Wearable Wireless Power Transfer using Direct-Write Dispenser Printed Flexible Coils

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***Abstract*—Direct-write dispenser printing represents a simple solution to rapid flexible and printed electronics prototyping and low-volume manufacturing. This work presents the design, fabrication and evaluation of magnetic resonance wireless power transfer (WPT) coils fabricated using dispenser printing. A double-sided inductor is designed and printed on a flexible polyimide substrate using a commercial dispenser printer. The dispenser printer is used to realize the single-sided coils which are heat pressed to form double-sided inductors using a conductive epoxy via. It is demonstrated that the proposed double-sided coils achieve over 53.8% higher quality factor than a single-sided coil, and 67% higher inductance than two series-connected coils. The coils are tuned to resonate at 6.78 MHz using lumped-matching. The proposed coils achieve a peak WPT efficiency of 50%.**

***Index Terms*—Additive Manufacturing, Coils, E-textiles, Dispenser Printing, Inductor, Internet of Things, Wireless Power Transfer**

I. Introduction

Additive manufacturing is increasingly seen as an enabling method of realizing flexible, wearable and organic electronic systems for the emerging unobtrusive Internet of Things (IoT) market [1]. Wireless Power Transfer (WPT) and energy harvesting represent potential candidates for powering and re-charging flexible electronics sustainably without the need for a physical connection [2]. Recent work has shown the possibility to realize electromagnetic and Radio Frequency (RF) energy harvesters and power transfer units based on printed and flexible electronics [3].

Dispenser printing allows "direct-writing" of a 2D circuit design on a flexible or a rigid substrate. Dispenser printing has been previously utilized to fabricate energy harvesters [4], textile displays [5], and antenna prototypes [6]. Compared to screen-printing and photolithography, dispenser printing allows a faster-turnaround as it does not require a dedicated screen or mask.

Magnetic Resonant (MR) WPT enables improved spatial freedom and coil-separation over inductive coupling, while theoretical maximum high WPT efficiencies of over 90%. Multiple flexible and wearable MR-WPT have been presented using flexible printed circuit boards (PCB) [7], embroidered textile coils [8], and adhered copper foils to flexible and textile substrates [9], [10]. However, the realization of MR-WPT systems using dispenser-printed flexible coils has not been previously investigated.

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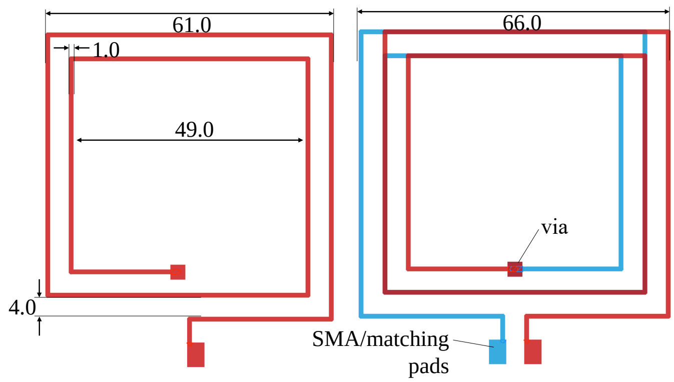

Fig. 1. Dimensions (in mm) of the proposed coil. Left: top layer (single-sided), right: double-sided coil.

This work utilizes a commercial dispenser printer to realize double sided MR-WPT coils on a thin and flexible substrate. It is shown that using the proposed double-sided geometry it is possible to improve the coil's quality factor by 53.8% compared to single-sided coils. The efficiency of the WPT link is investigated and it is shown that with a coil design optimized for printing, it is possible to achieve WPT efficiencies up to 50% and less than 2 dB degradation in performance when operating on-body.

II. Coil Design and Fabrication

A. Coil Design

The key to high WPT efficiency is a high coil Quality (Q)-factor (1), this is achieved using coils of minimal series resistance R and higher self inductance L [7].

$$Q = \frac{\omega L}{R} \tag{1}$$

When utilizing printed conductors, achieving conductivity similar to copper sheets or litz wires is not possible due to the higher surface resistivity (in order of 1Ω/square) and the high surface roughness of over 10μm. Therefore, increasing the number of turns or the coil's radius to improve the inductance will inevitably increase the series resistance. To increase the inductance of the coils a double-sided inductor is utilized. This allows reducing the number of turns, and hence the overall geometry of the whole WPT system. A double-sided two-turn coil of 1-mm trace width and 4-mm pitch is proposed. Fig. 1 shows the geometry of the coil.

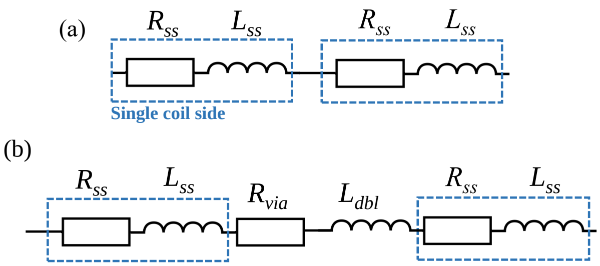

Fig. 2. Equivalent circuit of the (a) two single-sided (ss) inductors connected in series and (b) double-sided (dbl) inductor showing the additional inductance and resistance due to increased turns and the via.

The designed coils can be modeled as a series inductor and a parasitic resistor (Fig. 2-a), due to the series resistance of the conductive traces. While additional coil connections in series could be utilized to increase the inductance, the series resistance will increase reducing the coils Q. On the other hand, when the proposed double-sided geometry is utilized, an additional inductance term (L_{dbl}) is introduced due to the increase overall number of turns, as observed in Fig. 1, in addition to the inherent self-inductance of each of the coil's sides. Therefore, despite the increased series resistance introduced by the via (R_{via}), the improvement in the coil's inductance could be utilized to increase the coil's Q-factor.

The substrate chosen in this work is polyimide, due to its improved thermal and mechanical reliability while not compromising on flexibility, and the overall "low-cost" design-goal of printed IoT devices.

B. Direct-Write Dispenser Printing

A commercial dispenser printer (Voltera V-one) has been used to print the conductive traces onto the flexible polyimide substrate. 75 μm polyimide sheets have been adhered to a rigid surface, an alumina tile, using Kapton tape to keep the substrate planar during printing. The coil CAD drawing is loaded to the printer where a printing map is automatically generated. The silver ink is then jetted onto the substrate following thickness measurements to prevent a nozzle crash.

After the ink is jetted, the substrate is transported to a hot-plate to cure the ink. A standard soldering hot-plate is used to cure the ink at 220°C for 30 minutes. While the Voltera printer allows curing the boards on its own hot-plate with the conductor facing the hot plate, a standard hot-plate is used to provide the heat from below to prevent smearing the ink on the flexible substrate.

The process is repeated on a different polyimide sheet to fabricate the coil's bottom layer. After both layers are cured, heat-pressing with 100 μm thermo-plastic polyurethane adhesive sheet is used to realize the double-sided coil. The coils have been pressed at 190°C for 1 minute. A hole is then drilled and filled with conductive silver-loaded epoxy to create the via connecting both sides of the coil. Fig. 3 shows the fabrication steps of the coil from conductor printing to the complete structure with the via. The epoxy has been cured at 120°C for 5 minutes.

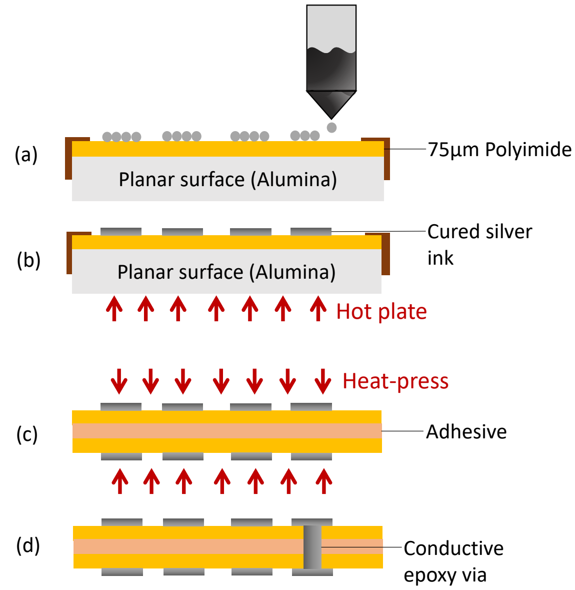

Fig. 3. Fabrication steps of the double-sided WPT coil: (a) silver ink printing on a planar polyimide substrate, (b) silver ink curing on a hot plate, (c) thermal-pressing of the single-sided top and bottom coils, (d) the assembled double-sided coil showing the conductive epoxy via.

Fig. 4. Photograph of the fabricated double-sided coil.

III. Coil Parameters

An impedance analyzer (Wayne Kerr 6500B) has been used to measure the electrical properties of the fabricated coil. This is paramount to tuning the coils to certain frequencies, calculating the Q-factor, and evaluating different fabrication methods [11]. The parameters of individual coil sides has been measured (single-sided) as well as the parameters of the double-sided coil. Table I shows the measured electrical characteristics of the single and double-sided coils.

TABLE I
Measured Coil Electrical Parameters at 6.78 MHz.

Coil	L (μH)	R (Ω)	6.78 MHz Q-factor
Single-layer	0.59	3.95	1.01
Double-sided	1.97	8.6	1.55

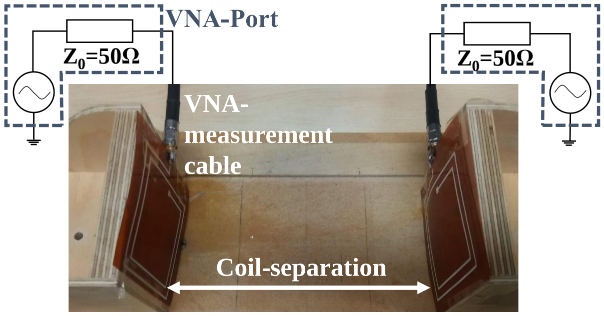

Fig. 5. Test setup of the printed coils using the VNA.

The double-sided coil, having a Q-factor of 1.55 as opposed to the single-sided 1.01 Q-factor, demonstrates the benefits of utilizing double-sided coils for additively-manufactured WPT coils.

IV. MR-WPT Testing and Evaluation

The coils have been matched using lumped capacitors to resonate at f_r=6.78 MHz, the Industrial Scientific and Medical band (ISM-band) used by the Airfuel WPT alliance. The value of the tuning capacitors has been calculated using (2). The capacitor for tuning used is a 270 pF ceramic capacitor.

$$C = \frac{1}{4\pi^2 f_r^2 L} \tag{2}$$

SMA coaxial connectors have been soldered to the coils, using a low-temperature solder not to damage the traces, to allow measurement of the WPT efficiency. A ZVB4 Vector Network Analyzer (VNA) has been used to measure the two-port s-parameters of the coils for different test conditions. The WPT efficiency can be calculated using the power forward transmission from the measured s-parameters $\eta_{WPT} = |S_{21}|^2$.

The coils, mounted on wooden test fixtures, have been positioned at variable separations to measure the s-parameters of the coils. Fig. 5 shows the experimental test setup of the coils using. Fig. 6 shows the two-port s-parameters, showing the voltage forward transmission (S_{21}) and reflection coefficient (S_{11}) at 1 cm separation 7. The forward voltage transmission and the WPT efficiency of the coils at variable separation is shown in Fig. 7.

In wearable applications, such as smart cycling gloves [8], the coils are expected to operate under close-proximity with the human body. In the case of using MR-WPT to transfer power from an energy-harvesting bicycle to a glove, the coils need to maintain high efficiency in tight coupling (<2 cm separation) and on-body. The s-parameters of the coils positioned on- and off-hand placed at 2 cm separation are shown in Fig. 8, demonstrating under 2 dB degradation in performance when operating on-body.

V. Conclusion

This paper presented direct-written dispenser printed flexible WPT coils for flexible IoT and wearable applications. The proposed double-sided printed coils achieve 53.7% higher quality factor compared to a single-sided printed coil of the same geometry and up to 50% WPT efficiency due to their double-sided structure enabling higher WPT efficiency without increasing the coils' dimensions. This demonstrates the feasibility of utilizing low-cost dispenser printing to realize WPT systems for next generation flexible and printed electronics.

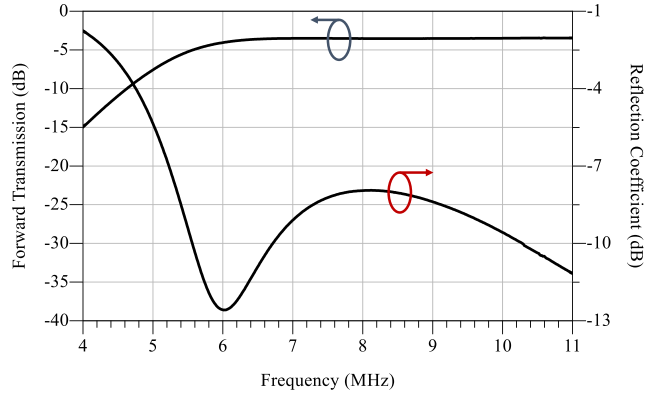

Fig. 6. Measured two port s-parameters of the coils at 1-cm separation showing a peak S_{21}=−5.6 dB.

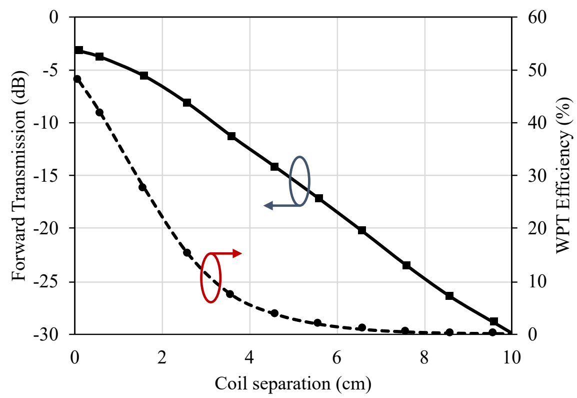

Fig. 7. Measured forward transmission and WPT efficiency of the printed coils at variable coil separation.

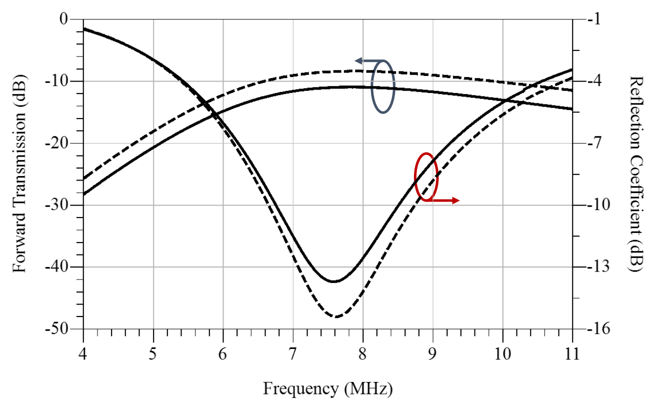

Fig. 8. Measured two port s-parameters of the coils at 2-cm separation in-space (dashed) and on-hand (solid).

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