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Evaluation of Polypyrrole-Coated Conductive Yarn for eTextile Applications - Embroidered RFID Antennas

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Abstract—**This paper presents a comparison of Polypyrrole (PPy)-coated conductive yarn and traditional silver-based conductive yarn in terms of electrical and mechanical properties. Next, the paper describes fabrication and measurement of passive ultrahigh frequency (UHF) radiofrequency identification (RFID) tag antennas fabricated from the two conductive yarns. The resistance of the PPy yarn was measured to be 0.3 MΩ/m, which is significantly higher than the resistance of the silver-based yarn (500 Ω/m). The tenacity of the PPy-based yarn was measured to be 42.7 cN/tex, which is more than twice that of the silver-based yarn (20.5 cN/tex). The peak read ranges achieved by the PPy-based RFID tags were around 1.5 meters in European and US center frequencies, while the peak read ranges of the silver-based tags were slightly below 4 and 5 meters at the European and US frequencies, respectively. Despite the PPy's shorter read ranges, the results are promising, as they indicate high potential of PPy-based yarns especially in mechanically demanding eTextile applications. As PPy yarn has a significantly lower environmental footprint compared to the silver-based yarn, the possibilities should definitely be studied further in the eTextile field.**

Keywords—biocompatible electronics, embroidery, eTextiles, passive UHF RFID, Polypyrrole, wearable electronics

I. Introduction

Electronic textiles (eTextiles) are a class of textiles that involve the integration of nested electronic components into the structure or can themselves be formed from electronically active materials [1]. The concept of developing conductive fibers capable of forming yarns has been extensively explored in existing research. For instance, silver and copper have been used to spin with cotton yarns or utilized to coat nylon and cotton yarns with different densities [2]. Additionally, polyester and polyester/rubber compounds have been coated with silver [3]. The complex poly (3,4-ethylene dioxythiophene):polystyrene sulfonate (PEDOT:PSS) is a conductive polymer, which has been explored to create conductive yarns [4]. In contrast to metallic materials (e.g. silver and copper), polymeric materials, consisting mainly of carbon and hydrogen chains, are more flexible and lighter. Belonging to this family of materials is polypyrrole (PPy), the conductivity of which is due to conjugated double bonds that make electron propagation possible [5-8].

Due to its biocompatibility and good adhesion to cellulose-based substrates, PPy is often grafted onto fabrics or yarns to impart electrical and thermal properties [6], [9]. The final conductivity depends on the polymerization conditions, for instance temperature, monomer and catalyst concentration, and reaction time [10]. The easy reaction conditions and properties of PPy have thus made it possible to produce electrically conductive filaments by grafting this polymer onto the surface of commercially available Tencel yarns. These maintain similar properties to pristine yarn in terms of touch and processability, which is why they can be knitted, woven, or even embroidered like any other conventional yarn [11].

In this study, the electrical and mechanical properties of PPy-yarn were measured. Next, dipole antennas were fabricated for basic passive ultrahigh frequency (UHF) radiofrequency identification (RFID) tags to analyze and present the wireless capabilities of the PPy yarn when embroidered. The results were compared to those of a conventional silver-based conductive yarn.

II. Material & Methods

A. Material fabrication

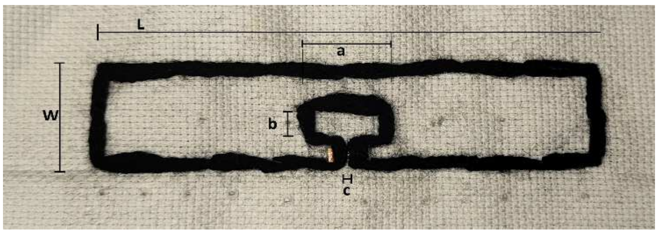
Pyrrole was purchased from Sigma-Aldrich and stored at 4 °C. Iron (III) chloride was purchased from Merck-Schuchardt and Tencel yarn from Toika. The amount of PPy used to coat the yarns was calculated based on the mass of the yarns. Initially the Tencel piece was soaked in deionized water (20 ml each 0.1 g of yarn) for 15 minutes. $FeCl_3$ is weighed according to the mass of the samples, as it must be 2.4 times the number of moles of monomer and added in the flask containing the yarn. The solution containing the yarn was then stirred for 30 minutes and cooled down to 0 °C using an ice bath. Meanwhile, 100 wt% of pyrrole in respect to the yarn was mixed in 10 ml of deionized water and cooled down too. Finally, the pyrrole dispersion was added drop by drop to the one containing the catalyst and the reaction was run for 7 hours. Afterwards, the PPy-grafted yarn was rinsed in deionized water three times to remove the impurities and then dried.

B. Mechanical and electrical comparison of the yarns

The tensile force is constrained by the tensile strength of the fibers, causing breaking of the yarn when the created tension goes beyond the fiber strengths. Tenacity is measured by calculating the force applied when the yarn is stretched to the breaking point [12]. In this study, the tenacity of the yarns was measured using a YG(B)021DX testing device. Three samples of 10 cm each were taken from both kinds of yarns and the average was calculated. Next, the yarn was stretched out on a plane and clipped at the ends about 2 inches high so that it was in tension. A multimeter (Wavetech Meterman LCR55) was connected to the ends and the resistance of the entire yarn was measured. The resistance of the silver-based yarn was taken from the yarn datasheet [13].

C. RFID tag creation

The wireless performance of an embroidered antenna is influenced by various factors, including the electrical characteristics of the conductive yarn, the structural design of the embroidery pattern, and the density of stitches and yarn within the pattern. This relationship has been explored in several studies [14-18]. The tag antenna under investigation (as depicted in Fig. 1) is a straight dipole antenna incorporating an inductive matching loop. This antenna design has been used in various studies [18-20], which makes it an excellent proof-of-concept design for this study.



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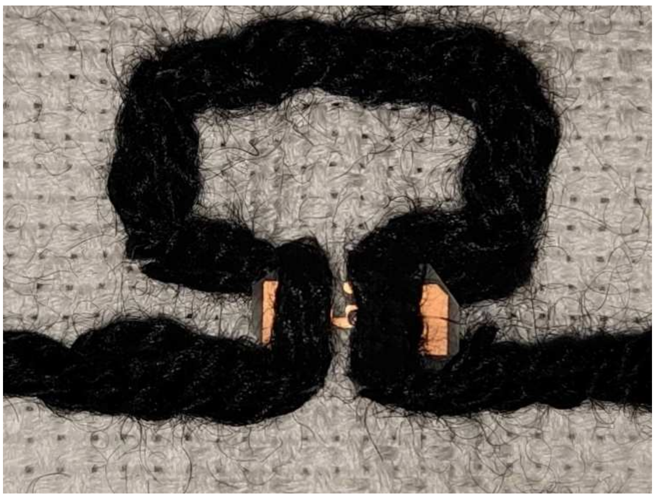

Fig. 1. The studied passive UHF RFID antenna fabricated using polypyrrole yarn and it's antenna geometry in millimeters (Top) and the close up of the connection between the antenna and the IC pads (Bottom).

Altogether two tag antenna samples (named PPy1 and PPy2) were stitched to Aida cloth, which is 100% cotton (open and evenly woven). Only the borderline, i.e., the contour of the antenna was embroidered. This provides the maximum amount of wireless performance using least amount of time and conductive yarn [20]. The contour was reinforced with a total of three rounds. For reference purposes, a commercially available silver plated yarn, specifically Shieldex multifilament yarn 110f34 dtex 2ply HC, was used to produce the same tag antenna. Due to lower resistivity, the silver-based antenna only had one round of thread.

NXP UCODE G2iL series RFID ICs were utilized. This RFID IC has a wake-up power of -18 dBm, equivalent to 15.8 µW. The manufacturer supplied the RFID IC in a fixture comprising copper traces patterned on a plastic film. The 3×3mm^2 pads of the fixture were affixed to the antenna by placing the fixture on the textile and sewing the antenna pattern on top of the IC copper pads making sure good interconnection (as presented in on Fig. 1), and no added adhesive materials were used.

D. Wireless evaluation of the tags

The tags underwent wireless testing in an anechoic chamber using Voyantic Tagformance measurement system, which comprises an RFID reader featuring adjustable transmission frequency and output power. The system facilitates the recording of the backscattered signal strength from the tag with a sensitivity down to -80 dBm. During testing, it records the threshold power of the tag at different frequencies (here: 850-950 MHz). The system then extrapolates this result to free-space conditions by using a system reference tag. Based on the measured threshold power of the tag under test, P_{th} and the threshold power of a system reference tag, P_{th*}, it computes the read range (d_{tag}) using the following relationship (as explained previously, e.g., in [19])

$$d_{tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{\Lambda}\frac{P_{th*}}{P_{th}}} \quad (1)$$

where, λ represents the wavelength transmitted from the reader antenna, Λ is a known constant describing the sensitivity of the system reference tag, and EIRP denotes the emission limit. In this context, we present all results corresponding to an EIRP value of 3.28W, which is the emission limit specified for European countries.

III. MEASUREMENT RESULTS & DISCUSSSION

A. Electrical and mechanical comparison

The results of the mechanical and electrical comparison of the studied conductive yarns are presented in Table I. The table presents the DC linear resistances and tenacities of the silver yarn and the Papy yarn. As can be seen, the resistance of the PPy yarn was measured to be 0.3 MΩ/m, which is significantly higher than the resistance of the silver-based yarn (500 Ω/m). The tenacity of the PPy-based yarn was measured to be 42.7 cN/tex, which is more than twice that of the silver-based yarn (20.5 cN/tex).

TABLE I. COMPARISON OF PPY-BASED AND SILVER-BASED YARNS

Yarn	DC Linear Resistance (Ω/m)	Tenacity (cN/tex)	Read range at 866 MHz	Read range at 915 MHz	Peak Frequency (MHz)
Silver	500	20.5	3.6	4.8	911
PPy 1	$0.3x10^6$	42.7	1.4	1.6	942
PPy 2			1.2	1.4	935

B. Wireless evaluation results

The peak read ranges of the fabricated RFID tags are presented in Table I at two specific frequencies: the central frequency for UHF RFID in Europe, which is 866 MHz, and the central frequency for UHF RFID in the United States (US), which is 915 MHz [21]. The peak read range was measured by taking three measurements from each antenna and selecting the best result for peak read range. The full read range results in a frequency range of 850-950 MHz for both types of tags can be seen in Fig. 2. The measurements were performed at 1 MHz interval and the data was taken from the measurement file and the performance is illustrated in Table I and Fig.2. The peak read ranges achieved by the PPy-based RFID tags were around 1.5 meters in both the European and the US center frequencies, while the peak read ranges of the silver-based tags were slightly below 4 and 5 meters at the European and the US center frequencies, respectively.

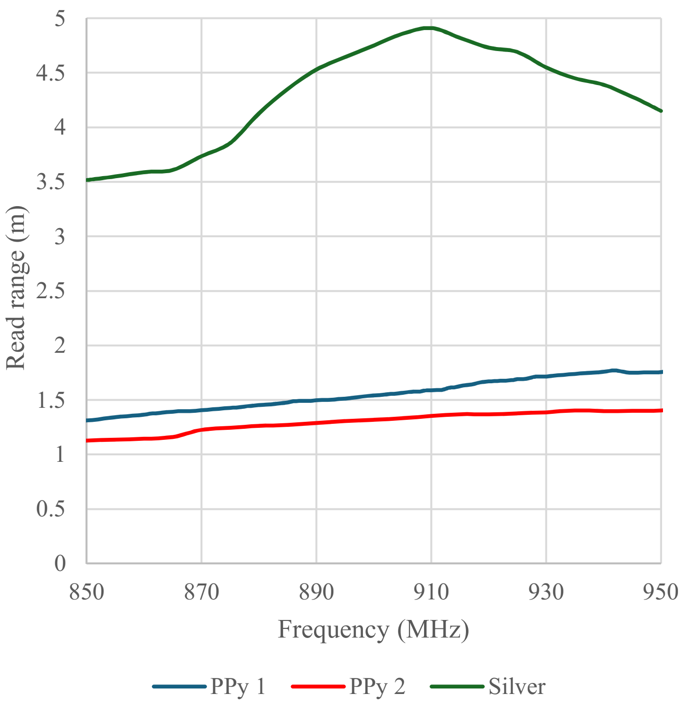

Fig. 2. Read ranges of PPy and silver tags at frequencies of 850 to 950 MHz.

C. Discussion

Observing Fig. 2, it is seen that the read ranges of PPy-based antennas show minor variations in read range, which are likely attributable to reproducibility challenges in embroidery stemming from the elasticity of textile and hand sewing imperfections. Also, the polymerization of pyrrole on a yarn in a stirred solution is inhomogeneous due to the vigorous stirring. This fact could also be a partial explanation for the difference in the read ranges of the two tags. Furthermore, it could be surmised that embroidery, which is less gentle than other techniques (e.g. knitting), may stress the coated yarn as it passes through the mesh of the fabric, slightly removing some of the PPy. However, the losses are not so significant as to drastically reduce the antenna's performance.

The difference in the read ranges of the tags fabricated using PPy conductive yarn and silver conductive yarn was more than 3 meters. The notable difference is due to the difference in conductivity between, the silver based conductive yarn being much superior in terms of conductivity. Still, the results suggest that the PPy yarns are a potential alternative. There are several factors why one may consider the PPy yarn more practical for certain applications. For example, the tenacity of the PPy-based yarn was measured to be more than twice that of the silver-based yarn. This means that the more lightweight and flexible PPy yarns are also able to withstand more tensile forces. This is a significant factor when it comes to embroidery machines as it is often observed that the silver yarn is not very practical due to breaking and tangling. Most importantly, the PPy yarn has a significantly lower environmental footprint compared to the silver yarns. Using PPy for coating yarns can certainly be seen as a valid and innovative option for creating flexible, durable, and high-performance devices. PPy is therefore a prodigious material that can replace the use of metals and expand the spectrum of applications and apparatuses, such as the wireless components presented in this work.

IV. CONCLUSION

This paper has presented preliminary results about fabrication and wireless evaluation of passive UHF RFID tag antennas using Polypyrrole-coated conductive yarn and compared those to a more conventional silver-plated conductive yarn. The results are promising as, despite the shorter read ranges, they indicate high potential of PPy yarns especially in mechanically demanding eTextile applications. The next step is to study improving the conductivity of the yarn. Further, making the yarn washable is an endeavor that could open even more application possibilities.

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