Design, fabrication, and wireless evaluation of a passive 3D-printed moisture sensor on a textile substrate

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Abstract—This paper introduces the first steps of fabrication and the initial wireless performance evaluation of a passive ultra-high frequency (UHF) radiofrequency identification (RFID)-based moisture sensor on a textile substrate. The sensor antenna was embroidered on a stretchable fabric firstly, and then embedded inside a 3D-printed platform. This 3D-printed sensor material changes its properties permanently, after exposure to a high moisture environment. Thus, the sensor can detect the increased moisture in the environment. Based on our initial results, this information can be clearly read from the changed backscattered signal of the embedded passive RFID tag. The fabricated sensor has an initial peak read range of 6 meters. After being dipped into water for 2 hours, the read range of the sensor has a significant decrease, but it is still readable from 5 meters. Thus, this moisture sensor can be read wirelessly from a convenient distance, when considering practical use of moisture sensors.

Keywords—Antennas; 3D printing; moisture sensor; embroidery; passive UHF RFID.

1. INTRODUCTION

Wireless sensors have rapidly become an integral part of our everyday lives. Whether they are monitoring health information through human's skin [1]-[3], detecting noxious gases in underground mines [4]-[6], or sensing the temperature levels of the environment [7]. Recently, especially wireless, battery-less, and thus maintenance-free passive radio-frequency-identification (RFID) sensors have attracted a growing interest [8]-[11].

In this publication, we present the first steps of our study towards design, development, manufacturing, and wireless evaluation of a passive ultra-high frequency (UHF) RFID-based moisture sensor. The 3D-printed sensor material on the textile substrate will change its shape permanently, after exposure to a high moisture environment. This will affect the functioning parameters of the RFID tag, and thus provides self-sensing properties based on the wireless read-out of the sensor platform. As the change is permanent, this simple and cost-effective sensor has countless applications. It could be used for example for detecting possible wetting of an item during logistics or detecting if a frozen food chain has been broken during the transportation. In this situation, when the item gets wet or when the ice melts, it will change the properties of the moisture sensor permanently, which can be easily detected by an RFID reader at the end of the supply chain.

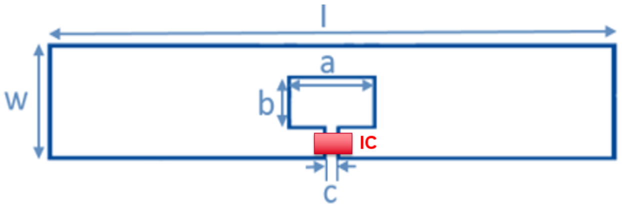
2. MANUFACTURING OF MOISTURE SENSORS

The passive UHF RFID tag antenna was fabricated on a stretchable elastic band. Firstly, this elastic band was stretched and fixed to 130 % of its original length. Next, the tag antenna was embroidered on the fabric using multifilament silver plated thread (Shieldex multifilament thread 110f34 dtex 2-ply HC). The tag was equipped with an integrated circuit (NXP UCODE G2iL series RFID microchip), which was attached to the antenna with conductive epoxy glue. The antenna geometry and dimensions are shown in Fig. 1.

Then, one 1.5 mm thick layer of Poro-lay gel-lay Porous Filament was 3D-printed on top of the RFID tag. The used printing parameters are shown in Table 1. The used material is made from a rubber-elastomeric polymer and a polyvinyl alcohol (PVA)-component. When in water, the PVA component disappears and the rubber polymer remains. After manufacturing, the sensor tag was dipped into water for 2 hours, until the PVA component of the 3D-printed structure totally dissolved. Then, the 3D-printed structure became soft and the tag became curvy, as shown in Fig. 2. When the sensor structure was dry again, it permanently held the curvy shape.

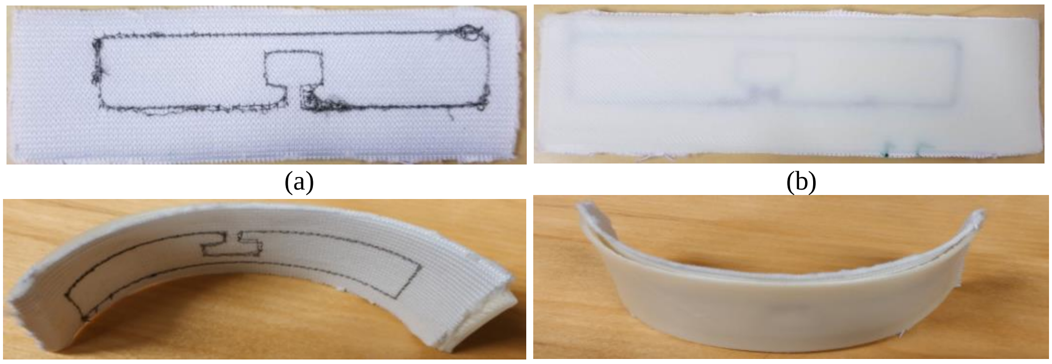
Table 1. The used printing parameters.

3D printing parameters	
Printing head temperature	220 °C
Plate temperature	50 °C
Infill percentage	80 %
thickness	1.5 mm



a (mm)	b (mm)	c (mm)	L (mm)	W (mm)
14.3	8.125	2	100	20

Fig. 1. The antenna geometry and dimensions.



(a) (b)

(b) (d)

Fig. 2. The manufactured sensor tag: (a) the antenna side before curving; (b) the 3D-printed structure side before curving; (c) the antenna side after curving; (b) the 3D-printed structure side after curving.

3. WIRELESS PERFORMANCE

The moisture sensors were measured in an anechoic chamber, using a measurement system containing an RFID reader unit with a capability to a power-frequency sweeps. All the measurements were conducted with the tag suspended on a foam fixture in the anechoic chamber. The sensors were measured initially and when they were dry again (after 2 hours in water).

The theoretical read range describes the maximal distance between the tag and reader antenna in free space, i.e., environment without reflections or external disturbances. The measurement equipment calculates the theoretical read range of the tag using its measured threshold power along with the measured forward losses. The forward loss, from the transmit port to the tag, is first calculated using a reference tag. The theoretical read range was calculated assuming that the read range was limited by the maximum allowed transmitted power levels and can be therefore calculated using Equation 1:

$$d_{Tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{P_{TS}L_{fwd}}} \qquad (1)$$

where λ is the wavelength transmitted from the reader antenna, EIRP is the maximum equivalent isotropically radiated power allowed by local regulations, P_{TS} and L_{fwd} are the measured threshold power and forward losses, respectively. We present all the results corresponding to EIRP = 3.28 W, which is the emission limit in European countries.

The backscattered signal power is utilized to monitor the wireless performance of these sensors in this study. In an anechoic space, the backscattered power at the reader antenna at distance d from the tags is given by Equation 2:

$$P_{rx} = P_{tx}{G_{tag}}^2{G_{reader}}^2\left(\frac{\lambda}{4\pi d}\right)^4 \alpha|\rho_1 - \rho_1|^2 \qquad (2)$$

where P_{tx} is the transmitted power from the reader, G_{tag} is the gain of the tag antenna, G_{reader} is the gain of the reader (transmit/receive) antenna, λ is wavelength, d is distance from the tag, ρ_1 and ρ_2 are the power wave reflection coefficients of the tag in two different chip impedance states (used for modulating the backscattered signal) and α is a coefficient that depends on the specific modulation details.

The backscattered power measurements, which are shown in Fig. 3, show a significant decrease after curving of the sensor. Based on these initial measurement results, the wireless performance of this moisture sensor will permanently change in a high moisture environment. The read range results, based on the measured backscattered signals from the tags, can be seen in Fig. 4. Based on the results, the initial peak read ranges of the tag, measured from both sides, were 6 meters. After dipped into water for 2 hours, the antenna became permanently curvy and the peak read ranges of the tags decreased to 5 meters. These read ranges are definitely suitable for many practical moisture sensor applications. Further, this sensor shows similar performance from both directions, which is promising for future development.

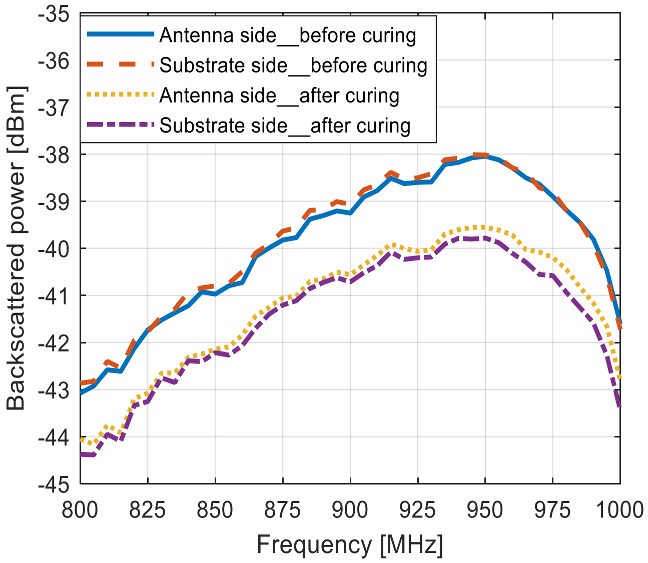


Fig. 3. The backscattered powers of the fabricated tags.

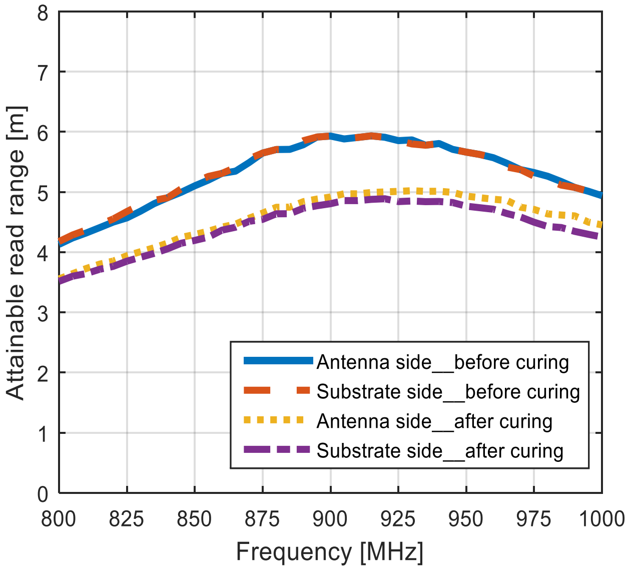


Fig. 4. The attainable read ranges of the fabricated tags.

4. CONCLUSIONS

In this study, we presented the first results of a new type of passive UHF RFID-based moisture sensor. This promising sensor platform has several advantages. Firstly, the utilized conductive yarn, textile fabric, and 3D printing filament are cost-effective materials. Further, the sensor is easy to fabricate because of the simple dipole antenna and the simple 3D-printed pattern. Due to the passive RFID-based functionality, the sensor itself does not need any energy source to function autonomously. This low-energy moisture sensor has versatile applications in moisture critical environments, for example during transportation. As it is fully passive, it can be permanently embedded into different types of structures. By modifying the 3D-printing parameters, for example the infill percentage and layer thickness, the PVA rinsing and thus antenna curving time can be modified accordingly, which means the sensor can be optimized for different environments and applications. The next steps of our work are to optimize the antenna design, study the effects of different manufacturing parameters on the sensor performance, and do detailed sensor measurements in different types of environments (temperature and humidity levels).

ACKNOWLEDGEMENTS

This research work was funded by The Academy of Finland and Jane and Aatos Erkko Foundation.

REFERENCES

1. X. Yi, T. Wu, Y. Wang, R. T. Leon, M. M. Tentzeris, and G. Lantz, “Passive wireless smart-skin sensor using RFID-based folded patch antennas,” International Journal of Smart and Nano Materials, vol. 2, no. 1, pp. 22–38, Jan. 2011.
2. B. Cook, A. Shamim, and M. Tentzeris, “Passive low-cost inkjet-printed smart skin sensor for structural health monitoring,” IET Microwaves, Antennas & Propagation, vol. 6, no. 14, pp. 1536–1541, Nov. 2012.
3. T. T. Thai, H. Aubert, P. Pons, M. M. Tentzeris, and R. Plana, “Design of a highly sensitive wireless passive RF strain transducer,” in Proceedings of 2011 IEEE MTT-S International Microwave Symposium, Baltimore, MD, USA, pp. 1–4, 5th-10th, June, 2011.
4. R. A. Potyrailo, and C. Surman, “A passive radio-frequency identification (RFID) gas sensor with self-correction against fluctuations of ambient temperature”. Sensors and Actuators B: Chemical, Vol. 185, pp. 587-593, 2013.
5. L. Yang, R. Zhang, D. Staiculescu, C. Wong, and M. M. Tentzeris, “A novel conformal RFID-enabled module utilizing inkjet-printed antennas and carbon nanotubes for gas-detection applications,” IEEE Antennas and Wireless Propagation Letters, vol. 8, pp. 653–656, Jul. 2009.
6. T. Le, V. Lakafosis, S. Kim, B. Cook, M. M. Tentzeris, Z. Lin, and C. P. Wong, “A novel graphene-based inkjet-printed WISP-enabled wireless gas sensor,” in Proceedings of 42nd European Microwave Conference, Amsterdam, Netherlands, pp. 412–415, 29th Octorber-1st November, 2012.
7. S. Bouaziz, F. Chebila, A. Traille, P. Pons, H. Aubert, and M. M. Tentzeris, “Novel microfluidic structures for wireless passive temperature telemetry medical systems using radar interrogation techniques in Ka-band,” IEEE Antennas and Wireless Propagation Letters, vol. 11, pp. 1706–1709, Feb. 2013.
8. T. Leng, X. Huang, K. H. Chang, J. Chen, M. A. Abdalla, and Z. Hu, “Graphene nanoflakes printed flexible meandered-line dipole antenna on paper substrate for low-cost RFID and sensing applications,” IEEE Antennas and Wireless Propagation Letters, Vol. 15, pp. 1565-1568, 2016.
9. Y. Feng, L. Xie, Q. Chen, and L. R. Zheng, “Low-cost printed chipless RFID humidity sensor tag for intelligent packaging,” IEEE Sensors Journal, Vol. 15, pp. 3201-3208, 2015.
10. D. Shuaib, L. Ukkonen, J. Virkki, and S. Merilampi, “The possibilities of embroidered passive UHF RFID textile tags as wearable moisture sensors,” in Proceedings of IEEE 5th International Conference on Serious Games and Applications for Health (SeGAH), Perth, WA, Australia, pp. 1-5, 2nd-4th, April, 2017.
11. S. Merilampi, T. Björninen, L. Ukkonen, P. Ruuskanen, and L. Sydänheimo, “Embedded wireless strain sensors based on printed RFID tag,” Sensor Review, Vol. 31, pp. 32-40, 2011.