and cable charging of electric vehicles [1]-[5]. However, current coils for electric vehicles use short-end coils, which are costly due to the use of heavy ferrite and a large number of resonant capacitors to increase the breakdown voltage. To reduce the cost, coils that do not use ferrite are being considered [6], [7]. Coils that do not require a resonant capacitor are called an open-end coil or self-resonant coil, which are generally used in the field of wireless power transfer in frequency bands above MHz [8]-[10]. Also, self-resonant coils in the 85 kHz band without ferrite and capacitors have been considered for DWPT [11], [12]. However, the reported coil size of the 85 kHz open-end coil is as large as 1280×380 mm at minimum. According to J2954, the international standard for wireless power transfer in electric vehicles set by SAE International, the maximum size of the ground-side coil is 500×650 mm [13], and the current coil size can not be adapted to SWPT. Therefore, this paper proposes an 85kHz ferrite-less and capacitor-less self-resonant coil that complies with the international standard coil size. First, the miniaturization of the self-resonant coil is verified by electromagnetic field analysis. Next, an actual coil is fabricated based on the analysis results, and power transmission experiments are conducted to demonstrate that the proposed coil can be applied to SWPT.

II. MULTI-LAYERED SELF-RESONANT COIL

When downsizing from the conventional coil size (1280×380 mm), the inductance becomes smaller and the resonant frequency shifts from the 85 kHz band to higher frequencies. As a result, it was impossible to keep the coil size within 1 m with the conventional two-layer structure. For this reason, in this paper, the policy is to increase the inductance and stray capacitance by increasing the layers of windings. Since the resonant frequency of an open-end coil is determined by its self-inductance and stray capacitance, it is difficult to fabricate an actual coil based on empirical rules only. Thus, we used the electromagnetic field analysis software FEKO to design a self-resonant coil with a coil size within the international standard of 500×650 mm. The analysis examined the change in electrical characteristics as the layers were increased from the 1st to the 6th layer. In this chapter, the parameters other than the number of layers are fixed in order to check the effect of multilayering. Fig. 1 shows the schematic diagram of the multilayered coil. Table 1 shows the parameters of the coil during the analysis. The interlayer pitch p_i is the distance between the center of the layers, and the line pitch p is the distance between the center of adjacent coil turns.

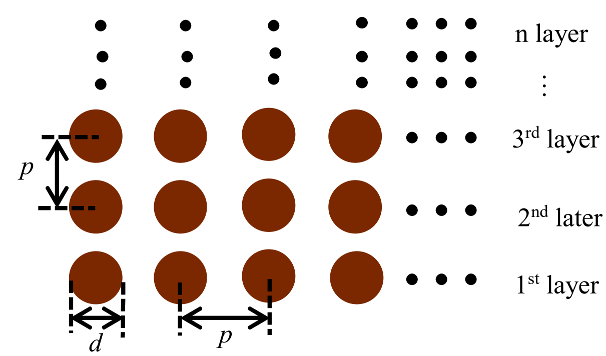


Fig. 1 Multilayer coil turns

TABLE 1. PARAMETERS OF THE ANALYTICAL COIL

Coil size	480×640 mm
Turns per a layer *t*	32
Inter layer pitch g_i	4 mm
Pitch *p*	6 mm
Conductor outer diameter *d*	3 mm

TABLE 2. ANALYSIS RESULTS OF THE MULTILAYER PROCESS

Number of layers	f_0 [kHz]	*R* [Ω]	*Q*	L [mH]	C [µF]
1	2273	1.25	309.0	0.0270	182
2	220.3	0.703	1831	0.930	561
3	162.1	0.709	2152	1.50	644
4	74.10	1.92	1847	7.60	607
5	69.61	1.71	2132	8.35	651
6	49.06	2.30	2157	16.1	654

Table 2 shows the results of FEKO analysis of the resonant frequency f_0, internal resistance *R*, *Q* value, inductance L, and capacitance C when the coil is multilayered from the first to the sixth layer. Note that no dielectric was set in the analysis. From the analysis results, it was found that the resonant frequency f_0 decreases as the inductance L and the stray capacitance C increase when the coil is multilayered.

III. DESIGN OF THE FOUR-LAYER OPEN-END COIL

Design a coil by FEKO that resonates in the 85 kHz band when the actual machine is manufactured. From the analysis results in Table 2, the resonance frequency f_0 of the four layers is the closest to the 85 kHz band, so the four-layer structure is adopted. Fig. 2 shows a modeling diagram of the proposed coil during analysis by FEKO. Fig. 3 shows the structural diagram of the four-layer coil. The structure of the four-layer coil is an open coil because the pieces of the 1st and 4th layers are connected to the power supply terminal, and the windings of the 2nd and 3rd layers are cut off and open. Table 3 shows the parameters of the four-layer coil in the FEKO analysis. Table 4 shows the results of the analysis. The analysis results show that the resonance frequency is 96.1 kHz, which is out of the 85 kHz band. This is because it is empirically known that the dielectric constant of the resin that forms the coils lowers the resonant frequency by about 10 kHz when the actual device is fabricated, compared to the analysis where no dielectric is set. For this reason, the number of turns and the pitch between the wires were adjusted to be about 10 kHz higher than 85 kHz.

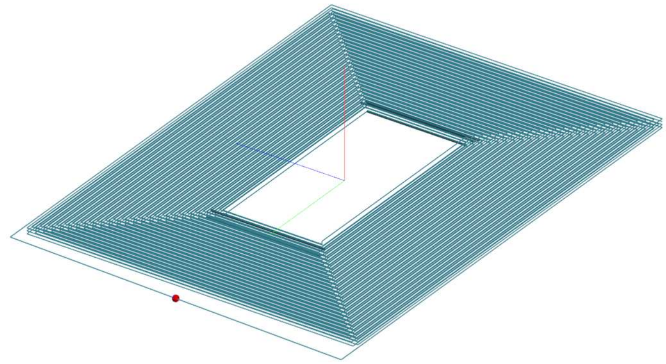
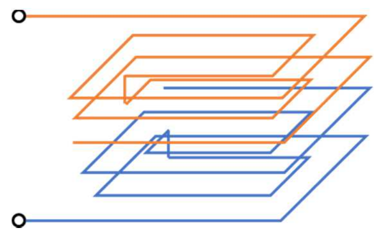


Fig. 2. Modeling diagram of a four-layer open-end coil by FEKO



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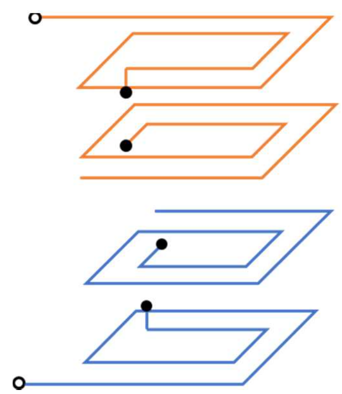


(b)

Fig. 3. Structural diagram of a four-layer open-end coil. a) Schematic diagram. b) Exploded view.

TABLE 3. PARAMETERS OF THE 4-LAYER OPEN-END COIL IN THE ANALYSIS

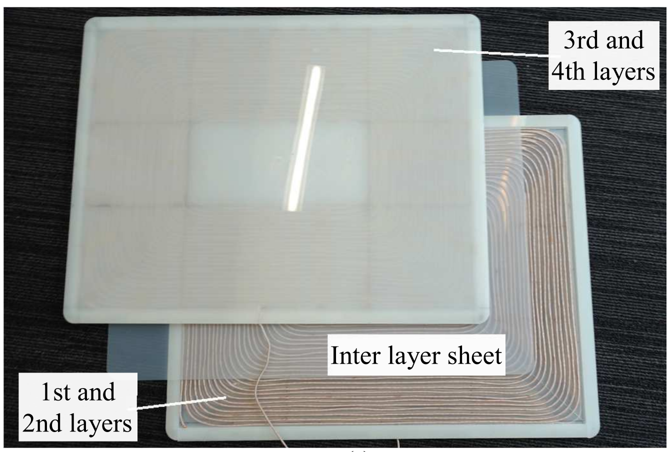
Coil size	480×640 mm
Turns per a layer *t*	25
Inter layer pitch g_i	4 mm
Pitch *p*	7 mm
Conductor outer diameter *d*	3 mm

TABLE 4. ANALYSIS RESULTS FOR 4-LAYER OPEN-END COIL

Parameters	Value
Resonance frequency f_0	96.1 kHz
Internal resistance R	1.72 Ω
Q factor ($\omega L/R$)	1812
Inductance L	5.17 mH
Capacitance C	531 μF

IV. FABRICATION OF THE FOUR-LAYER OPEN-END COIL

The four-layer open-end coil shown in Fig. 4 was fabricated as per the parameters in Table 3. Also, the receiver coil used in the power transmission experiment is shown in Fig. 5. The receiver coil is a short-end coil using ferrites and capacitors for resonance. The specifications of each coil are shown in Table 5. The material used to make the four-layer coil is polypropylene (PP resin). As shown in Fig. 4(b), the first and second layers are connected by litz wires, and the turns is cut in the middle of the second layer. The third and fourth layers have the same structure as the first and second layers.



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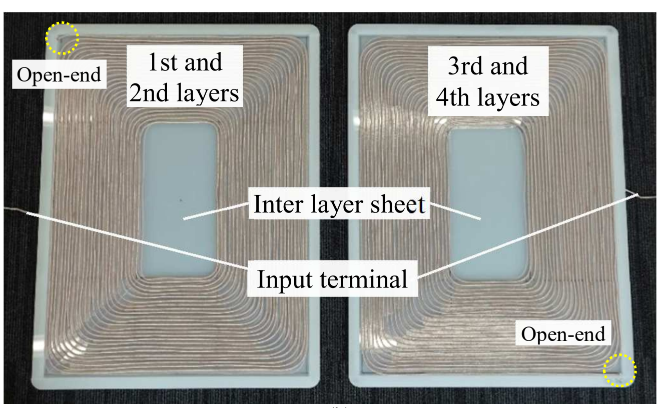

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Fig. 4. Fabricated four-layer open-end coil a) External view, b) Detail view

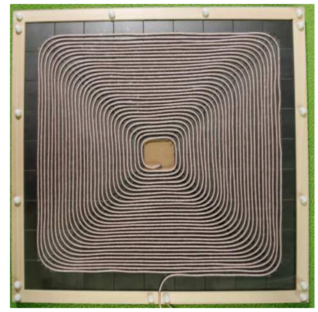


Fig. 5. Receiver coil

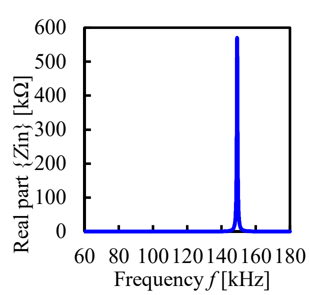
TABLE 5. SPECIFICATIONS OF THE FOUR-LAYER COIL AND THE RECEIVER COIL

	Four-layer coil	Receiver coil
Coil size	480×640 mm	400×400 mm
Number of layers	4	1
Turns per a layer t	25	30
Inter layer pitch g_i	4 mm	6 mm
Pitch p	7 mm	-
Conductor outer diameter	3 mm	3 mm
Wire length	169 m	31 m
Weight	9.6 kg	8.6 kg
Ferrite	w/o	w/
Capacitor	w/o	w/

V. EVALUATION OF ELECTRICAL CHARACTERISTICS

A. *Impedance characteristics*

The characteristics of the fabricated four-layer coil were measured with Keysight's E4990A impedance analyzer. Fig. 6 showed the real and imaginary parts of the impedance characteristics, and Fig. 7 showed the magnified view. Table 6 showed the measurement results of the resonant frequency f_0, internal resistance R, Q value, inductance L, and capacitance C of the four-layer coil and the receiver coil. The imaginary part of the impedance characteristic at 0 Ω shows that the resonance occurs at 80.5 kHz. Therefore, it was able to satisfy the 85 kHz band, which is the frequency band of the international standard.



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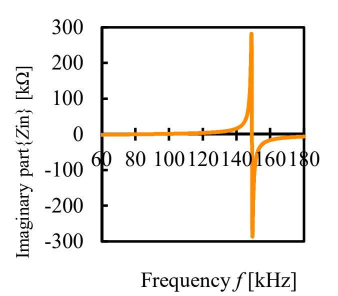

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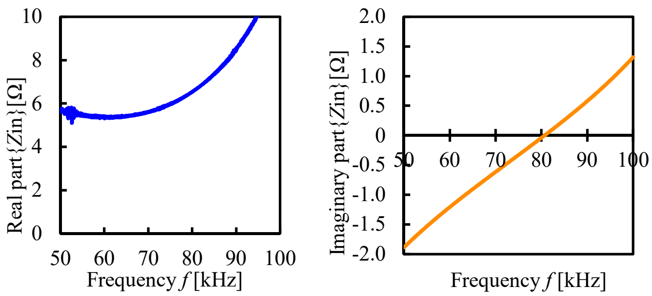
Fig. 6. Impedance characteristics (Overall view). a) Real part. b) Imaginary part.



(a) (b)

Fig. 7. Impedance characteristics (magnified view). a) Real part. b) Imaginary part.

TABLE 6. CHARACTERISTICS OF THE FOUR-LAYER COIL AND THE RECEIVER COIL

	four-layer coil	Receiver coil
Resonance frequency f_0	80.5 kHz	80.0 kHz
Internal resistance R	6.01 Ω	0.324 Ω
Q factor (ωL/R)	394	704
Inductance L	4.68 mH	0.338 mH
Capacitance C	0.835 nF	11.7 nF

B. *Transmission characteristics*

To evaluate the transmission characteristics, the power transmission experiment of less than 50 W based on the Radio Law in Japan were conducted. Receiver coil was installed in the center of transmitter coil. The input voltage is 20 V. The transmission efficiency η was calculated using the following equation.

$$\eta = \frac{\left|I_{R_\mathrm{L}}\right|^2 R_\mathrm{L}}{|I_1|^2 R_1 + |I_2|^2 R_2 + \left|I_{R_\mathrm{L}}\right|^2 R_\mathrm{L}} \quad (1)$$

I_1 is the primary side current, I_2 is the secondary side current and I_{RL} is the current flowing in the load resistor R_L. Since the load R_L is connected in series with the power receiving side, I_2=I_L. R_1 and R_2 are the measured values of the impedance analyzer. The load power P_L was obtained by the following equation.

$$P_\mathrm{L} = R_\mathrm{L}|I_\mathrm{L}|^2 \quad (2)$$

The load power P_L was calculated as a 600 V conversion value from the measured value obtained with an input voltage of 20 V.

The frequency characteristics at a transmission distance (air-gap) of 200 mm are shown in Fig. 8. The maximum transmission efficiency $\eta_{\max}$ is about 97.2%, which is higher than that of the conventional type even though the coil is smaller. The load characteristics of the efficiency η and power P_L when the load R_L is varied from 1 Ω to 1 kΩ are shown in Fig. 9 At a transmission distance of 100 mm, the efficiency η of more than 90% is maintained even when the load R_L is varied up to 1 kΩ. For transmission distances of 200 and 250 mm, it was shown that more than 10 kW of power could be obtained by reducing the efficiency to 80% and sacrificing efficiency. The maximum transmission efficiency $\eta_{\max}$ and the optimum load power $P_{\mathrm{L},\eta\max}$ for different transmission distances from 100 mm to 500 mm are shown in Fig. 11. The maximum transmission efficiency of more than 90% was achieved when the transmission distance was 100 mm to 340 mm.

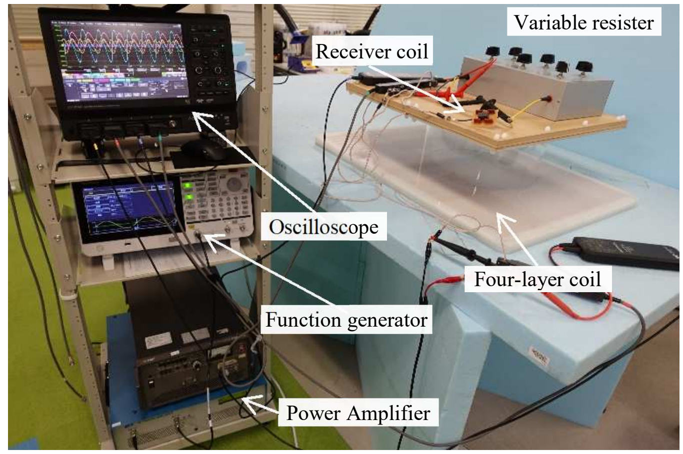
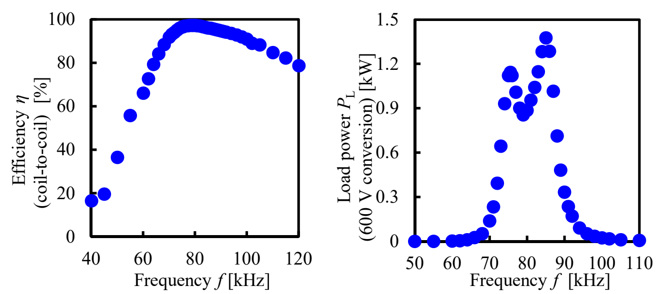
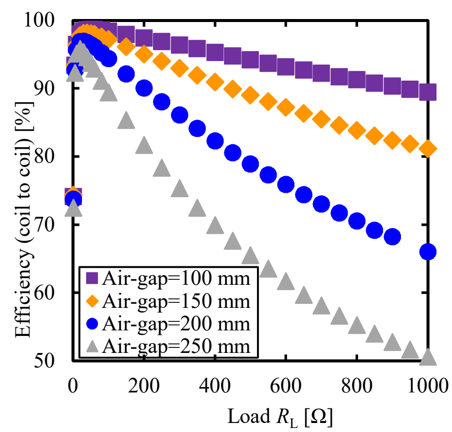


Fig. 8. State of power transmission experiment (Air-gap=150 mm)



(a) (b)

Fig. 9. Frequency characteristics (Air-gap=200 mm). a) Transmission efficiency η. b) Load power P_L.



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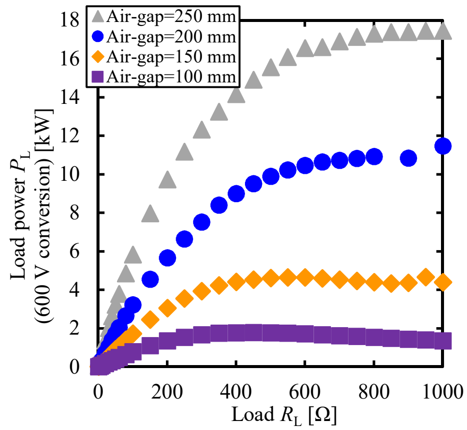

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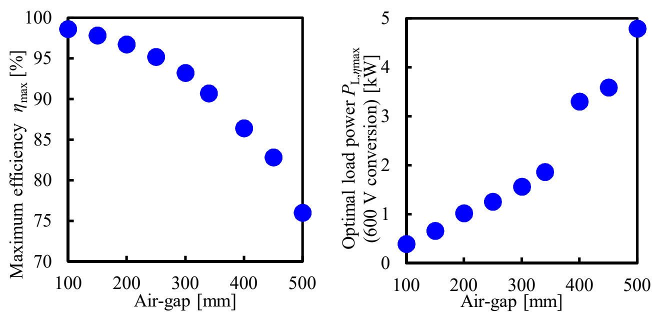
Fig. 10. Load characteristics. a) Transmission efficiency η. b) Load power P_L.



(a) (b)

Fig. 11. Changes in efficiency η and power P_L as the air gap is varied from 100 to 500 mm. a) Maximum efficiency η_{max}. b) Optimal load power $P_{L,\eta max}$.

C. WPT power class achievement for four-layer coil

From the results of the load characteristics in Fig. 10, the power P_L at 95%, 90% and 85% efficiency at each transmission distance are shown in Table 7. At about 85% efficiency, a power class of WPT3 or higher was achieved at transmission distances of 200 mm and 250 mm. At 90% efficiency, a power class of WPT2 or higher was achieved for transmission distances of 150 to 250 mm. Therefore, it was found that the four-layer coil proposed in this paper can realize wireless power transfer system at the normal power supply level (WPT3) as a coil for SWPT.

TABLE 7. WPT POWER CLASS ACHIEVEMENT

Air-gap	Efficiency 95%	Efficiency 90%	Efficiency 85%
100 mm	1.77 kW (WPT1)	1.44 kW (WPT1)	-
150 mm	3.05 kW (WPT1)	4.42 kW (WPT2)	4.54 kW (WPT2)
200 mm	2.65 kW (WPT1)	5.67 kW (WPT2)	8.15 kW (WPT3)
250 mm	2.01 kW (WPT1)	5.84 kW (WPT2)	7.98 kW (WPT3)

VI. CONCLUSION

In this paper, a four-layer ferrite-less and capacitor-less coil for stationary wireless power transfer are proposed. It was successfully achieved to miniaturize the 85 kHz self-resonant coil, which was impossible with the conventional structure, and to resonate in the 85 kHz band within the size of the international standard. According to the results of power transmission experiments, maximum transmission efficiency of more than 97% was achieved over a transmission distance of 200 mm. In addition, at the transmission distances of 200 mm and 250 mm, the WPT2 power level for electric vehicles was obtained at 90% efficiency. Therefore, it was shown that the required power level for electric vehicles can be achieved under the constraints of international standards without using ferrite and capacitors.

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