2nd URSI AT-RASC, Gran Canaria, 28 May – 1 June 2018

Wearable UHF RFID Sensor Tag in 3D-Printing Technology for Body Temperature Monitoring

R. Colella, and L. Catarinucci
Department of Innovation Engineering, University of Salento, 73100 Lecce, Italy

Abstract

Wearable UHF RFID tags with sensing capabilities are more and more adopted in many applications where the need of transmitting body sensor data in a passive way along with identification is crucial. In the meanwhile, additive manufacturing 3D-printing technology is knowing a remarkable resonance also in the electromagnetic community since it enables the design of novel customized electromagnetic structures and antennas. In this work the effectiveness of the combination between Radiofrequency Identification (RFID) technology and 3D-printing has been demonstrated through the design, realization, and test of a new wearable passive UHF RFID sensor tag for body temperature monitoring based on the 3D printing.

1. Introduction

During the last years, wearable Radiofrequency Identification (RFID) sensor tags in UHF band (860 ÷ 920 MHz) are knowing a remarkable development in many fields of application that arouse interest in the electromagnetic community with novel studies and research on specific antenna layouts and innovative wearable solutions. [1]-[3] In particular, the need of compactness joint to the capability of the antenna to work close to the human body while maintaining high radiation efficiency, cost-effectiveness, robustness, bandwidth, and conformability make challenging the design.

In the meanwhile, the advent of novel additive manufacturing 3D-Printing technologies based on the use of low-cost thermoplastic materials (i.e. ABS - Acylonitrile Butadiene Styrene, or PLA - Polylactic Acid, etc.), for modeling structures, components, and three-dimensional objects has considerably stimulated the electromagnetic community paving the way to novel and appealing approaches to realize microwave components and antennas in a fraction of the time and at a fraction of the cost required by traditional techniques [4]-[7]. Moreover, 3D-printing technology enables the design of customized antenna substrates with desired shape, thickness, and composition. Indeed, 3D printers can realize the interior of the printed object, named infill, not completely solid. Then, by controlling the infill percentage of the deposed material, the density of the substrate can be adjusted to obtain the desired electric permittivity and loss tangent. Thanks to these peculiarities, 3D-Printing technology could be really helpful in realizing tailored wearable antennas where the need of customizing thickness, shape, and dielectric properties of the substrate is crucial to improve the antenna performance.

In order to demonstrate the effectiveness of this approach in the framework of wearable UHF RFID devices, in this work a fully-passive RFID sensor tag with temperature sensing capabilities based on a 3D-printed meandered antenna working in the European RFID band has been designed, realized, and tested. Conductive parts have been realized by shaping a copper tape through specific techniques [8], whilst dielectric structures have been realized in PLA, whose dielectric properties have been evaluated. The metallic ground-plane of the antenna, took into account in the design and useful to improve the robustness of the antenna with respect to the human body, has been integrated into the structure during the printing process. Finally, to assure the contact with the human skin, a sensor-provided board equipped with a RFID chip embedding a temperature sensor has been mounted on the bottom side of the tag and connected to the antenna through via holes realized on the PLA substrate.

2. Design and Antenna Simulation of the Wearable 3D-printed UHF RFID sensor tag

In this section the design of a novel wearable UHF RFID sensor-tag is presented. Based on a wearable antenna designed and integrated into a 3D-printed structure of PLA, the sensor tag is specifically designed to passively sense and transmit the body temperature.

Being unconventional, the PLA material used for 3D-printing the antenna substrate and other parts of the tag has been preliminarily characterized in terms of relative dielectric constant and loss tangent when varying the infill percentage from 20% to 100% through a proper set-up based on the T-resonator method, as better described in [9]. Obtained are at 866 MHz are summarized in Tab. I.

In Fig. 1 a transversal section of the sensor-tag is reported. The upper part is the copper radiating element of the antenna having a thickness of 35 μm. The radiating element is applied on a 5.6mm-thick 3D-printed PLA substrate with 100% of infill (ε_r=2.57, $tan\delta$=0.0069) and enclosed into a 1.5mm-thick cover realized in PLA with 40% of infill (ε_r=1.62, $tan\delta$=0.0036) having two lateral mounting brackets. An opportunely shaped metallic background to assure the desired platform tolerance useful in wearable applications is also considered to improve the robustness of the antenna with respect to the human body [2]. Moreover, the tag is provided with a rectangular enclosure, realized on the bottom side of the substrate, to host a circuit board (whose details will be provided below) mounting the RFID chip embedding the temperature sensor. In particular the chip EM4325 by EM-Microelectronics having an import impedance of 23.3-j145Ω at 866MHz has been selected for this purpose. It is worth observing that circuit board is placed upside down on the bottom side of the structure so to assure the contact between the human skin and the RFID chip for measuring the temperature. Consequently, two via-holes passing through the 3D printed substrate are needed to contact the antenna placed on the top side of the structure. For better understanding the structure, in Fig. 2a and Fig. 2b both the top and the bottom 3D views of the proposed sensor-tag designed in CST Microwave Studio are shown. On the one hand, Fig. 2a clearly shows how the PLA substrate, the radiating element of the antenna, and the cover are assembled together. Moreover, a detail of four insets useful to fasten the structure on the wrist is also reported. On the other hand, Fig. 2b shows the metallic background of the antenna, along with the enclosure of 20x14 mm^2 and thickness 0.4mm that hosts the circuit board with the RFID chip.

In Fig. 3 the design of the radiating element of the antenna is shown in detail and in Tab. II the values of the parameters optimized during the simulation phase are reported. According to [10] The element is composed of a meandered line with a central loop, useful for optimizing the conjugate impedance matching, and an outer edge.

Table I. Measured PLA dielectric parameters at 866 MHz by varying the infill percentage

Infill Percentage	Dielectric Constant	Loss Tangent
20%	1.49	0.0029
40%	**1.62**	**0.0036**
60%	1.91	0.0047
80%	2.23	0.0052
100%	**2.57**	**0.0069**

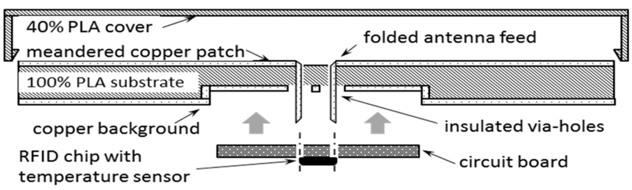

Figure 1. Layout of the 3D-printed wearable sensor-tag

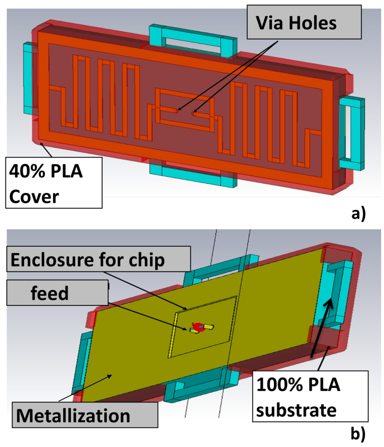

Figure 2. 3D-printed wearable sensor tag simulation: top view a) ; bottom view b).

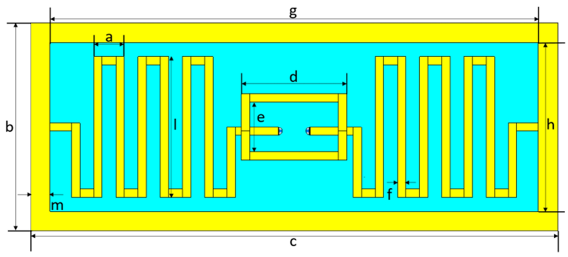

Figure 3. Antenna radiating element layout

Table II. Overall dimensions of the wearable tag antenna for the RFID sensor tag

Parameter	Size [mm]	Parameter	Size [mm]
a	4.4	g	70.4
b	30	h	24.4
c	76	i (sub. thick.)	5.6
d	22.4	l	20.336
e	9.6	m	2.8
f	1.2		

In order to numerically analyze the interaction between the antenna and the human body and tune the antenna parameters, an homogeneous average equivalent model of a human tissue, consisting in a block material with ε_r = 36, σ = 0.62 S/m [1] and size 20x10x10cm^3, has been added to the simulation scenario in direct contact with the bottom side of the tag antenna. With the parameters of Tab. II an antenna input impedance of Z_{ant}=22.44+j146 Ω has been obtained at 866 MHz, which assures an appreciable conjugate matching with the chip, and a total size of the device of 80x34 cm^2. Simulations also highlight an antenna directivity of 6.3 dBi, an antenna efficiency of -5.2 dB at 866 MHz, and linear polarization.

3. Realization of the 3D-Printed Wearable Sensor-tag

On the basis of the simulated layout, the novel sensor tag has been realized through a professional 3D printer. In particular, a Sharebot NextGeneration printer, with a 1.75 mm filament extruder and a 0.35 mm nozzle has been used. A printing speed as low as 25 mm/s for the first layer (so to facilitate the adhesion with the basement of the printer) and at 50 mm/s for the rest of the structure has been set along with a bed temperature of 65 °C. Moreover, an extruder temperature of about 210 °C has been selected to melt the PLA filament.

With the above reported settings, the antenna substrate has been firstly realized by setting an infill of 100%, the metallic ground-plane has been manually embedded into the 3D structure during a controlled break of the printing process. The main radiating structure has been directly applied on the top layer of the tag and then protected with the cover. The cover has been printed in a separate process, with an infill of 40%, and then hooked to the to the substrate to complete the device. All the metallic parts have been realized in 35μm-thin copper by using a CNC machine to cut an adhesive copper tape according to the prototyping method proposed in [8]. Figure 4 shows the details of the 3D-printed tag antenna with reference to the top side (Fig. 4a) and bottom side (Fig.4b) of the antenna. Finally, the circuit board a has been realized on a FR4 substrate and placed on the bottom side of the tag in the specific slot (Fig 4b). The antenna has been connected to the board through two via-holes realized during the printing process as well. The size of the board is 19.78 x 13.78 mm^2 and the thickness is of 0.4mm in order to fit the enclosure on the bottom of the tag. As clear from Fig. 4b, the board is composed of the EM4325 chip and several pads and lines, useful either for programming the chip through SPI interface or for connecting other optional sensors. Moreover, in Fig. 4c a use case where the 3D-printed sensor-tag is applied on a human arm through velcro tape is shown.

4. Results

Once realized, the 3D printed wearable sensor tag has been characterized from the electromagnetic point of view in two different working conditions: when applied on human tissue, and on air (without any background). In particular, the measurement platform proposed in [11], specifically designed for a full tag analysis, has been

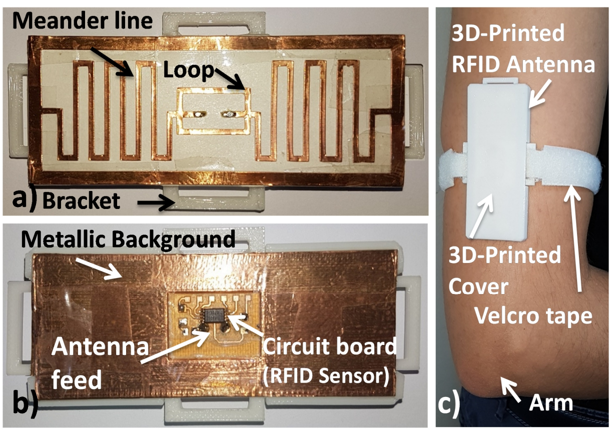

Figure 4. Realization of the 3D-printed wearable sensor-tag: top view a); bottom view b); sensor tag on arm

adopted. A tag holder with permittivity close to 1 has been used for on-air measurements. Instead, a block of 20x10x10 cm^3 with $\varepsilon_r \approx 36$, and $\sigma \approx 0.62$ S/m has been used as artificial human tissue. This material has been synthesized in laboratory by means of a specific saline solution filling a PVC box.

The first test has been performed by placing the tag at a fixed distance of 1 m from the platform antenna and by measuring the tag sensitivity. As asserted in [11], this metric is one of the main indicators of the "quality" of RFID tags since it strictly depends on the tag antenna gain, on the chip sensitivity, and on the goodness of the chip-antenna conjugate impedance matching (transmission coefficient). Obtained sensitivity results in the European band are summarized in Fig. 5. The red line is referred to the tag on-air, whilst the blue line in referred to the case of tag applied on human tissue. An average performance improvement of about 10 dB is quite evident when the tag is applied on the artificial tissue, confirming the capability of the designed wearable antenna to work properly when applied on the human body.

The second test consists in evaluating the radiation pattern of the tag antenna. During this measurement, the tag performs a 360° rotation around its central axis (thanks to a specific functionality of the platform that controls a stepper motor) by changing its mutual position with respect to the platform antenna. In such a way the radiation behavior of the tag can be analyzed when varying the interrogation angle and, consequently, the antenna radiation pattern can be computed. In Fig. 6, for instance, the measured radiation patterns in the H-plane can be appreciated for both the analyzed working conditions. As expected, the test on air produces an almost omnidirectional radiation pattern, because of the relatively reduced metallic backplane. The presence of the human body causes two effects. The former is the performance improvement, as highlighted in Fig. 5. The latter is the reduction of the back-lobe and consequently a more directive radiation pattern.

The third test is devoted to the evaluation of the capability of the tag to retrieve the body temperature. The tag has been dressed as shown in Fig. 4c and kept at a distance of

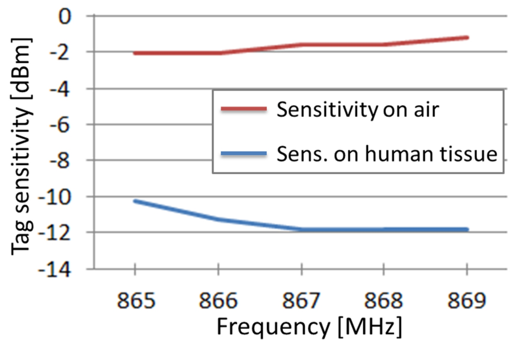

Figure 5. Measured tag Sensitivity of the wearable 3D-printed sensor tag

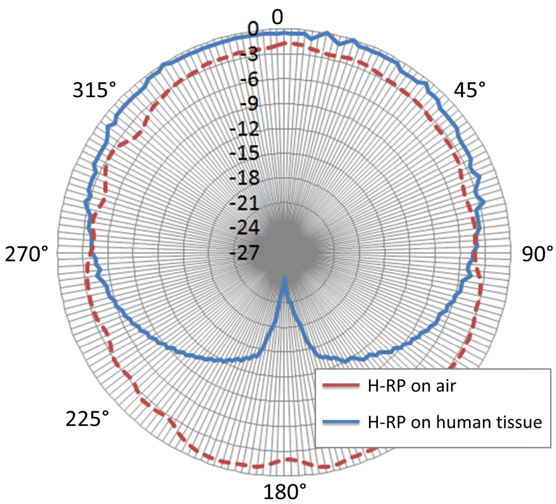

Figure 6. Measured Radiation pattern of the wearable 3D-printed sensor tag: on air a); on human tissue b).

1.5 m from the antenna (gain 5.6 dBi) of a CAEN "Ion" RFID reader configured to get the tag temperature. During this test the temperature has been correctly read several times with and accuracy of 0.25 °C.

Finally, a last test aiming at evaluating the maximum reading range of the sensor tag has been performed by dressing the tag and by gradually increasing the distance between the CAEN reader antenna and the tag. A maximum working distance of about 4.30 m has been revealed with an output reader power of 30 dBm. It is important to observe that when the tag is configured to retrieve also the measured temperature, the reading range is reduced to 3.10 m, due to the portion of the harvested power used to control the sensor. Moreover the working range for reading the sole identification code collapses down to 1.8 m when the same test is performed with the tag on air, according to the previously obtained results.

5. Conclusions

In this work a fully-passive wearable UHF RFID sensor tag with temperature sensing capabilities based on a 3D-printed antenna working in the European RFID band has been designed, realized, and tested. Leveraging on the peculiarities of the 3D-printing technology, all the dielectric parts of the designed antenna have been customized in terms of shape, thickness, and composition in order to optimize the its performance when applied on the human body. At this regard, simulations and measurements have been executed considered an artificial model of the human tissue having its average dielectric characteristics. The realized sensor tag exhibits a very good performance in terms of antenna radiation efficiency, tag sensitivity, and working rage, also when measuring the body temperature in a passive way, demonstrating the effectiveness of the 3D-printing technology in the framework of wearable RFID devices.

7. References

1. G. A. Casula, A. Michel, G. Montisci, P. Nepa and G. Valente, "Energy-Based Considerations for Ungrounded Wearable UHF Antenna Design," in *IEEE Sensors Journal*, vol. 17, no. 3, pp. 687-694, Feb.1, 1 2017.

2. C. Occhiuzzi, S. Cippitelli, and G. Marrocco, "Modeling, design and experimentation of wearable RFID sensor tag", IEEE Trans. Antennas Propagation, 58(8), pp. 2490–2498, 2010.

3. Makinen, T. Kellomaki, "Body effects on thin single-layer slot, self-complementary, and wire antennas," *IEEE Tranactionson Antennas and Propagation*, vol. 82, no. 1, pp. 385-392, Jan. 2014.

4. S. Jun, B. Sanz-Izquierdo, E.A. Parker, "3d Printing Technique for the Development of Non-Planar Electromagnetic Bandgap Structures for Antenna Applications," *Electronics Letters*, 2016, 52, pp. 175-180.

5. S.S. Patel, I.J.G Zuazola, and W.G. Whittow, "Antenna with Three Dimensional 3d Printed Substrates," *Microwave and Optical Technology Letters*, 58, (4), pp. 741-744, 2016.

6. Q. Liu, T.R. Le, S.L. He, and M.M. Tentzeris, "Button-shaped radio-frequency identification tag combining three-dimensional and inkjet printing technologies," *IET Microwaves Antennas & Propagation*, vol. 10, pp. 737-741, 2016.

7. S. Preradovic, "Printed 3D Stacked Chipless RFID Tag with Spectral and Polarization Encoding," *Microwave Journal*, v. 59, pp. 122-132, 2016.

8. L. Catarinucci, R. Colella, and L. Tarricone, "Smart Prototyping Techniques for UHF RFID Tags: Electromagnetic Characterization and Comparison with Traditional Approaches," *Progress in Electromagnetics Research*, vol. 132, pp. 91-111, 2012.

9. L. Catarinucci, R. Colella, P. Coppola and L. Tarricone, "Microwave characterisation of polylactic acid for 3D-printed dielectrically controlled substrates," in *IET Microwaves, Antennas & Propagation*, vol. 11, no. 14, pp. 1970-1976, 11 19 2017.

10. N. M. Faudzi, M. T. Ali, I. Ismail, *et al.*"Compact microstrip patch UHF-RFID tag antenna for metal object," *2014 IEEE Symposium on Wireless Technology and Applications* Kota Kinabalu, 2014, pp. 160-164.

11. R. Colella, L. Catarinucci, P. Coppola, and L. Tarricone, "Measurement Platform for Electromagnetic Characterization and Performance Evaluation of UHF RFID Tags," *IEEE Transactions on Instrumentation and Measurement*, vol. 65, pp. 905-914, 2016.