Self-Healing UHF RFID Tag Antennas: The Concept and First Results with a Slot-Type Antenna

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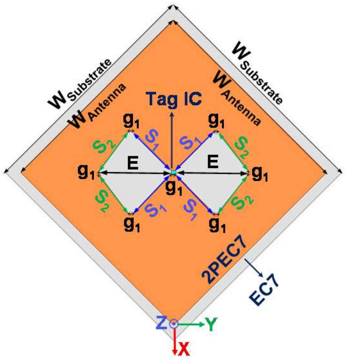
***Abstract*—Self-healing functional polymers, composites, and blends have the potential to provide cutting-edge solutions for advancing fully soft, elastic electronics, antennas, and sensors. In this letter, we present the first prototype and performance evaluation of a slot type passive UHF RFID tag antenna made of self-healing insulative elastomer substrate and self-healing conductive laser cut PEDOT:PSS-based blend film. The measured maximum read range of the self-healing tag varied from 1.7 to 1.8 meters within the frequency range of 860–960 MHz, which covers the UHF RFID bands used worldwide. Taking into account the current conductivity of the self-healing polymer (150 S/m), this is a promising result and demonstrates, for the first time, a completely self-healing polymer-based UHF RFID tag antenna. In addition, we have demonstrated direct attachment of the RFID IC strap to the radiator without any additional adhesives. Moreover, the good agreement between the simulated and measured data confirms the applicability of the antenna modelling approach to the fully self-healing elastomer-based antenna. The work presented in this paper provides proof-of-concept in development of self-healing antennas, sensors and electronics. One of the most important aspects for future work is increasing the conductivity of the self-healing polymer.**

***Keywords*— Passive UHF RFID tag, read range, self-healing elastomer, self-healing RFID tag antenna, slot antenna.**

I. INTRODUCTION

Radio Frequency Identification (RFID) technology has emerged as a highly promising solution for a wide variety of purposes, offering efficient and reliable methods for identification, tracking, and sensing [1]. Over the past two decades, intense efforts have been dedicated to advancing RFID technology by the emphasis on developing more compact, flexible, and durable tags, and less time consuming and more cost-effective manufacturing processes [1], [2]. Various conductive materials have been studied for flexible tag antennas, to establish reliable wireless communication and high data transfer rates in passive UHF RFID system [1], [3]. In [4] and [5], polymeric core-shell fibers with metallic coating were embroidered on the fabrics and reported for wearable RF electronics and as RFID tag antenna. Carbon nanotube (CNT)-coated textiles were embedded into polymer-ceramic composites for conformal and lightweight antennas [6]. Fabrics knitted with metal filaments were utilized for smart textiles [7]. Zhou et al. [8] made a method for producing highly conductive and stable graphene-based printable ink for wireless RFID sensing. Simorangkir et al. [9] presented conductive fabrics embedded polydimethylsiloxane substrates to solve the issue of poor adhesion at polymer-metal interface providing robust and flexible antennas suitable for wearable applications. In [10] and [11], UHF RFID tag antenna-based metamaterial was introduced for wearable applications. Beyond the numerous material technologies currently available for integrating RFID tags into different platforms, the self-healing functional materials hold a significant potential to revolutionize flexible and stretchable electronics, and wireless sensing technologies. The autonomous self-healing carries out its functions without the need for external intervention or energy input, similarly to the skin or tissue regeneration. Upon a scratch or crack, the material initiates a spontaneous self-repair that can complete within a few minutes or hours, depending on the specific properties of the polymer system. This healing process is significantly more rapid—by a factor of dozens or even hundreds—than the time required for healing a minor wound on human skin [12], [13], [14]. The self-healing materials introduce advanced functionalities and enhance the durability of wireless devices in extreme conditions, including cold, saline, high-pressure, and space environments. In our previous work [15], preliminary numerical simulations were used to assess the feasibility of self-healing elastomers [12], [13] for creating a fully self-healing passive UHF RFID tag. In this numerical study [15], a key challenge for the tag's functionality was its limited conductivity up to 150 S/m [12], whereas regular metallic conductors typically exhibit conductivities in the range of 30–60 MS/m. This limitation indicates relatively high resistive losses, which result in degraded impedance matching, reduced antenna radiation efficiency, and eventually impact the read range. Despite these limitations, the simulation results showed reasonable performance (considering all added hard-to-come-by functionalities), allowing a functional passive UHF RFID tag IC to be read at a distance exceeding two meters using a slot antenna made of autonomously self-healing elastomers.



W_Substrate	110 mm
W_Antenna	100 mm
S_1	25.4 mm
S_2	22.6 mm
g_1	2 mm
E	34.4 mm
Substrate thickness (EC7)	1 mm

Fig. 1. Geometry and schematic illustration of the fully self-healing RFID tag antenna configuration.

Although self-healing materials may exhibit lower conductivity than conventional metals, their stretchability, strain-dissipative and adhesive properties, and ability to autonomously repair damages multiple times (without possible performance degradation) introduces unique advantages for deformable and resilient RFID applications. For example, this enables robust integration as components and ICs can also self-bond with only physical contact and applied pressure. Herein, for the first time, the functionality of the prototyped fully self-healing passive RFID tags was evaluated with varying conductor thicknesses, demonstrating a proof-of-concept with a read range of 1.8 meters. Given the current conductivity levels, our ongoing efforts aim to improve the conductivity and strain-insensitivity to significantly enhance the electrical performance metrics even under strain, making self-healing materials a truly viable alternative for durable RFID technologies.

II. ANTENNA DEVELOPMENT AND NUMERICAL ANALYSIS

A. Antenna Configuration

Fig. 1 depicts the configuration of the developed self-healing diamond slot-type tag antenna. The dimensions correspond to approximately λ/4 × λ/4 foot-print size at the target frequency of 915 MHz, ensuring a compact radiator design. To maximize the available radiator linear length, diamond-shaped slots were incorporated symmetrically at the center of the antenna. The slot-type radiator is made of the self-healing PEDOT:PSS-based conductor (2PEC7) with the preferred film thickness ranging from ~ 50 to 300 μm. To achieve a fully self-healing functional structure, the radiator was self-bonded on a self-healing elastomer substrate (EC7) having a relatively permittivity ε_r= 3.1 and a dielectric loss tangent $\tan\delta = 0.015$ at our target frequency. The elastomer substrate thickness is preferably in the range of 25 μm – 2 mm. However, a 1 mm substrate thickness was selected for optimal performance, and as thicker substrates are generally not ideal for the intended applications, and more difficult to fabricate due to level of degassing required to completely remove the air entrapped inside the elastomer matrix.

B. Antenna Performance Indicator

The primary performance parameter of passive RFID tags is the attainable read range (d_{tag}), which depends on the power transfer efficiency (τ) between the antenna and the RFID integrated circuit (IC) and the turn-on power of the IC (P_{IC0}). In free space [16]

$$d_{tag} = \frac{\lambda}{4\pi}\sqrt{\frac{\tau \cdot e_r \cdot D \cdot EIRP}{P_{IC0}}}, \tag{1}$$

where λ is the wavelength of the reader's signal and e_r and D denote the antenna radiation efficiency and directivity, respectively, and the term *EIRP* is the maximum effective isotropic radiated power of the reader governed by the radio regulations (commonly *EIRP*= 3.28 W or 4 W). In addition, τ is given by [16]

$$\tau = \frac{4\mathrm{Re}(Z_A)\mathrm{Re}(Z_{IC})}{|Z_A+Z_{IC}|^2}. \tag{2}$$

where Z_A and Z_{IC} are the impedance of the antenna and the RFID IC, respectively. To maximize d_{tag}, tag antennas are normally designed to have impedance that is the complex conjugate of the tag IC impedance. This approach provides the maximal antenna-IC power transfer efficiency: τ = 1.

In this work, we used NXP UCODE G2iL series RFID IC [17], characterized by an impedance resulting from a parallel connection of a 0.91 pF capacitor and a 2.85 kΩ resistor, which yields $Z_{IC} \approx 12.8 - j190.3\ \Omega$ at 915 MHz. The selected RFID IC has the turn-on power $P_{IC0} = -18$ dBm and we followed the *EIRP* regulation of *EIRP* = 3.28 W. Following these guidelines, the initial objective was to optimize the antenna impedance to effectively match to the capacitive impedance of the IC. Thus, simulations conducted using Ansys HFSS led to modifications in the diamond-slot geometry, and the surrounding structural elements. For this purpose, we analyzed the slot geometry by varying three primary parameters (S_1, S_2, and E), as shown in Fig. 1, and found that it was not possible to attain a perfect conjugate-matching. In particular, the slot dimensions significantly affect radiation efficiency, and limited conductivity complicates achieving inductive input impedance for the complex conjugate matching with the tag IC. This issue is also present in the regular inductive loop matched dipoles. Narrower conductive traces and increased Ohmic loss further reduce the efficiency. Therefore, we focused on optimizing the design parameters to maximize the read range rather than optimal impedance matching. To this end, the HFSS optimization tool, based on a genetic algorithm, was used to maximize the read range by adjusting key parameters (S_1, S_2, and E). The optimized slots' dimensions resulted in the structure depicted in Fig. 1. We further evaluated the impact of varying the thickness of the conductive layer. As are obvious in Fig. 2, increasing the conductor thickness enhances the power transfer efficiency, enabling the antenna to attain an effective impedance matching. Fig. 3 presents the radiation efficiency (dashed lines) and the attainable read range (solid lines) for the different conductor thicknesses. According to (1), applying a thicker conductor of 300 μm enables the reader to access stored data in the tag IC from a greater distance of 2 m at the direction of ±y-axis, with a power transfer efficiency of 16%, and a radiation efficiency of 13.5% at 915 MHz, as shown in Fig. 2 and Fig. 3, respectively.

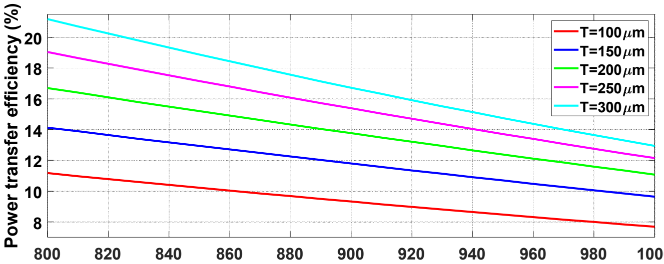


Fig. 2. Power transfer efficiency for different thicknesses.

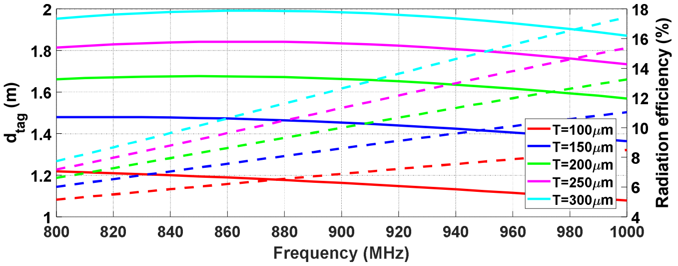


Fig. 3. Attainable read-range (solid lines) and radiation efficiency (dashed lines) for various conductor thicknesses.

III. PROTOTYPED ANTENNA AND WIRELESS MEASUREMENT

A. Prototype Fabrication

The slot-type, passive UHF RFID tags at varied thicknesses of 2PEC7 were fabricated in four steps (i) – (iv).

(i) 0.1 – 0.3 wt.% carboxyl functionalized multiwalled CNTs were ultrasonicated with toluene (at < 20 mg/ml) before mixed with EC7 [12]. The total solution volume was fixed to attain a desired thickness for the drop casted film. The addition of CNTs was done to improve the long-term dimensional stability and creep resistance, and to reduce the self-healing and adhesion properties of EC7 to enable easier sample handling. The addition of toluene allows controlling the viscosity for improved removal of entrapped air from the film.

(ii) The 2PEC7 were prepared as previously reported in [13]. The solution was tape casted onto a polyethylene terephthalate (PET) carrier substrate at various thicknesses. The sizes of individual films were ≈450 mm × 75 mm. The films were self-bonded together via self-healing by placing the films in a physical contact with each other to form a double-layered film (inverted 2PEC7-F2 film structure [14]) with size of ≈400 mm × 140 mm. The total thicknesses corresponded to the desired conductor thicknesses for the antennas. The films were kept at 70 °C to further remove air due to the lamination process. The film was laser cut with LPKF Protolaser U3 in accordance with the slot-type radiator design. Excessive parts from the films were removed by peeling with tweezers along the cuts.

(iii) The conductive film structures were gently pressed against the EC7 substrates to adhere and bond the elastomer parts together via self-healing. Before totally removing the PET films by peeling, the samples were kept at 70 °C for 5 – 10 min.

(iv) The RFID ICs were manually placed to desired location on 2PEC7 with the tweezers. Due to excellent adhesive and self-healing properties of 2PEC7 [14], a good mechanical and electrical connection was achieved from the IC to the conductive layer with two 2PEC7 films placed on the copper contacts (Fig. 4). After the assembly, the UHF RFID tags were kept in a room temperature before the measurements.

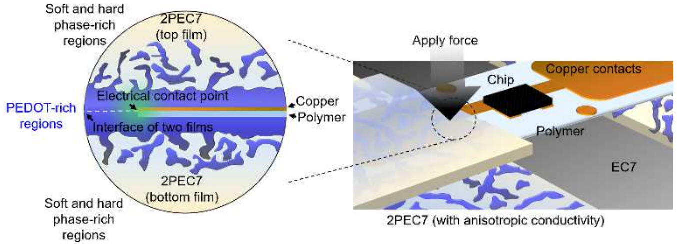


Fig. 4. Schematic illustration of the electrical connection.

B. Measurement Setup, Results and Discussion

We evaluated the performance of the RFID tags with the various conductor thicknesses using the Voyantic Tagformance Pro RFID measurement system, which is setup in an anechoic chamber to minimize interference. This system includes the tag under test, a reader antenna, and associated control software. Fig 5. (b) shows the wireless measurement setup, where the prototype tag is aligned with the reader's horizontal polarization, with XY-plane measurements showing peak gain along the y-axis. The reader antenna is a Voyantic Standard Patch with 8 dBi gain and horizontal linear polarization. The RFID measurement system features an adjustable transmission frequency range from 600 MHz to 1.2 GHz and an output power of up to 30 dBm. The system can detect backscattering signal strengths as low as −80 dBm. To begin testing, we characterized the wireless channel between the tag under test and the reader antenna using a manufacturer-provided reference tag with known properties. Subsequently, we recorded the minimum continuous transmission power (P_{th}) required to successfully receive a response to the reader's query command according to ISO 18000-6C standard. Applying the measured output threshold power of the reference tag (P_{th*}), the manufacturer-provided sensitivity constant of the reference tag at each frequency (Λ), and the emission power limit of the reader ($EIRP$), the attainable read range for RFID tag as a function of frequency can be computed by

$$d_{tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{\Lambda}\frac{P_{th*}}{P_{th}}}. \tag{3}$$

Fig. 6 compares the simulated (dashed lines) and measured (solid lines) results for various conductor thicknesses. The measured results presented a reasonable agreement with the

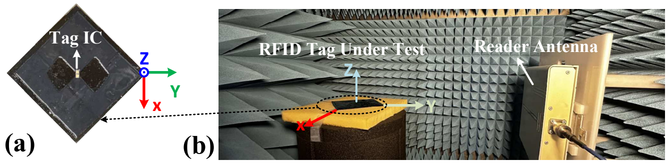


Fig. 5. (a). Prototyped self-healing slot-type passive UHF RFID tag, (b). measurement setup in anechoic chamber.

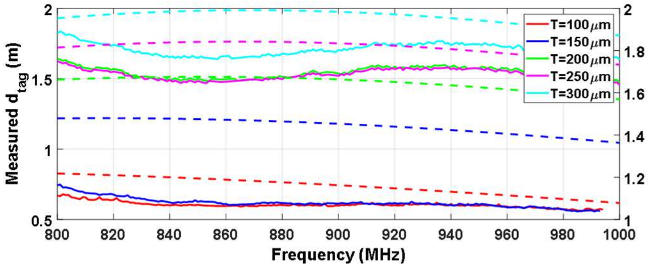


Fig. 6. Comparing simulated (dashed lines) and measured (solid lines) read range for different conductor thicknesses.

simulated ones. These results confirmed that employing thicker conductors allows reader to retrieve the stored data at a longer distance from the RFID tag IC. However, the difference between the simulated and measured attainable read range may be caused by several factors, e.g. complex anisotropic electrical properties, attainable level of electrical contact between the IC pads and 2PEC7s, and time-dependent morphological changes in the materials over time in the real environment. The measured prototyped tag (with 2PEC7 of 300 µm) enables data extraction from the IC at a maximum attainable read range of 1.8 meters with a sufficient transmitted power of 18.3 dBm at the desired frequency of 915 MHz. Overall, conventional RFID tag antennas rely on high-conductivity metals for optimal efficiency but are susceptible to mechanical deformation and environmental degradation. Intrinsically conductive polymers (e.g. PEDOT:PSS) offer flexibility but conductivity without post-treatments is $\sim 10^3 - 10^5$ S/m. Self-healing elastomer blends, despite their lower conductivity (150 S/m), enable spontaneous self-healing, thus enhancing RFID tag longevity. With the attainable read range, our design demonstrates a proof-of-concept for passive UHF RFID applications, showing that optimizing conductor thickness can reduce Ohmic loss. Continued advancements in the materials technologies will improve performance, confirming their potential as a durable and flexible alternative to conventional tag materials.

V. CONCLUSION

This study demonstrates proof-of-concept of using self-healing conductive and insulative elastomers to create a fully self-healing passive UHF RFID tag. This was achieved by developing and fabricating a diamond-slot tag antenna with a square foot-print measuring 100 ×100 mm^2. The suitable agreement between simulation and measurement results confirms that the innovative materials and methods enable soft, self-healing RFID tags for diverse applications, from healthcare and robotics to consumer electronics and beyond. With our first prototype, we achieved a 1.8 m read range at 915 MHz, which is a promising proof-of-concept result with the current 150 S/m conductivity. In addition, we have demonstrated direct attachment of the RFID IC strap to the radiator without any additional adhesives. Future work will focus on evaluating performance and recovery under strain and after mechanical damage and cutting. Most importantly, we aim to improve the self-healing material properties and address antenna impedance matching issues.

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