Extended Range Wireless Power Transfer With Inkjet Printed Thin-film Flexible Loop Coils

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***Abstract*—A major issue of inductive wireless power transfer (WPT) is limited range of separation between transmitter and receiver coils. We propose a novel inkjet printed (IJP) thin film loop coil method that extends the range of WPT. The coils were fabricated with 2 layers of IJP silver traces with an IJP insulation layer. The fabricated coils extended the range to more than 7 inches and transferred more than 5 V with up to 80 mA current.**

I. Introduction

Wireless power transfer (WPT) is useful to power or recharge electronic devices. Inductive coupling is one of the most common types of WPT mechanism. This technique uses low frequency near field non-radiative wireless coupling of frequency of 100 to 200 kHz such as Qi WPT [1]. This technique has very low dosimetry related risks and is considered safe for human proximity [2].

WPT can employ planar spiral coil (PSC) design for transmitter (TX) and receiver (RX) coils [3]. This allows the transmitter and receiver circuits to have thiner profiles. As the magnetic flux in inductive coupling is concentrated at the center of coils, the coils need to be placed coaxially at close proximity. The magnetic flux declines with the cube of the distance and power transfer decreases at square of this rate (60 dB/decade). Many research groups are investigating approaches to resolve these limitations using multiple transmitter coils, larger coil sizes, or ferromagnetic materials [1], [4].

While in traditional WPT, the TX coil and RX coil must be placed on top of each other (axially aligned with very small gap of 1 inch or less), we have previously presented a novel patent-pending technique that extends the range by using a set of loop coils where multiple inductive coils can be connected in series or parallel without any external power [5], [6]. In this paper, we show a novel loop coil fabrication with inkjet printing (IJP) additive manufacturing technique that produces thin film (less than 50 μm) flexible PSC type loop coils.

II. IJP Fabrication

IJP fabrication process and the multilayer IJP fabrication are depicted in Fig. 1. IJP coils were designed using Inkscape vector graphics software, then converted into printing format. Two sets of IJP loop coil were designed: one with 8 turns for both TX and RX side coils, and another with 10 turns for TX side coil and 8 turns for RX side coil. For both sets of loop coils, the distance between the transmitting and receiving side was 7 inches. For all silver (Ag) traces, the trace width was 1 mm and the gap between traces was 1 mm. The width and height for 8 turn coils were 34.7 mm and 37.6 mm, respectively. For 10 turn coils the width and height were 42.7 mm and 45.6 mm, respectively.

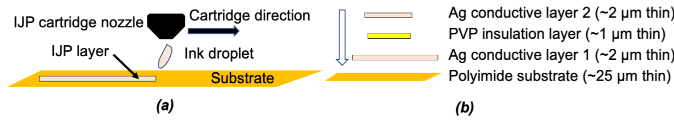

Fig. 1. (a) IJP printing process. (b) Multilayer IJP printing (exploded view).

For conductive layer printing, Metalon JS-A191 (Novacentrix Inc., TX) silver ink was used. JS-A191 ink contains 40% Ag nanoparticles by weight, where the Ag concentration is 25-50% with 10-15% ethylene glycol and 0.2 – 1% polyethylene glycol 4-(tert-octylphenyl) ether. For nonconductive layer printing, we have used a custom made Poly(4-vinylphenol) (PVP) ink as reported previously [7].

We have used Dimatix Materials Printer (DMP-2850, Fuji-Film Inc.) for IJP fabrication. The substrate was 25 μm thin flexible polyimide (PI) film. For printing the loop coils, we have used jetting voltage and jetting frequency of 31 V and 20 kHz, respectively for Ag layer. For printing of PVP ink, we have used jetting voltage of 25 volts and 20 kHz for jetting frequency. IJP fabrication was performed with 15 μm drop spacing and 1693 dpi printing resolution.

Thermal curing of printed layers was performed using a Heratherm Oven (Thermo Fisher Scientific Inc., MA). Bottom Ag layers was cured at 250°C for 30 mins. Six coatings of PVP was printed on top of bottom Ag layer to make the insulation between top and bottom Ag layers. Each time 2 coating of PVP were printed and cured at 190°C for 30 mins. Finally, the top Ag layer was printed and cured at 190°C for 30 mins.

III. Theory of WPT with the Proposed Loop Coils

The conceptual diagrams are given in Fig. 2. Fig. 2(b) shows the schematic for 2 loop coils in series. The loop coil 1 (LC1) placed over the TX coil generates induces electromotive force (EMF) based on the number of turns and coupling coefficient. The loop coil current (i_{loop}) can be given by V_{EMF}/Z_{loop}, where Z_{loop} is the impedance of the loop coil. The loop coil 2 (LC2) generates magnetic flux, proportional to i_{loop} and the number of turns, that produces EMF at the RX coil.

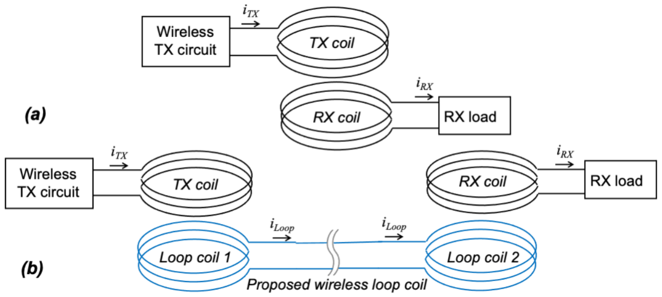

Fig. 2. Conceptual diagrams of coil placements for (a) traditional WPT and (b) proposed WPT with loop coils for an extended range.

IV. Experimental Setup

We have used commercial Qi wireless transmitter (EK1854, GeekFun), TX coil (WTSC-6R3K-A11B), and RX coil (WR483245-15F5-G). The experimental setup had LC1 on TX coil and LC2 on RX coil (Fig. 3). For RX loading, a load resistor (R_L) was connected with a shunt resistor (1% of R_L) in series with RX coil. The output voltage was monitored across these resistances using an oscilloscope (KT-DSOX1204G-InfiniiVision, Keysight). The voltage across the shunt resistor was used to calculate the current through R_L. The same technique was used for TX side.

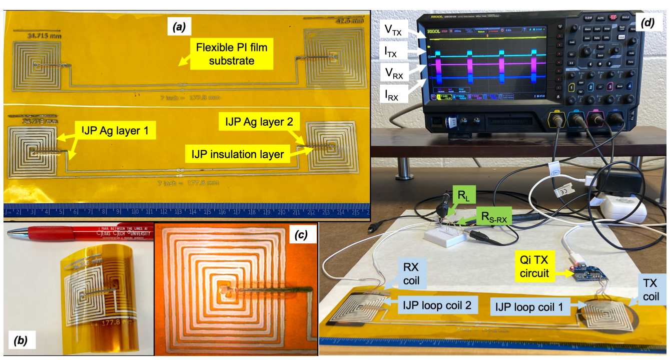

Fig. 3. (a) Photograph of two IJP loop coils on PI film. Top: LC1 = 10 turns, LC2 = 8 turns. Bottom: LC1 = 8 turns, LC2 = 8 turns. (b) Rolled up IJP loop coils showing flexibility. (c) Microscope image showing details of the two IJP Ag layers and the insulation IJP PVP layer in between the two Ag layers. (d) Experimental setup with Qi TX circuit with a commercial TX coil and a commercial RX coil coupled by the proposed IJP loop coils (LC1 and LC2) to wirelessly transfer power.

V. Experimental Results

As the current in loop coil is dependent on its impedance, lower impedance is preferred. But IJP Ag traces have higher impedance (than copper). In this work, we have used higher curing temperature and duration for IJP layer 1 of Ag to reduce overall impedance of the loop coils. For instance, using 180°C heat for 15 mins obtained 12.9 Ω resistance, 200°C for 30 mins resulted 5.9 Ω, and 250°C for 30 mins produced 3.6 Ω resistance for the case of 8 turns (both LC1 and LC2) loop coils. For IJP layer 2 of Ag, always a lower temperature and duration was used to prevent degradation of printed PVP layer.

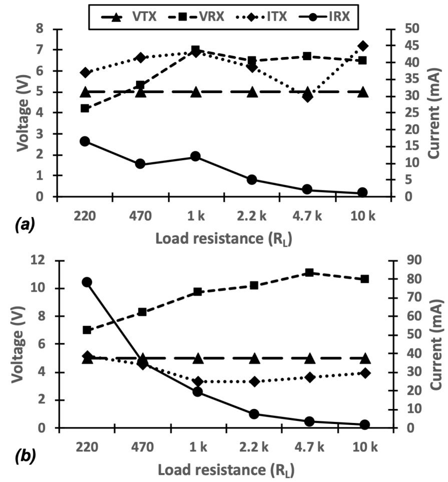

Fig. 4. (a) Plot of transmitter voltage (V_{TX}) and current (I_{TX}), and receiver voltage (V_{RX}) and current (I_{RX}) for various load resistances (R_L) for 8-turn LC1 and 8-turn LC2 IJP loop coil. (b) Plot of the same parameters for 10-turn LC1 and 8-turn LC2 IJP loop coil.

We have reported results with traditional WPT settings earlier [6], thus this work only presents the results with IJP loop coils. Fig. 4 plots the results of power transfer for the 2 sets of coils: one with LC1 = 8 turns and LC2 = 8 turns, and another with LC1 = 10 turns and LC2 = 8 turns. Results demonstrate the receiver voltage is higher for higher R_L, while the receiver current decreases for higher R_L. Maximum current of 80 mA was noted at 7 V for 220 Ω in Fig. 4(b).

VI. Conclusion

We have demonstrated that flexible IJP loop coils, with <50 μm thickness, can be used for wireless power transfer at a large distance. This technique might be useful for powering implantable and wearable devices for medical applications.

Acknowledgement

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