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2.45 GHz Silicone-based Rectenna: Manufacturing Techniques and Design

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***Abstract*—Flexible antennas are raising increasing interests especially when implemented to provide energy to sensors in wearable contexts. The exploitation of polymer-based substrates such as silicones, have paved the way to innovative solutions that are a promising tradeoff between performance and ease of customization. To enable this, fabrication techniques that combine inkjet printing with PDMS casting have provided a more agile realization of such devices. This work proposes the design process of a rectenna system operating at 2.45 GHz to be used in wearable wireless power transfer applications. A two-component PDMS compound, Silpuran® 6000/05 A/B, has been exploited to create a flexible substrate, whose geometry can be easily customized with specific thickness to favor the rectenna performance. An experimental campaign has allowed the electromagnetic characterization of the polymer and subsequently the linear and nonlinear subnetwork of the rectenna system have been optimized by means of electromagnetic/nonlinear co-simulation. The prototype of the radiating element has been realized and experimentally validated showing promising performance, leading this system to be a remarkably attractive solution for flexible and wearable radiofrequency frontends.**

***Keywords*—flexible antennas; inkjet printing; wireless power transfer**

I. INTRODUCTION

Recently, scientists have focused on developing low-cost flexible electronics using new materials and printing technologies. The desire for cost-effective mass production methods is driving interest in radiofrequency identification (RFID) tags, antennas, keyboards, displays, and flexible sensors [1], [2]. Rapid prototyping of electronics and sensors is vital, especially in demanding environments. Two types of printing technologies emerge: those that require mask-based or photolithographic processes, such as screen printing and printed circuit board (PCB) technologies, and direct printing technologies, such as inkjet printing (IJP). A comparison of PCB technology with IJP demonstrates that, while IJP is ideal for rapid prototyping, it has constraints in terms of accessible materials. In contrast, PCB-based systems excel in large manufacturing but present obstacles for rapid prototyping, particularly in research contexts. A similar consideration applies to roll-to-roll lithography, which is appropriate for mass production due to high-resolution patterning but has greater costs at low production rates. A generic large-area electronic structure, as an antenna, is composed of a substrate, backplane electronics, a front plane and sometimes encapsulation. To make the structure flexible, all components must comply with bending to some degree without losing their function. For flexible antennas, these materials are carefully chosen to give an acceptable amount of mechanical deformations (such as bending, twisting, and wrapping) with minimal influence based on diverse conditions and sufficient electromagnetic (EM) radiation protection [3]. In this paper, we investigate the use of novel silicone-based materials in antenna fabrication. To fully realize the potential of these materials, a thorough and precise characterization approach is required. This entails a thorough evaluation of their EM properties, structural characteristics, and any other relevant element that affects their performance in the context of antenna systems.

The complexity of this characterization is critical for optimizing the integration of these novel materials, assuring their compatibility with the necessary antenna requirements, and, ultimately, improving the overall efficiency and functionality of the antenna design. Major design considerations and performance metrics for flexible antennas are discussed and several reported antennas with different technologies are compared. Metal conductivity frequently determines the radiation efficiency of antennas, i.e., in flexible antennas, and the relative resistance of the conducting sheet causes significant losses. As a result, while the conductivity of certain innovative technologies may be suitable for stretchable electronics, it may not be an adequate conductor for effective radiofrequency (RF) applications. It is generally known that a metal less conductive than copper leads to lower gain, efficiency, and bandwidth. As a rule of thumb, a conductivity of up to an order of magnitude less than copper conductivity is acceptable for antenna applications. However, accepting the tradeoff between performance and agile realization and wearability, different materials with respect to copper are being exploited to design flexible antennas. The primary application of metal-based nanoparticles is due to their conductivity. Because silver oxide is similarly conductive, silver nanoparticles are particularly desirable because their conductivity does not significantly deteriorate because of oxidation [4]. While printing techniques have the potential to drastically lower the cost of fabricating antennas, the performance of printed antennas may be compromised in comparison to solid metal antennas. When compared to traditional metal tracing, the conductivities of adhesive fluid and metal particles-based conductive inks are typically lower [5]. Because of their tensile strength and ease of production, polymer-based conductive materials, including conductive nanoparticles of copper, silver, and gold, are becoming widely spread and more and more popular [6]. These materials and the agile linked fabrication processes have been highly exploited to design light, flexible wearable antennas [7–9]. This article presents the design steps to be able to exploit a specific polydimethylsiloxane (PDMS) polymer to create flexible wearable antennas to be applied in wireless power transfer (WPT) applications.

II. MANUFACTURING PROCESS OF THE SILICONE SUBSTRATE

The goal of this project is to design a wearable rectenna on a flexible silicone substrate. The versatile realization process enables a custom realization of the substrate, especially in terms of geometrical arrangements.

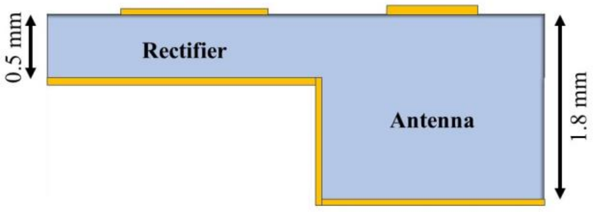


Fig. 1. Schematic stack-up of the designed silicone substrate with two different thickness of 0.5 and 1.8 mm for circuitry and antenna design, respectively.

To improve the performance of the radiating part and the nonlinear subnetwork without having the chance to vary the substrate dielectric properties separately, two different thicknesses have been exploited, as depicted in Fig. 1, suitable for radiating and guiding operations, respectively. In particular, the part hosting the antenna has thickness of 1.8 mm, whereas the one hosting the linear and nonlinear part of the rectifier is equal to 0.5 mm, guaranteeing better guided performance and a more compact matching network [10].

A. *Preparation of the Silicone-based Substrate*

The used PDMS polymer is the Silpuran® 6000/05 A/B which is a two-component compound with 1:1 mixing ratio, easily manufactured through a blade casting process. This material is usually adopted as the right solution for a variety of coating requirements providing not only elasticity and flexibility but also hydrophobic qualities. All these characteristics and the straightforward manufacturing process makes this material an excellent candidate to realize wearable antennas that are not only flexible, but also water repellent due to the possibility of coating them entirely with PDMS thin film, to ensure water-repellency [11]. In this context, a blade caster TQC Sheen AB3655 is used to cast the PDMS compound in a mold, allowing constant pouring velocity to prevent air bubble formation and a homogeneous substrate with a desired thickness. The obtained substrate is then left at a controlled temperature to enable the PDMS cross-linking process. For substrates of 1–2 mm of thickness, a resting time of 24 hours at room temperature has been chosen, whereas, for lower thickness, only 2 hours. After this step, the PDMS is cured in the oven at 100°C for 1 hour.

B. *Inkjet Printing Techniques*

Antenna metallization is accomplished by an inkjet printing process. The choice of the deposition-substrate is essential to good printing. Chemical composition, surface roughness, porosity, hydrophobicity, adhesive compatibility, and surface uniformity are all crucial factors to consider when choosing the deposition-substrate. Its surface physical characteristic greatly affects the shape retention and adhesion of the ink. While a smoother surface could yield better results, a rough surface can limit printing precision. A polyimide (PI) deposition-substrate layer with 25 μm thickness from Caplinq has been chosen in this work due to its suitable inkjet printing qualities. When compared to the PDMS substrate thickness, this PI layer has negligible impact on the antenna's EM radiation and can be ignored. Sigma-Aldrich silver dispersion-nanoparticle ink (30–35 wt. %) in triethylene glycol monomethyl ether is used as the electrode antenna. It has a specific resistivity of 11 μΩ cm, resulting in a conductivity of 90909 S/m. As presented in [12], the efficiency and radiation characteristics of an antenna are marginally altered by conductivity of that order. The printing process is conducted employing the Microfab Drop-On-Demand inkjet printer with a regulable temperature printing plate with back pressure holes. To improve printability qualities, the silver ink is sonified for five minutes at 37 kHz to eliminate any lumps before printing, and the PI substrate is cleaned of isopropyl alcohol (IPA) and is kept on the printing plate at 50°C. As the last manufacturing step, the obtained antenna metallization is deployed on the PDMS substrate and insulated by another thin PDMS layer with the same casting process as a superstate over the metallization to shield and isolate the prints. The sole distinction between the two PDMS layers is that the thinner one is mixed with IPA to decrease viscosity and improve castability. A mixture of 6 g of component A, 6 g of component B, and 12 g of IPA was made to achieve a thickness of about 150 μm.

III. DIELECTRIC PROPERTIES CHARACTERIZATION AND ANTENNA PERFORMANCE

Previous studies [13] have introduced analytical methods for characterizing materials through resonant techniques. Specifically, these methods take advantage of the microstrip T-resonator topology discussed in [14], [15], which is composed of a microstrip line connected to a quarter-wavelength open stub, see Fig. 2(a), whose geometrical length is planned to series-resonate at a specified frequency (here, 1 GHz).

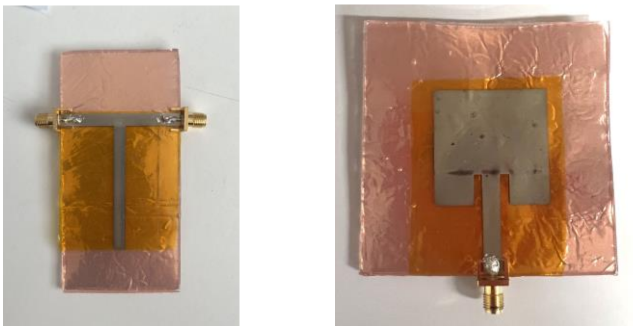
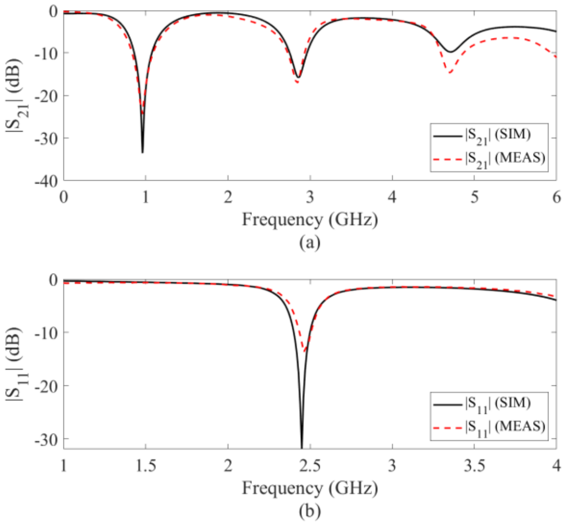

(a) (b)

Fig. 2. (a) Fabricated T-resonator for the retrieval of the dielectric constant and loss tangent, and (b) patch antenna at 2.45 GHz.

The T-resonator is inkjet printed on a 25 μm thick Kapton film that is attached to a 2 mm thick silicone substrate and then coated with a 150 μm thick layer of the same silicone. The initial relative dielectric constant ε_r and tangent loss tangent $tan(\delta)$ are fixed at a preliminary value that can be found in the literature for a specific frequency (in this case, $\varepsilon_r = 2.5$). Then, the dielectric permittivity and the loss tangent of the material in the frequency range of interest are characterized using an iterative process based on measurements and full-wave analyses of the same structure.

The simultaneous matching of the simulated and measured two-port S-parameters is the main objective.

Here, in Fig. 3(a), it is possible to appreciate the simulated and measured values of the transmission coefficient S_{21} module which are in good agreement and allows to account for values of $\varepsilon_r = 2.84$ and $tan(\delta) = 0.052$ at 2.45 GHz, which is the frequency that has been selected for the final WPT application. A patch antenna is designed by full-wave simulations and realized, as shown in Fig. 2(b), and its simulated and measured reflection coefficients are reported in Fig. 3(b). A gain of 5 dBi has been experimentally found, with a simulated radiation efficiency of about 30%. In order to ensure feasibility also in presence of bending, full-wave simulations have been carried out to investigate the antenna radiation properties when undergoing bending. Results have shown that for a curvature of 60° the radiation efficiency slightly decreases to 25.6%, thus ensuring good wearability characteristics.



(a)

(b)

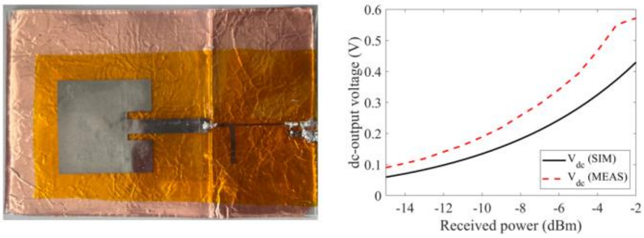
Fig. 3. (a) T-resonator simulated and measured $|S_{21}|$ for the realized prototype; (b) simulated and measured $|S_{11}|$ reflection coefficient of the planar antenna at 2.45 GHz that has been fabricated.

IV. RECTIFIER DESIGN

To carry out the design of a wearable rectenna for WPT purposes, a rectifier and a dedicated matching network should be implemented. The agile silicone manufacturing has allowed the creation of a substrate that can have different thicknesses while guaranteeing a seamless connection of the two parts. The design and optimization of the rectifier and the linear subnetwork dedicated to the impedance matching between the antenna and the rectifier is carried out by means of the harmonic balance algorithm with the goal of maximizing the RF-to-dc power conversion efficiency for different received power levels, ranging from –15 to –2 dBm, computed as:

$$\eta_{RF\text{-}to\text{-}dc} = P_{dc} / P_{RF} \qquad (1)$$

where P_{RF} is the power received by the antenna. The chosen rectifier topology is a standard half-wave rectifier in shunt configuration making use of one Skyworks SMS7630-079LF diode, chosen for its low threshold voltage (0.34 V) and breakdown voltage of 2 V. The obtained optimized conversion efficiency over the received power range results in a 18.3% for a –15 dBm up to 42% for a value equal to –2 dBm. The realized prototype is displayed in Fig. 4(a): the single-stub matching network has allowed good impedance matching conditions without exceeding in overall encumbrance. The dc-output voltage in open circuit conditions has been measured for the realized prototype. As first, the correct received power has been estimated by using the antenna only, then the antenna is substituted with the designed rectenna, and the dc-output voltage is measured for a received power range from –15 to –2 dBm. Results are plotted in Fig. 4(b), showing a promising agreement.



(a) (b)

Fig. 4. (a) Realized prototype of the flexible rectenna; (b) measured (black line) and simulated (red dashed line) dc-output voltage versus received RF power in open circuit conditions.

V. CONCLUSION

In this article, the exploitation of manufacturing techniques and advanced printing capabilities have allowed the design of a 2.45 GHz rectenna system from scratch, providing a freedom on geometrical choices and realization. The silicone-based substrate boasts two different thicknesses: the thicker hosting the radiative part and the thinner hosting the rectifier and its linear subnetwork. The metallization is inkjet-printed by means of liquid silver for a thickness of about 8 µm on a 25 µm Kapton film. The antenna radiating performance is experimentally validated resulting in a measured gain of 5 dBi and the system dc-output voltage has been quantified showing good agreement with the simulated results. Future implementations will carry out improvements on the layout and the manufacturing process to make such design highly compatible with the state-of-the-art performance of similar systems realized on more standard substrate, while having the added value of ensuring the wearability and flexibility required by wearable WPT systems.

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