A Sandwich Structure for Cost-Effective Printed-Circuit-Board Wireless Power Resonator

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***Abstract*— This paper presents a cost-effective and high-performance design of printed-circuit-board (PCB) wireless power resonators. Unlike traditional PCB resonators that have inherent parallel LC configuration, the new PCB resonator structure can be flexibly configurated as either a parallel LC or a series LC resonator. Instead of using expensive high-frequency PCB materials to reduce the dielectric loss, we propose to use a sandwiched structure to form a low-loss resonant capacitance. The sandwiched structure comprises two layers of variable trace width PCB inductors and one layer of low-loss dielectric. Due to the utilization of low-loss dielectric, the displacement current is "redirected" from flowing through high-loss PCB substrate to low-loss dielectric. In turn, it is possible to achieve high quality factor at the designated resonant frequency with cost-effective PCB materials such as FR-4. The principles and design considerations to reduce inter-capacitance of the PCB resonators are discussed. Hardware prototypes are built, and the comparative study shows that the proposed design method can significantly increase the quality factor and transmission efficiency of wireless power resonators.**

Keywords*— *Magnetic resonance, printed-circuit-board (PCB) resonators, planar magnetics, resonant power conversion, wireless power transfer.

I. Introduction

Wireless power resonators (see Fig. 1) formed by wire-wound inductors and discrete capacitors are widely used for wireless power transfer (WPT) applications [1]-[3]. However, as the skin effect intensifies at megahertz frequencies, even the ac resistance of Litz wires increases sharply [4] and the AC copper loss of the wire-wound inductors increases significantly [5]. In addition, the precision of the resonant frequency of WPT resonator based on discrete components is adversely affected by the parasitic components and high inductance tolerance. On the contrary, monolithic resonators based on printed-circuit-board (PCB) technology provide more precise distributed inductance and capacitance to form the required resonant tank [6], [7]. The thickness of the PCB traces is close to the skin depth of copper at megahertz [8]. The distributed inductors do not necessarily cause higher conduction loss [9], [10]. Moreover, PCB technology offers precision of component parameters in manufacturing process. Therefore, the resonant frequency and quality factor of the PCB resonators are more accurate and consistent in mass production [11], [12]. Some advantages of using mmonolithic PCB resonators have been demonstrated for powering high voltage power grid online monitoring equipment [5], [6].

For megahertz operation, one technical issue arises with the use of low-cost PCB materials such as FR-4. The loss tangent of these PCB materials is relatively high, and hence the self-resonant capacitance becomes very lossy. Generally, the PCB resonators with FR-4 have lower quality factors as compared to those with expensive low-loss substrates [5], [8]. The cost of a high-frequency and low-loss PCB material such as RO4350 material is about 15 times of that of FR4 material. The high production cost of PCB resonators with low-loss substrates may prohibit wide-spread applications of PCB resonators in megahertz WPT applications.

In this paper, we propose to use a new sandwiched structure for PCB resonators to reduce the dielectric loss. The design comprises two layers of planar PCB inductors and one layer of low-loss dielectric (e.g., Polytetrafluoroethylene) for self-resonant capacitance. The use of low-loss dielectric lowers the dielectric loss of parasitic capacitors and, hence, high quality factor is attained. Moreover, as the PCB substrate is excluded from the self-resonant structure, the use of cost-effective PCB substrate (e.g., FR-4) becomes feasible.

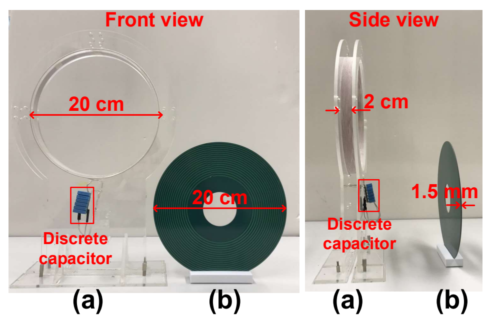

Fig. 1. Wireless power resonators. (a) discrete resonator; (b) monolithic resonators.

II. Self Resonant Structure

A. Resonator structure and model

Fig .2 (a) shows the proposed PCB resonator of which the first and third layers are the single-layer copper tracks with variable trace width for forming the distributed PCB inductors. The second layer is low-loss dielectric (e.g., Polytetrafluoroethylene, air, etc.). Fig. 2 (b) shows the 3D structure of the PCB windings and cross-sectional view of the capacitors. Fig. 3(a) shows the equivalent circuit model. The resonator is modeled as a distributed LC circuit. The distributed inductor L_n represents the inductance of the n^{th} turn PCB trace on the first layer, and L'_n represents the inductance of the n^{th} turn PCB trace on the third layer. The distributed capacitor C_n and C'_n represent the parasitic

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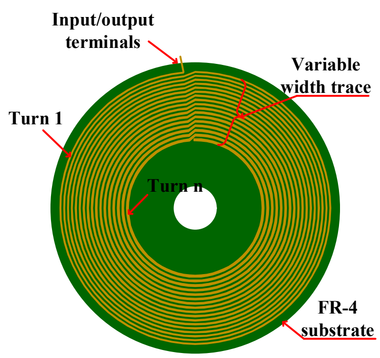
capacitance between the n^{th} turn PCB trace. The self-inductance, mutual inductance, capacitance, and the corresponding equivalent series resistance (ESR) of the circuit model are characterized using finite element method software (e.g., FEMM [13]). Fig. 3(b) shows the input impedance Z_{in} seen from the input terminals, where the resonator can be simplified as a LC series circuit at the first resonant frequency point f_s. The quality factor Q of the resonator at the series-compensated wireless power resonator is

$$Q = \frac{f_s}{\Delta f} \tag{1}$$

where Δf is the 3 dB bandwidth.



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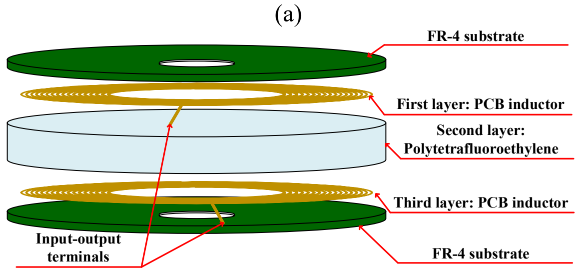

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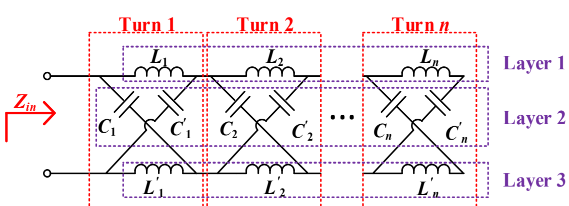
Fig. 2. The proposed PCB resonator. (a) The single-layer variable trace width PCB inductors at the first and third layer. (b) The structure of PCB resonator.



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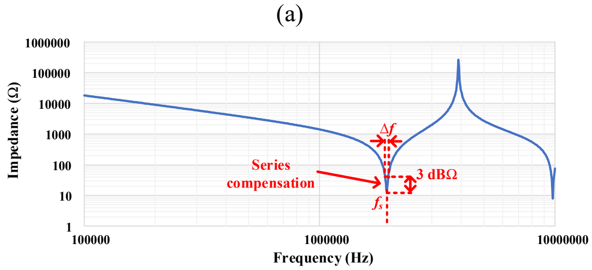

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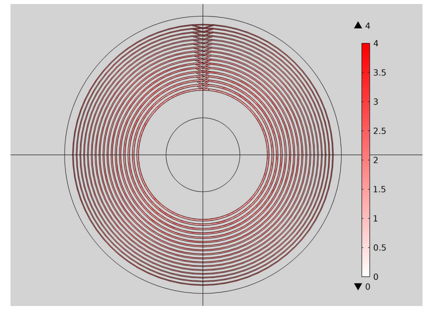
Fig. 3. Circuit model of the proposed PCB resonator. (a) distributed LC model. (b) Input impedance of the resonator.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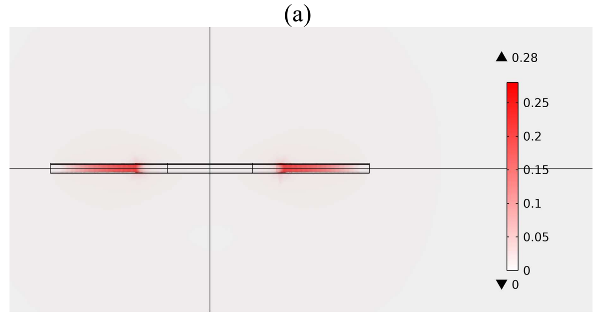
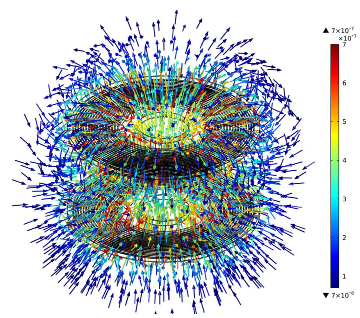

(b)

Fig. 4. Simulated current density of the PCB resonators (a) Surface current density of layer 1 (unit: A/m). (b) Displacement current density in layer 2 (unit: A/m2).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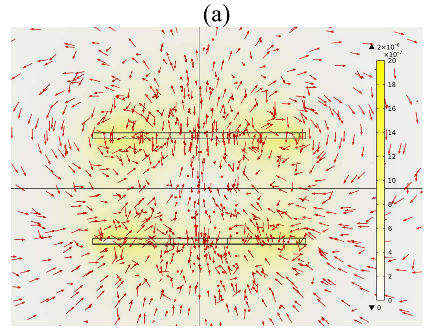

(b)

Fig. 5. Magnetic flux density (unit: T) of a pair of resonators from (a) 3D view and (b) cross-section view.

B. Loss mechanism

The ohmic loss of the PCB inductors is caused by the non-uniform current distribution. The effective area of the PCB trace is reduced because of the skin and proximity effect at high frequency. Fig. 4(a) shows the COMSOL [14] simulation results of surface current distribution on layer 1. To reduce the ohmic loss, the inner turns are constructed with wider trace width while the outer turns are constructed with narrower trace width.

The dielectric loss of the PCB capacitor is linked to the loss tangent of the dielectric material and the displacement current in the dielectric material. In conventional PCB resonator design [6], the displacement current flow through the high loss FR-4 substrate directly and the resultant dielectric loss is relatively high. In this work, we use a sandwich structure to "redirect" the displacement current such that it flows through the low-loss dielectric layer rather than the PCB substrate (see Fig. 4(b)). This design can reduce dielectric loss without using expensive PCB substrates.

C. Magnetic field distribution

In order to assess the coupling between two adjacent PCB resonators, the COMSOL simulation results of magnetic flux density plots of a pair of wireless power resonators are shown in Fig. 5. The magnetic flux generated by the transmitter resonator (the upper resonator in Fig. 5) induces an electromotive force in the receiver coil (the lower resonator in Fig. 5) and, therefore, the power can be transmitted via magnetic coupling. The sandwich structure does not affect the magnetic coupling between two resonators.

III. Experimental Results

To verify the performance of the wireless power resonators, a 2 MHz one-to-one WPT system is built. The photos of the prototype and experimental setup are shown in Fig. 6. The resonator comprises two pieces of single-layer FR-4 PCB boards. Polytetrafluoroethylene is used to construct the dielectric layer (i.e., layer 2). The thickness and radius of the PCB boards are 1 mm and 105 mm, respectively. The copper thickness is 4 oz (≈0.355mm). The thickness of the dielectric layer (i.e., layer 2) is 5 mm. The radius and trace width of the PCB traces are shown in Table I.

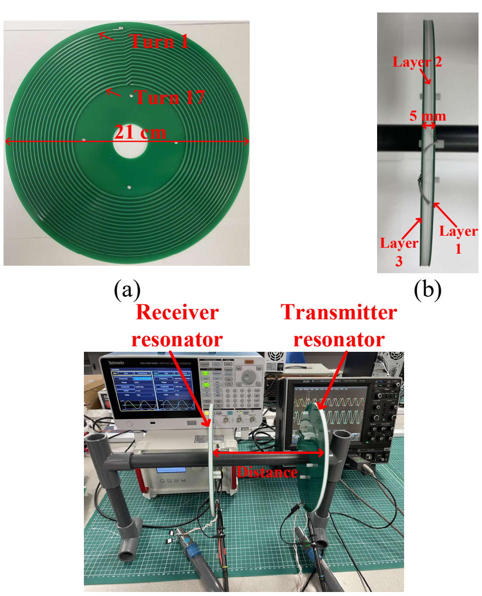


Fig. 6. Photos of the wireless power resonator. (a) Front view of the PCB inductors on layer 1 and layer 3. (b) Side view of the wireless power resonators. (c) Experimental setup of a wireless power transfer system.

TABLE I
Radius and Trace Width of The PCB Traces

Turn	Outer radius (mm)	Inner radius (mm)
1	99	98.3
2	96.24	95.51
3	93.45	92.68
4	90.63	89.83
5	87.77	86.94
6	84.88	84.01
7	81.95	81.04
8	78.98	78.03
9	75.97	74.98
10	72.92	71.89
11	69.83	68.75
12	66.69	65.56
13	63.5	62.32
14	60.27	59.04
15	56.98	55.69
16	53.63	52.29
17	50.23	48.83

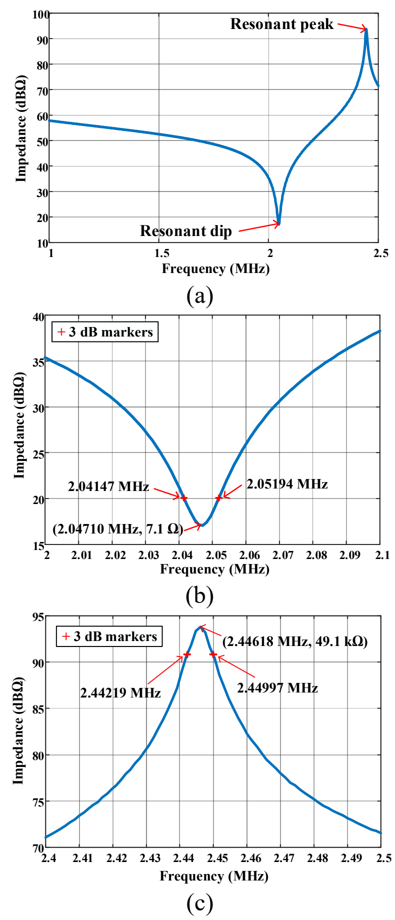


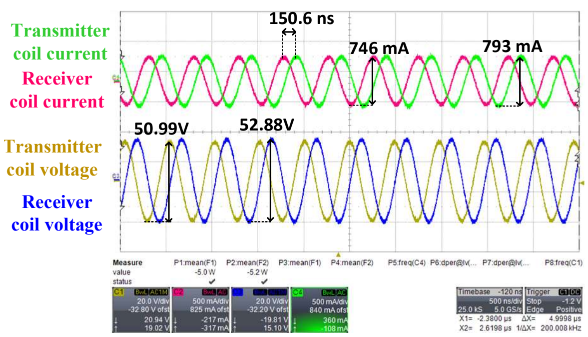
Fig. 7. (a) Input impedance of the wireless power resonator. (b) 3 dB bandwidth of the resonant dip for series compensation with Q=195. (c) 3 dB bandwidth of the resonant peak for parallel compensation with Q=314.

Fig. 7 shows the input impedance of the wireless power resonator. The self-resonant frequency for series compensation is 2.047 MHz and the quality factor is 195, while the self-resonant frequency for parallel compensation is 2.446 MHz and the quality factor is 314. Fig. 8(a) shows the voltage and current waveform of the wireless power transfer system at 2.042 MHz. The peak-to-peak AC input voltage and

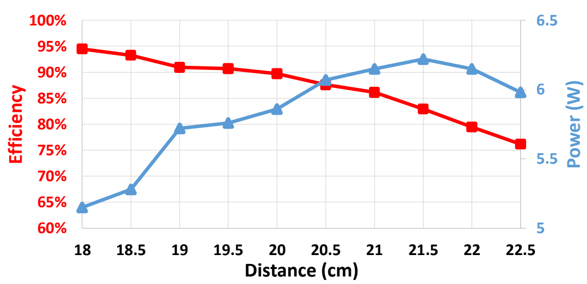
TABLE II
COMPARISON OF PCB RESONATORS

	This work	[5]	[6]	[7]	[8]	[9]
Quality factor Q	**195 (Series compensation) 314 (Parallel compensation)**	132 (Parallel compensation)	52 (Parallel compensation)	178 (Series compensation)	1183 (Parallel compensation)	185 (Series compensation)
PCB substrate	**FR-4**	F4BMX	FR-4	N.A.	FR-4	RO3003
Ferrite core	**No**	No	No	No	Yes	No
Cost	**Low**	High	Low	N.A.	High	High

current are 52.88 V and 793 mA, while those at the output are 50.99 V and 746 mA. Fig. 8(b) shows the transmission efficiency of the wireless power transfer system. As the distance between the resonators increases, the transmission efficiency decreases. The maximum efficiency of 94.5% is achieved when the distance between two resonators is 15 cm. Table II shows the comparison of PCB resonators.



(a)



(b)

Fig. 8. Experimental results of the wireless power transfer system. (a) Time-domain waveforms. (b) Efficiency.

IV. CONCLUSIONS

This paper reports a new sandwich structure for cost-effective PCB resonators. The sandwich structure facilitates dielectric loss reduction without using expensive high-frequency and low-loss PCB substrates. The experimental results show that the PCB resonator achieves a quality factor of 195 at 2 MHz and maximum transmission efficiency of 94.5%. These features suggest that wireless power resonators with the sandwich structure are promising solutions for next-generation high-frequency high-efficiency wireless power transfer systems.

V. ACKNOWLEDGEMENT

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