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The effects of recurrent stretching on the performance of electro-textile and screen-printed ultra-high-frequency radio-frequency identification tags

Johanna Virkki[1], Toni Björninen[1], Sari Merilampi[2], Lauri Sydänheimo[1] and Leena Ukkonen[1]

Abstract

Future welfare and healthcare applications require wearable radio-frequency identification (RFID) tags where the tag antenna is an integral part of clothing and endures repeated stretching. In this study, wearable passive ultra-high-frequency (UHF) RFID tag antennas were fabricated from silver-plated stretchable fabric and by screen printing them on non-conductive, stretchable fabric. The reliability of the tags was studied by stretching them repeatedly from the initial length of 10 cm to 13.5 cm, up to 200 stretching cycles. According to our results, the electro-textile tags achieved read ranges of 6.5 meters, also after the 200 harsh stretches. The screen-printed tags initially achieved read ranges of 9.5 meters and after the 200 stretches the read ranges were only 2.5 meters shorter, that is, still about 7 meters. These measurement results and the strengths and weaknesses of both types of wearable tags are discussed in this paper.

Keywords

textile antennas, wearable electronics, radio-frequency identification, reliability, stretching

The miniaturization of electronics and sensors and the development of versatile wireless systems is generating an explosive growth in the applications of wearable electronics.[1,2] Recently, many innovative products have appeared and expectations of the potential of wearable electronics are high. For example, wearable RFID (radio-frequency identification) tags have an enormous potential in future welfare and healthcare applications.[3] These applications require the tag antenna to be an integral part of clothing and to endure different environmental stresses, such as repeated washing and stretching.

In this study, we present two types of wearable UHF (ultra-high-frequency) RFID tags and test their ability to withstand continuous stretching. Type 1 tag antennas were manufactured from silver-plated stretchable fabric and Type 2 tag antennas were manufactured by screen printing polymer thick film (PTF) silver ink on stretchable, non-conductive fabric.

The work presented here is organized as follows: the second section 2 gives a short review of UHF RFID systems and introduces the development of wearable antennas and RFID tags. The third section briefly introduces our tag design and the used fabrication methods. The stretching tests and tag measurements are presented in the fourth section. The fifth section

[1]Department of Electronics and Communications Engineering, Tampere University of Technology, Finland
[2]Research and Competence Centre (Welfare Technology), Satakunta University of Applied Sciences, Finland

Corresponding author:
Johanna Virkki, Department of Electronics and Communications Engineering, Tampere University of Technology, P.O. Box 692, FI-33101 Tampere, Finland.
Email: johanna.virkki@tut.fi

presents the results and discussion and the sixth section summarizes the conclusions of this study.

Wearable antennas and radio-frequency identification tags

RFID technology provides the automatic identification and tracking of items. This is achieved by labeling them with battery-free remotely addressable electronic tags composed of an antenna and an integrated circuit (IC). The use of propagating electromagnetic waves at UHF frequencies for powering and communicating with the passive tags enables rapid interrogation of a large quantity of tags through various media from the distances of several meters. In comparison to bar-codes, RFID tags allow the data stored in them to be updated wirelessly at any time. These are the main advantages that initially sparked the interest in passive UHF RFID systems.

For more information on RFID technology, we refer firstly to two landmark papers[4,5] presenting early investigations. A survey of the history of RFID is presented by Landt[6] and Nikitin[7] and a comprehensive introduction to today's systems and standardization is provided by Want,[8] Dobkin,[9] International Organization for Standardization[10] and EPCglobal.[11] Finally, a thorough discussion of the design of antennas for RFID tags can be found in Marrocco[12] and Perret et al.[13]

Thanks to the versatility of passive RFID technology, new applications are continually emerging. In particular, passive tags are promising candidates to provide wireless identification and cheap, unobtrusive and completely maintenance-free wireless platforms in body-centric sensing systems.[14–18] This development is building upon and extending the great amount of research on wearable textile antennas conducted during the past decade.[19–24] Here also the emergence and systematic high-frequency characterization of novel electro-textile materials and new manufacturing methods, such as embroidery and screen printing, have played a key role.[25–31] At the moment, embroidery and screen printing are perhaps the most actively studied methods of creating antennas for wearable passive UHF RFID tags,[14,17,32–34] while recently progress has also been made in inkjet-printed wearable antennas.[35,36] Still, the reliability of wearable antennas is another major issue to be addressed before the large-scale deployment of body-worn antennas and RFID tags.[37–42] Indeed, in virtually all applications, the body-worn devices will be continually exposed to various environmental stresses, such as stretching and washing. Finally, a design challenge shared by the body-worn antennas regardless of the material and fabrication method is the inherent electromagnetic antenna-body interaction.[3,14,15,17,23] Typically, the proximity of the dissipative body tissue limits the antenna efficiency and changes notably the antenna impedance and directivity compared to free space. However, through application-specific design, body-worn passive RFID tags can achieve read ranges of several meters. State of the art examples include folded microstrip patch tags[15,17] readable up to 3.5 and 5 meters when mounted on the human chest and on a laboratory human phantom, respectively.

Today, passive UHF RFID tags are used in the access control domain in hospitals to alert if, for instance, a patient with a memory disorder wanders out of the supported living area. Equipped with wearable RFID tags, such tracking systems would also be useful in homes for the elderly and other personal care institutions, such as nursing homes and kindergartens.[43–47] Instead of just tracking people, RFID tags offer versatile possibilities, as RFID tags can, for example, be used in systems where the tag is responsible for the communications link from the user to the reader, while the actual data is provided by external sensors. The use of wearable electronics with sensors allows the body status to be monitored by devices that measure heart or brain activity, blood pressure, body temperature or other bodily functions.[1–3,14–17]

Tag design and the fabrication methods

In this study, wearable passive UHF RFID tags equipped with two different types of antennas were fabricated and tested. Type 1 tag antennas were manufactured from Less EMF Stretch Conductive Fabric (Cat. #321).[48] This is silver-plated stretchable fabric made of nylon (76%) and elastic fibers (24%), with a thickness of 0.40 mm and weight of 4.3 oz/yd^2. The commercial elastic fiber fabric used in Type 1 tags offers the unique ability to stretch in both directions, a temperature range from -30 to 90°C and low surface resistivity of less than 0.5 Ω/sq (unstretched). This fabric ban be easily cut with scissors and its texture is very similar to conventional fabrics. Thus, from the perspective of fabrication and user's comfort, this material was considered a promising candidate for wearable electronics.

Type 2 tags were manufactured by screen printing[14,30,31,38,39] PTF silver ink on stretchable, elastic band fabric substrate, following the procedure detailed by Kellomäki et al.[38] Compared with other printing methods, the advantages of screen printing, which was used to fabricate the antenna for the Type 2 tag, include the low cost of equipment and ability to deposit thick films and large areas in one pass. There is also no need for pretreatment of uneven substrates, such as fabrics. In screen printing, the ink is pressed through a screen (a fabric mesh of threads) onto the substrate with a squeegee. Non-image areas of the screen mesh are blocked out with a stencil, and in the image areas the screen is left open. In this study, flatbed screen printing was used in sample preparation. To provide a consistent and thick ink film of appropriate thickness, three cascade print cycles were performed. After printing, the samples were cured at 120°C for 15 minutes. The used ink was one-component silver ink consisting of polyester resin and silver particles. Silver content is 60–65 wt% and polyester resin content is 11–14 wt%. Particle sizes are mainly in the range from 3 to 15 μm.

For the purpose of this study, we chose the antennas to be T-matched dipoles.[12] This is a very common class of antennas used in RFID tags. Moreover, in the antenna design, we purposefully avoided narrow conductors that might increase the risk of a complete breakage of the electrical conductivity in a certain region in the antenna during the stretching.

In the simulation-based design with ANSYS HFSS v.15 (full-wave electromagnetic field solver based on the finite element method), we modeled the Type 1 antenna conductor using the measured sheet resistance value of 1.25 Ω/sq,[29] which accounts also for the presence of the dielectric textile material. The antenna length (L) and width (W) were chosen to be 20 mm and 100 mm, respectively, to create a rather wide conductor area with sufficient length to provide high radiation efficiency in the considered frequencies. After this, the design goal was to adapt the parameters a and b (Figure 1) so that the antenna impedance is conjugate-matched with the IC impedance at 940 MHz. This maximizes the power transfer efficiency from the antenna to the IC. This is crucial for efficient power harvesting. For Type 2 antennas, we did not have such a detailed conductor model available. However, based on Hertleer et al.,[37] we estimated the dielectric parameters of the substrate fabric to be $\varepsilon_r = 1.65$ and $\tan\delta = 0.02$ and based on the data from the ink manufacturer, we modeled the cured silver PTF ink layer with the electrical conductivity of 1.25 MS/m. This simulation predicted that the antenna geometry adapted for Type 1 tags would provide the same conjugate-matched frequency also for Type 2 tags. As discussed in the next section, measurements confirmed this prediction.

Microscope images of the electro-textile antenna surface and the screen-printed antenna surface can be seen in Figure 2. The tag IC is an NXP UCODE G2iL series IC with the wake-up power of −18 dBm (15.8 μW). The manufacturer had mounted the chip in a fixture

Geometrical parameters in millimeters

L	W	a	b	c
100	20	14.3	8.125	2

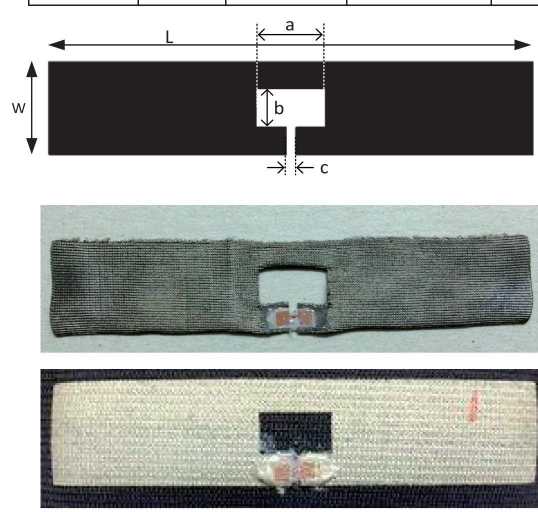

Figure 1. Antenna geometry and fabricated prototype tags.

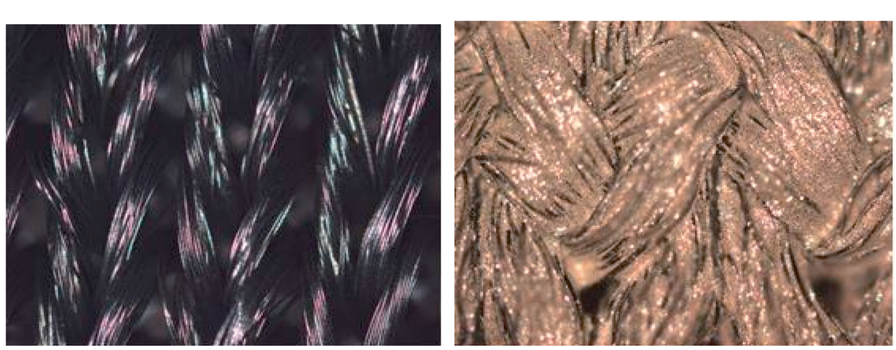

Figure 2. Microscope images of the electro-textile antenna (a) and screen-printed antenna (b), magnification x5.

patterned from copper on a plastic film. We attached the 3 × 3 mm^2 pads of the fixture to the electro-textile material using conductive epoxy. After curing of the electrical antenna–IC joint, we rigidified the textile around the IC using normal textile glue. This provides further support and protection to the tag IC.

Stretching tests and tag measurements

The reliability of the tags was studied by stretching them repeatedly from the initial length of 10 cm to 13.5 cm. The tags were stretched 10, 20, 30, 40, 50, 100, 150 and 200 times and measured after each stretching test, using the Voyantic Tagformance RFID measurement system.[49] As in this work, the main focus was to evaluate the influence of recurrent stretching on the textile material; we conducted all the measurement with the tag suspended on a foam fixture ($\varepsilon_r \approx 1$) in an anechoic chamber. In this way, the measurement is highly repeatable and the stretching will be the only factor affecting the measurement outcome.

The measurement system was used to measure the key properties of passive UHF RFID tags: threshold power and theoretical read range in the 800–1000 MHz frequency range. Threshold power is the minimum output power of the reader, to activate the tag. Theoretical read range describes the maximal distance between the tag and reader antenna in free space, that is, environment without reflections or external disturbances; hence the term theoretical read range.

Firstly, we characterized the wireless measurement channel in terms of the measured power loss factor (L_{iso}) from the generator's output port to the input port of an equivalent polarization-matched isotropic antenna placed at a reference location. We computed L_{iso} as

$$L_{iso} = \frac{\Lambda}{P_{th*}} \tag{1}$$

where Λ is a constant provided by the system manufacturer to describe the sensitivity of the reference tag at each frequency and P_{th*} is the measured threshold power of the reference tag in polarization-matched configuration. Using this information, we obtained the power density generated at the reference location at with an arbitrary output power (P_{tx}) of the reader:

$$S_{inc} = \frac{L_{iso} P_{tx}}{\lambda^2/4\pi} = \frac{4\pi\Lambda}{\lambda^2 P_{th*}} P_{tx} \tag{2}$$

Here λ is the free-space wavelength at the frequency of the transmission. During the threshold measurement of the tag under test, Equation (2) gives the threshold power density $S_{inc,th}$ corresponding to $P_{tx} = P_{th}$. In this formulation, P_{th} implicitly includes the possible polarization mismatch power loss. However, in the measurement, we used a linearly polarized transmit-antenna aligned for polarization matching with the measured dipole tags.

On the other hand, in free space conditions, at the critical transmit-antenna–tag separation: $d = d_{tag}$, and the power delivered to the tag IC equals the wake-up power of the chip. Correspondingly, the incident power density is equal to the threshold power density. Thus:

$$\frac{EIRP}{4\pi d_{tag}^2} = \frac{4\pi\Lambda}{\lambda^2 P_{th*}} P_{th} = S_{inc,th} \tag{3}$$

where $EIRP$ is the regionally regulated equivalent isotropically radiated power. This implies

$$d_{tag}(P_{th}, P_{th*}) = \sqrt{\frac{EIRP}{4\pi\, S_{inc,th}}} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{\Lambda}\frac{P_{th*}}{P_{th}}} \tag{4}$$

which is a fully measurement-based estimate of the theoretical read range of the tag. In practice, the properties of the transmit-antenna–tag wireless channel vary from site to site. Thus, in order to provide a universal characterization, we chose to evaluate the tags in terms of the theoretical read range. All the measurement results presented below were obtained following the UHF RFID systems emission regulation in Europe with $EIRP = 3.28$ W.[11]

Results and discussion

The measurement results (read ranges in air) of the electro-textile and screen-printed tags are shown in Figures 3 and 4, respectively.

According to our results, the electro-textile UHF RFID tags achieved peak read ranges of almost 7 meters at the frequency range of 920–940 MHz. The shielding of the tag IC with the textile glue had a negative effect on the read range of the tag. However, we found that stretching had a reverse impact: after 10 stretches the read range had improved almost back to the starting level. With more stretches, the read range still continued to improve, and after 200 stretches it was slightly above the initial value, measured before applying the textile glue. This improvement of the read range can be explained by the characteristics of the fabric and the permanent elongation of the tag antenna (after 200 stretches, the antenna had become 5 mm longer).

The screen-printed UHF RFID tags achieved peak ranges of 9.5 meters at a frequency of 930 MHz. In case of the screen-printed tags, the shielding of the tag IC with the textile glue had a positive effect on the read range of the tag. One reason for the positive effect may

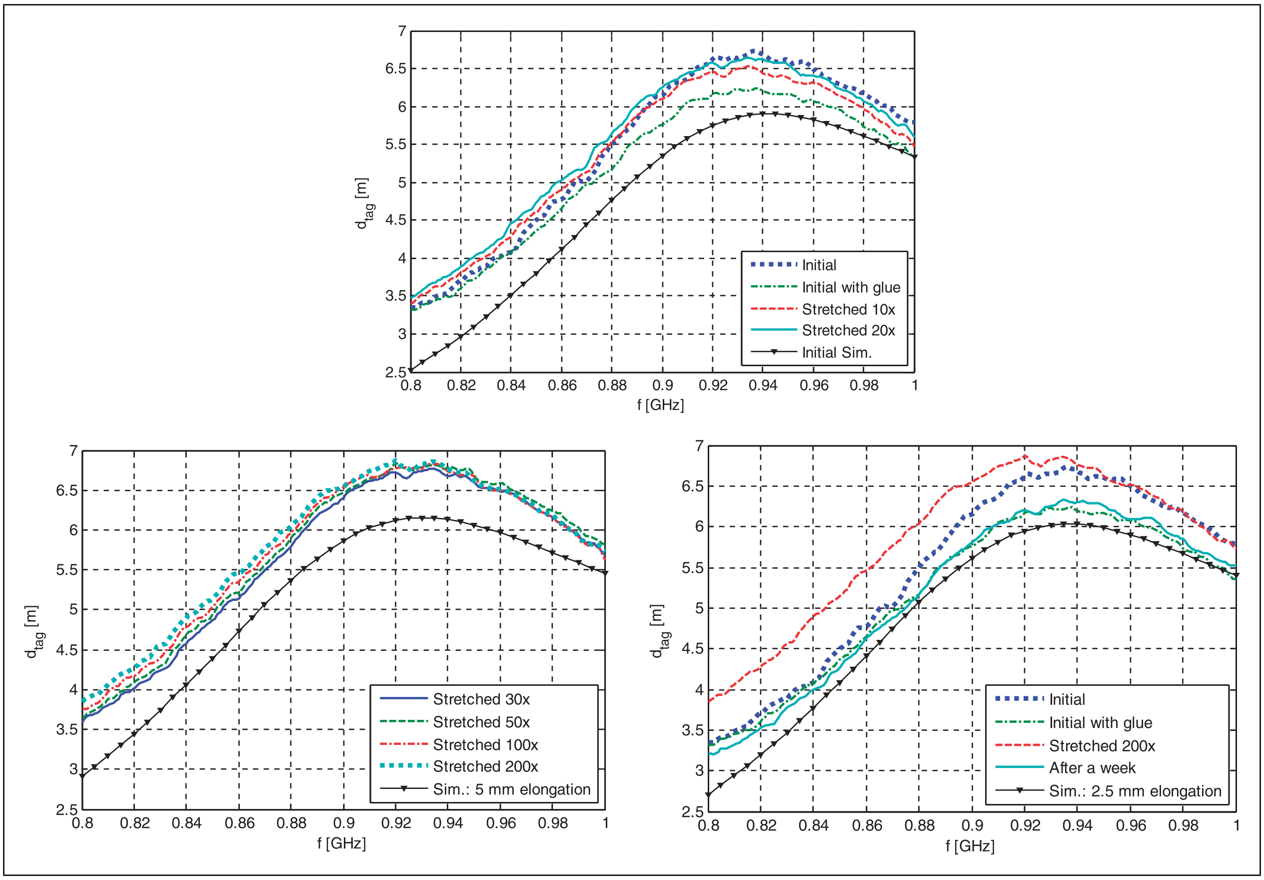

Figure 3. Measurement results for the electro-textile tags.

be the fact that the glue makes the ink film denser by gluing the threads more tightly against each other, which has a positive effect on the effective conductivity of the tag. The glue is put on the high current density region of the antenna and by reducing the ink film losses the read range will be positively affected. However, more research is required to confirm this.

The read range of the tag shortened already after 10 stretches and this negative trend continued when more stretching was done. After 200 stretches, the tags achieved a peak read range of about 7 meters at a frequency of 910 MHz. Stretching also had an effect on the optimum frequency range of the tag; it seems that stretching caused the tag antenna to operate at slightly lower frequencies. This is attributed to the changes in the ink film: the ink is not only absorbed into the fabric fibers, but also into the fabric structure.

Figure 5 presents a cross-section of ink printed on fabric, during 50% stretching, showing cracks that stretching of the fabric causes. The cracks occur due to the structural change of the fabric rather than the microstructural changes of the ink film. The ink film does not stretch but when the fabric is strained, the crossing threads separate from each other, as does the ink on the threads, which can be seen in Figure 5. The pictures on the lower left corner are taken from above the sample antenna and they illustrate the behavior of the fabric. The magnification shows that no microstructural changes in the ink film occur during straining.

This means that before stretching the tag for the first time, the ink film was continuous. When the first stretches were applied, the ink film cracked and formed a web-like structure, where the ink film is only continuous on the threads. This structure is still electrically conductive, but due to the macro cracks, the ohmic loss increased dramatically. However, the material recovered well from stretching and no plastic deformation was found. Because the substrate material settles well, the treads with the ink film will be almost at their original places after the recovery. This is why the conductivity also recovers. However, after multiple stretches, the ink film will be defected by the increasing number of cracks and the aggregate displacement of the threads occurring after the recovery. This leads to increased ohmic loss and mistuning of the antenna impedance, leading to reduction and frequency shift in the peak read range of the tag. Since no permanent elongation was observed in the screen-printed tags,

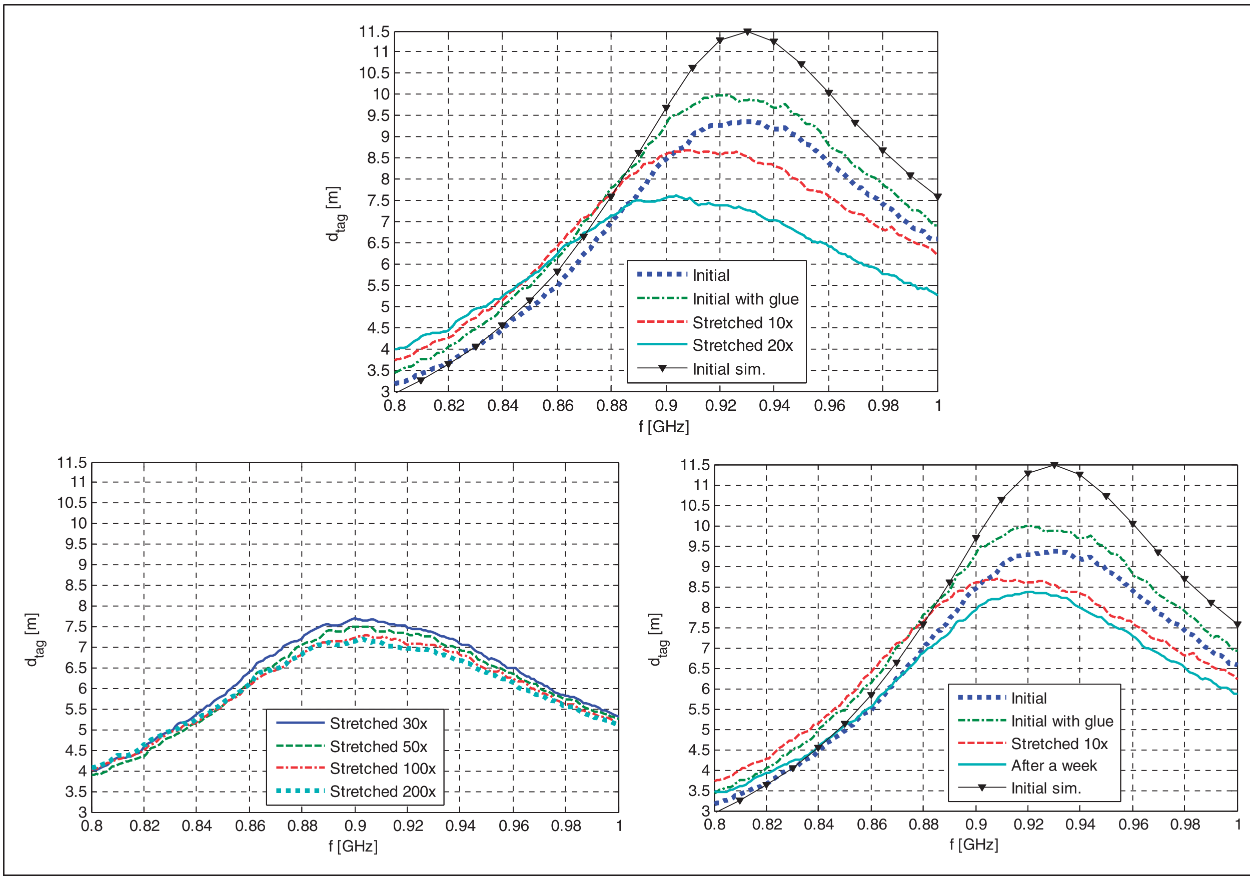

Figure 4. Measurement results for the screen-printed tags.

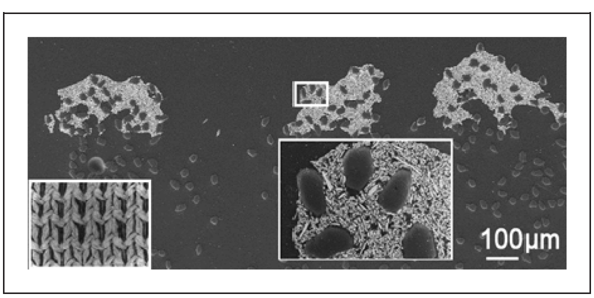

Figure 5. Screen-printed tag antenna during stretching.[31]

we concluded that the impact of the cyclic stretching on the tag performance was caused solely by the changes in the ink film structure.[31]

Because no elongation is seen, no positive impact on the read range is found in the case of the screen-printed tags. However, it is seen from the results that the difference between the tag after 10 and 20 cycles is more severe than, for example, the difference between 100 and 200 cycles. This indicates that after continuous cyclic stretching, the ink film will no longer be as much affected, because the ink film cracks and thread displacement have already occurred during the first tens of stretches.

According to our results, both types of RFID tags are can be used in many real-life wearable RFID applications where constant stretching may occur. Both types of stretchable tags have their strengths and weaknesses, which are an important topic in our future research. The electro-textile tag is likely more robust against mechanical stress as it maintains its performance well. However, the electro-textile tag needs a mechanism to integrate it into clothing. Therefore, the stretching properties of the clothing or the attachment material should be similar to the electro-textile. Screen printing can be performed directly on different textiles, but the substrate affects the tag performance and stretching properties. The screen-printed tag of this study will only stretch in one direction, whereas the electro-textile will stretch in any direction. The electro-textile is then comfortable to use but may be severely affected by the distorted tag dimension. Many of these challenges may be solved by selecting the right place in clothing. By further material development, the ink could be modified to be more absorbed into the textile. This might bring the performance closer to the electro-textile. In addition, there are already many different ink solutions commercially available to test.

Another practical issue is that while the tags are part of clothing, circularly polarized reader antenna would be more suitable to achieve independency from the tag position. This will cause a polarization loss to occur and slightly shorten the read range. The presence of the human body will also have an appreciable impact on the tag antenna. These aspects need to be accordingly accounted for in the design of wearable tags. However, the focus of this paper was in comparing and analyzing the different stretchable tags after cyclic stretching.

Conclusions

We studied the impact of recurrent stretching on the performance of electro-textile and screen-printed UHF RFID tags. According to our results, both the electro-textile and the screen-printed UHF RFID tags showed read ranges of more than 6 meters after 200 harsh stretches. This performance is without a doubt sufficient for many practical applications, where the tags may experience recurrent stretching. The insight from the analysis of the microstructure of these novel conductive textiles helps in selecting the most suitable material for a specific application. The future research will focus on further reliability testing of wearable tags in washing cycles and in different temperature and humidity conditions. Stretchable electro-textiles will also be used in wearable strain sensors.

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