Silicone-based,3D-Printing Manufacturing for the Development of a Novel Passive Tag for SWIPT

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***Abstract*—This work leverages the numerous advantages of silicone-based and 3D printing manufacturing technologies, i.e. ease of use, cost-effectiveness and design degrees of freedom, for the development of a wearable, flexible, completely passive, simultaneous wireless information and power transfer system. A low-cost polydimethylsiloxane compound, Silpuran® 6000/05 A/B, is 3D-engineered with an optimized internal structure to realize a flexible substrate providing antenna performance comparable to those achieved with specialized RF materials. This system consists of a receiving tag equipped with a cross-polarized dual-fed antenna, operating in the 2.4 GHz band, for far-field energy harvesting and data communication, and an integrated receiving coil for near-field power transfer working at 13.56 MHz. This system, optimized for Internet of Things, radio frequency identification, and wireless sensor networks applications, provides a compact and efficient solution for simultaneous power and data transfer, showcasing how 3D printable, low-cost, customized materials enable the fabrication of flexible, high-performance wireless systems while reducing manufacturing complexity and costs.**

***Index Terms*—3D printing, flexible antennas, RFID, SWIPT, near-field WPT, far-field EH.**

I. INTRODUCTION

THE increasing demand for autonomous, low-power devices has driven research into efficient wireless power transfer (WPT) techniques to reduce reliance on traditional batteries. Within this context, 3D printing, or additive manufacturing (AM), emerges as key enabler technology for developing RF and microwave prototypes in both industry and academia. It offers a cost-effective, high-precision, and rapid alternative to traditional fabrication methods while enabling advanced design flexibility. By engineering the internal structure of 3D-printable materials, it is possible to tailor their electromagnetic (EM) properties, paving the way for efficient, lightweight, flexible, and wearable substrates of next-generation wireless systems, which require compact, adaptable, and self-sustaining solutions [1]. This work aims at highlighting the significant benefits of combining silicone-based and 3D-printing manufacturing solutions while also taking advantage of recent technological advancements of simultaneous wireless information and power transfer (SWIPT) [2]. The latter, typically relies either on near-field (NF) or far-field (FF) WPT methods, limiting the system's adaptability and efficiency in dynamic environments. However, this work introduces a novel radio frequency identification (RFID) tag that combines two distinct radiating elements, for simultaneous energy harvesting (EH) and data transmission, leveraging both NF and FF power transfer techniques [3]. To accomplish this, the system, illustrated in Fig. 1(a), features a dual-polarized antenna operating in the 2.4 GHz (ultra-high frequency – UHF) band, utilizing both coaxial and microstrip feeding techniques, to enhance polarization diversity and enable efficient simultaneous power reception and communication. Additionally, the same tag integrates a dedicated receiving (RX) inductive coil operating at 13.56 MHz (high frequency – HF) for NF power transfer, ensuring efficient short-range EH.

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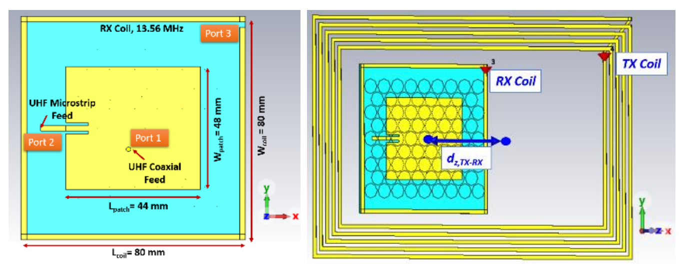


(a) (b)

Fig. 1. (a) Layout of the dual-port antenna operating in the 2.4 GHz band for communication (port 1) and FF EH (port 2) purposes, and the RX coil at 13.56 MHz for NF WPT (port 3); (b) TX and RX coils are aligned and spaced 3 cm apart ($d_{z,TX-RX}$).

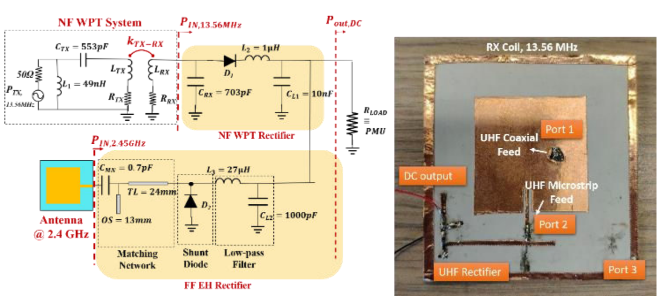
II. SWIPT SYSTEM DESIGN AND SIMULATED PERFORMANCE

A. 3D-Printed Substrate and Design of the Dual-Band Tri-Port Flexible Tag

The tag is inkjet-printed on a 25-µm Kapton film, which covers a 1.8-mm silicone substrate and is coated with a 150-µm silicone layer. This flexible, stretchable, and water-repellent silicone is a polydimethylsiloxane (PDMS) compound, the Silpuran® 6000/05 A/B, whose EM properties (ε_r = 2.84 and $tan(\delta)$ = 0.052 at 2.45 GHz) have been characterized in [4]. Due to the high intrinsic losses, the substrate requires internal structural engineering to optimize EM performance, as analyzed in [1]. To reduce the effective dielectric constant and losses while enhancing antenna gain, efficiency, and mechanical stability, a 3D-printed honeycomb-core structure with octagonal cells, studied in [1], is designed. The 1.8-mm PDMS layer is then shaped via blade casting within a 3D-printed mold, and enclosed by Kapton films, where the inkjet-printed metallization is applied and coated with a 100-µm silicone layer. The dual-port SWIPT patch antenna features a dual-polarized radiating element: the communication antenna, coaxially-fed and linearly polarized along the *y*-axis, operates at 2.48 GHz with a 3.7 dBi gain, whereas the WPT/EH antenna, microstrip-fed and polarized along the *x*-axis, operates at 2.43 GHz with a 5.3 dBi gain (port 1 and port 2 in Fig. 1(a), respectively). At the edges of the same antenna substrate, a single-turn RX coil (equivalent inductance and resistance are L_{RX} = 198 nH and R_{RX} = 0.08 Ω, respectively) has been embedded, sufficiently spaced from the antenna's ground plane. The five-turn transmitting (TX) coil of the NF WPT link (equivalent inductance L_{TX} = 217 nH and resistance R_{TX} = 0.18 Ω) measures 13 × 20.2 cm², and is aligned along the *z*-axis, facing the RX coil, at a distance of $d_{z,TX-RX}$ = 3 cm (Fig. 1(b)), which is optimized to achieve a coupling factor between TX and RX of 0.037.

III. Rectifier Circuit Design for Dual-Band RF-to-DC Conversion and Simulation Results

The circuit representation of the overall SWIPT system is shown in Fig. 2(a). A dual-input, single-output rectifier has been chosen to enable RF-to-DC power conversion at both 13.56 MHz and 2.45 GHz. For the NF WPT branch, the power generator ($P_{TX,13.56MHz}$) with its internal 50-Ω resistance is connected to the resonant transmitting coil. On the receiving side, the resonant RX coil is loaded by its rectifier, which consists of a series Schottky diode (Skyworks SMS3922-079LF) followed by a LC low-pass filter. On the other hand, the RF-to-DC rectifier working at 2.45 GHz, designed on the same antenna's substrate, includes a matching network (MN), a shunt diode (Skyworks Schottky diode SMS7630-079LF), and a LC low-pass filter. Both rectifiers are connected in parallel, sharing the same load (R_{LOAD}), which is optimized to emulate the maximum power point tracking (MPPT) functionality of a commercial power management unit (PMU), specifically the e-peas AEM30940.



(a) (b)

Fig. 2. Schematic circuit diagram of the overall SWIPT system with corresponding optimized circuit components values: NF WPT and FF EH systems at the top and at the bottom, respectively; (b) fabricated prototype on Rogers RO3003 for preliminary EH measurements.

For numerical simulations of the NF inductive link, a $P_{TX,13.56MHz}$ = 30 dBm is chosen. This results in an overall TX-to-DC efficiency ($\eta_{RF,TX-to-DC}$) of 36%, calculated as the ratio between the DC output power ($P_{out,DC}$) and $P_{TX,13.56MHz}$, yielding a harvested DC power of 360 mW. On the other hand, the input power at the UHF rectifier ($P_{IN,2.45GHz}$) varies depending on the harvested power. However, the system has been optimized for low-power scenarios, where the harvested power may be as low as –20 dBm, yielding an $\eta_{RF\text{-}to\text{-}DC}$ efficiency of 23.4% (calculated as the ratio between $P_{out,DC}$ and $P_{IN,2.45GHz}$), and a corresponding $P_{out,DC}$ of 2.3 µW. Under more favorable conditions, with RF harvested power $P_{IN,2.45GHz}$ reaching 0 dBm, the $\eta_{RF\text{-}to\text{-}DC}$ efficiency increases to 48%, resulting in a $P_{out,DC}$ of about 0.5 mW.

To validate the harvesting results, a preliminary prototype of the dual-band tri-port flexible tag was fabricated on a 0.76-mm-thick flexible Rogers RO3003 substrate with adhesive copper metallization, as shown in Fig. 2(b). Initial measurements of the NF WPT system were conducted with the RX coil positioned 2 cm far from the TX coil. With a TX power of $P_{TX,13.56MHz}$ = 18 dBm, the system achieved a rectified DC voltage of 788 mV across an optimal equivalent load of 32 Ω, resulting in an efficiency $\eta_{RF,TX-to-DC}$ of 30%. The next phase will focus on FF energy harvesting (EH) measurements for the same prototype, alongside the fabrication and testing of the system on a flexible engineered Silpuran substrate.

IV. Fellowship Impact and Next Career Plans

Receiving this award has been an incredible honor, boosting my confidence and strengthening my motivation to pursue innovative advancements in RF and microwave engineering as a Woman in Microwaves. This award will give me the opportunity to spend a research period at Northwestern University, USA, where I will collaborate on cutting-edge projects to expand my knowledge on energy-autonomous and battery-free RF devices for wearable and implantable healthcare applications.

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