Design and Fabrication of Embroidered RFID Antennas for Wearable Applications

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***Abstract*— With advances in materials and fabrication methods, wireless communication devices are widely employed in Internet-of-Things (IOT) and human wearable applications. In this paper, we present a set of RFID labels using embroidered yarns that can be seamlessly integrated into clothing or textiles in fabrication processes. Detailed embroidery methods based on conductive yarns and textile substrates are proposed. The simulation and measurement results show that textile-based RFID antennas can provide stable electromagnetic performances and compete with the metallic counterparts.**

***Keywords:* Embroidery, RFID, nonwoven, conductive yarns, wearables.**

I. INTRODUCTION

Passive ultra-high frequency (UHF) radio frequency identification (RFID) technologies are widely employed in logistics applications as well as wireless body area networks (WBAN) for healthcare, secure monitoring and biomedical applications [1-3]. With the ever increasing volume of RFID labels being deployed into garments and apparel industries, integration of RFID and fabric manufacturing processes attracts great interests because of its low-cost and low-overhead potentials. Conductive yarns, [4, 5], versatile fabrics[6, 7] and sewing techniques[8] are all proposed as alternative materials in RFID label and antenna construction.

The computerized embroidery has become a promising technique for RFID antenna manufacturing process, which can produce repeatable, reliable and reusable conducting surface geometries. With this technique, RFID antennas can be seamlessly integrated into textiles or clothing for unobtrusive wearing. To date, researchers have explored various embroidery antennas on flexible textiles. Antennas and other radio frequency (RF) components, such as transmission lines, patch antennas, and antenna arrays, were designed and embroidered in [9]. Effects of stitch spacing and stitch geometries on RF performance of microstrip antennas were analyzed in [16]. Yarns electrical and mechanical properties were examined in [4, 6]. Simulated and experimental RF characteristics were reported in [10-12].

One challenge of embroidered RFID label manufacturing is to mount RFID microchip directly onto the fabric surface [13]. This challenge is caused by the embroidery construction itself. As shows in the examples, the conductive yarns' mechanical and electrical properties are dramatically altered under high tension and operation speed of the embroidery machine [5]. Besides, the imbalanced tension between bobbin (down) yarns and up yarns can easily result in filaments floating. With the tradeoff between mechanical flexibility and electrical conductivity of yarns, the resistivity of embroidered RFID tag is often higher than that of copper and aluminum films that are widely used in today's RFID labels [7].

In this paper, we design and fabricate a set of slotted patch RFID antennas, with microchips readily and reliably mounted directly onto the woven fabrics using an interposer structure known as "strap". The embroidery parameters (slot size, stitches, tension, conductive yarns and fabrics) are optimized. Simulation as well as field test and measurements demonstrate that the electromagnetic performances of embroidered RFID tags are comparable to those with metallic (copper or aluminum) antennas.

II. EMBROIDERED RFID ANTENNA DESIGN CONSIDERATION

RFID antennas can employ different forms and geometries, such as dipole, monopole, patch, inverted-L, etc. Each form has its own EM properties and performance metrics. In this paper, we utilize a slotted patch antenna as the base geometry form for the embroidered antenna design. There are two main considerations in the antenna geometry selection, 1) Antenna geometry without fine structures that need high resolution in embroidery process, and 2) Antenna geometry without narrow lines that create higher resistant paths. The antenna base geometry being selected, as shown in Fig. 1 below, satisfies the two requirements.

The antenna base form shown in Fig. 1 is tuned to match Impinj Monza 4QT UHF RFID chip. It operates within the UHF frequency band from 860MHz – 960MHz with its S11 minimized at around 915MHz. The geometry of the antenna is presented in Fig.1, with the parameters listed on the side. The antenna has an input impedance of Z = 11 + 143i at 915MHz at the terminal of the chip IO pads.

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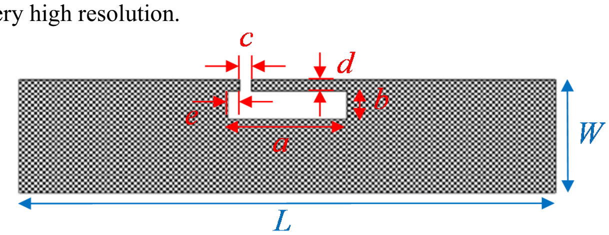
Considering the embroidering process will definitely induce geometrical variations, antenna geometries have to tolerate these variations to maintenance a stable performance. Compared with other antenna alternatives, the antenna being proposed is relatively simple and has no geometries that require very high resolution.



L	*W*	*a*	*b*	*c*	*d*	*e*
90	20	20	5	2	2	2
90	20	**18~22**	**4~7**	2	2	2

Fig.1. Geometrical parameters of proposed RFID antenna (in millimeters).

HFSS simulation of the antenna radiation pattern is shown in Fig. 2.

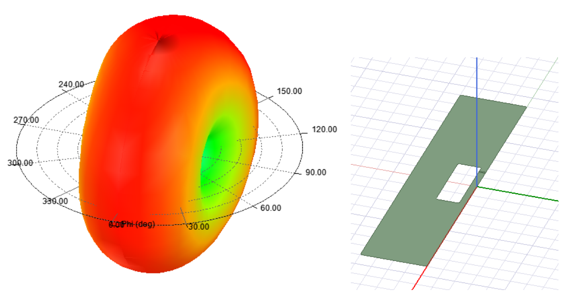


Fig.2. Total gain radiation pattern at 915 MHz.

III. EMBROIDERED RFID ANTENNA FABRICATION

Versatile yarns were integrated for aesthetic geometries or structures by embroidery techniques [14]. To implement these techniques on the proposed slotted RFID antennas, conductive yarns can serve as the bottom yarns (crossing a bobbin fastener), or serve as top yarns (passing fasteners and needle). However, high friction generates when the yarns cross through the eye of the needle or spit from the bobbin fastener. It requires the conductive yarns to exhibit certain flexibility and strength so as not to be broken by the high tension. Meanwhile, the yarns should have high quality to withstand the conductivity deterioration caused by the broken filaments or peeling off of the coating layer.

Comparison of mechanical and electrical characteristics over various types of yarns (silver plated polyamide yarns, nickel-copper braids and metal filament stainless) is shown in Table 1. Considering both mechanical and electrical trade-offs, Silverpam 250 (from TIBTECH Innovations Inc.) is selected as the yarn for embroidering RFID antennas.

Considering that the substrate shrinkage between stitches may result in dimension variations in the embroidery process, 12 different variations from the base antenna geometry are fabricated. Because the opening slot (parameter a and b) is the most sensitive structure of the antenna, the 12 variations change the slot size from 18mm to 22mm in length and from 4mm to 7mm in width, as listed in Table 2.

Fig. 3 illustrates antenna fabrication process with a computer-aided digital machine (JCZA 0109-550 (700), ZSK Stickmaschinen GmbH). Meanwhile, it shows embroidery materials, including non-woven cotton substrate, which maintains stable mechanical performance against tension and deformation, conductive yarns, up and bobbin (down) yarns.

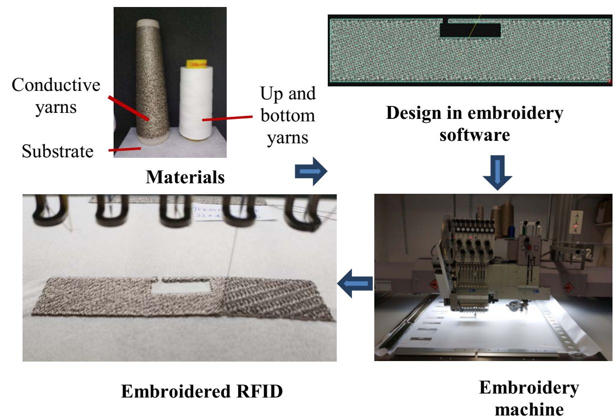


Fig.3. Fabrication process of embroidered RFID antenna.

The RFID microchip is first mounted onto an interposer structure, known as a "strap". The strap has larger and flexible conducting pads, which increase the conducting and contacting area on the embroidered surfaces. After embroidery, the strap is directly fixed on to the antenna surface using conductive adhesives, shown in Fig. 5.

IV. MEASUREMENT RESULTS

TUT (Tag-antenna Under Test) system is used to measure the embroidered RFID tags' reading range and sensitivity. The TUT system is installed inside an anechoic chamber. Fig. 4 illustrates the reading range and sensitivity measurement setup. The RFID reader antenna transmits signals at a fixed distance from TUT.

In order to measure the sensitivity, the reader transmission power level can be attenuated from 30 dBm to 5dBm with a 1dBm step. During the test, the transmission power is decreased until the reader cannot receive any response from the tag. The sensitivity measurement is repeated at every frequency step from 860 MHz to 960 MHz with 5MHz spacing. The reading range can be estimated based on the sensitivity measurements, using the Friis equation.

Table 1. Characteristic comparison of selected yarns

Technology	Name	DC Resistance (Ohms/m)	Diameter (mm)	Suppliers	Merits	Demerits
Silver coated	SILVERPA M 250	50	0.08	TIBTECH Innovations Inc	Lightweight and good elasticity	Break under high tension
Silver plated polyamide yarns	Shieldex® 235/36 dtex 4-ply HC +B	33	0.6	Statex Inc	Anti-static and anti-bacterial properties[15]	Larger in diameter than standard sewing thread
Nickel-co pper braids	Liberator™ 40	3.3	0.4	Syscom Advanced Materials Inc	Lightweight, excellent thermal stability, strength cut resistance and tailored electrical conductivity[16].	Light twisted; Fuzzing after embroidery; "Hairy thread" causes short-circuit
Stainless steel filament	The THERMOT ECH "N"	11	0.7	TIBTECH Innovations Inc	Constant conductivity ; Withstanding sweat, saline water, light oxydation or washing processes[17].	Heavy-weight; large diameter.

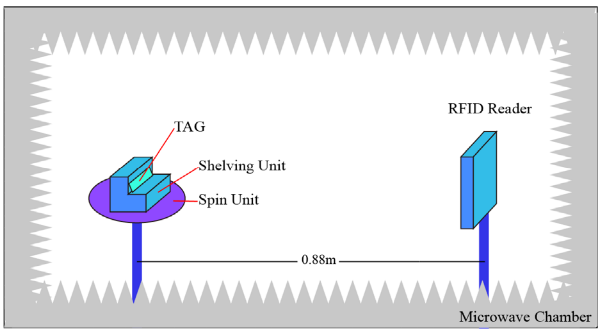


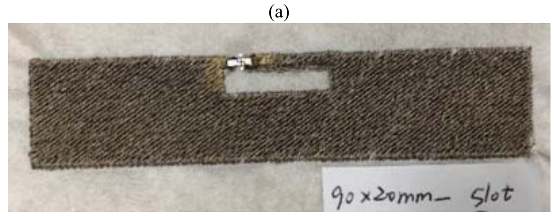
Fig.4. Measurement set up.

Table 2 shows the performances of the 12 samples of RFID labels with the embroidered antennas. Most of them are readable; expect sample 1, sample 4 and sample 10. Because we only prepare one sample for each of the 12 size variations, the non-readable labels may be caused by the damaged chip during the sample preparation.

Table 2. Performances of textile-based RFID antennas

No	Slot size/mm ($a \times b$)	Detection Status（if it can receive signals）
1	18×4	×
2	18×5	√
3	18×6	√
4	18×7	×
5	20×4	√
6	20×5	√
7	20×6	√
8	20×7	√
9	22×4	√
10	22×5	×
11	22×6	√
12	22×7	√

(a)



(b)

Fig.5. Fabricated antenna: (a) Metallic antenna, (b) embroidered antenna.

As a comparison, an RFID label with the baseline antenna geometry, fabricated in etched copper film, is also tested and measured to compare the performances with embroidered RFID antennas, as shown in Fig. 5(a).

The frequency response comparison between metallic antenna and embroidered antenna is shown in Fig. 6. The results indicate that the RFID label with embroidered antenna exhibits about 3~6 dB attenuation in sensitivity. This sensitivity degradation is caused by the higher resistance from the conducting yarns. The increased resistance will increase the energy dissipation during antenna transmission, which lowers its sensitivity. However, the frequency response profile stays the same, with the same optimal operation frequency.

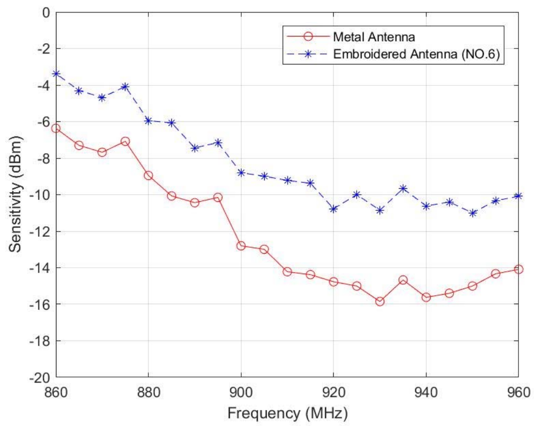


Fig. 6. Sensitivity comparison of a metallic antenna with an embroidered antenna.

Fig. 7 compares the measured sensitivities of all the 12 textile-based antennas with various slot sizes. The antenna with slot size 20mm x 7mm (No.8) exhibits the best sensitivity in the frequncy range from 860 MHz to 960 MHz (less than -10dBm).

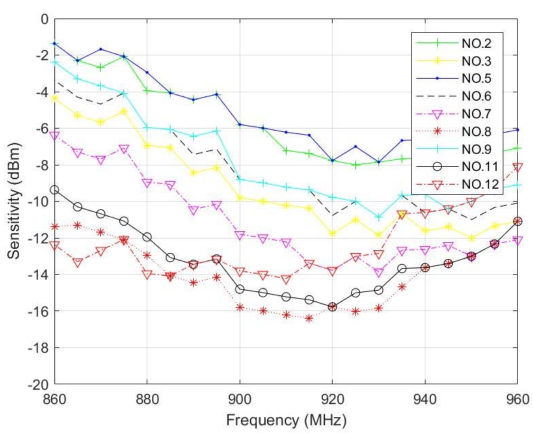


Fig. 7. Sensitivity of embroidered RFID antennas.

To further explore the influence of the slot size, we compared the performances of a set of antennas with monotonically increased slot areas (No.5 ~ No.8). The results in Fig. 8 indicate that an antenna's optimal operating frequency becomes lower with a larger slot area, which is consistent with the simulation results. Meanwhile, the loss of antenna decreases with the increase of the slot area. This suggests that a textile-based RFID antenna's sensitivity can be improved by enlarging its size within the operation frequency range.

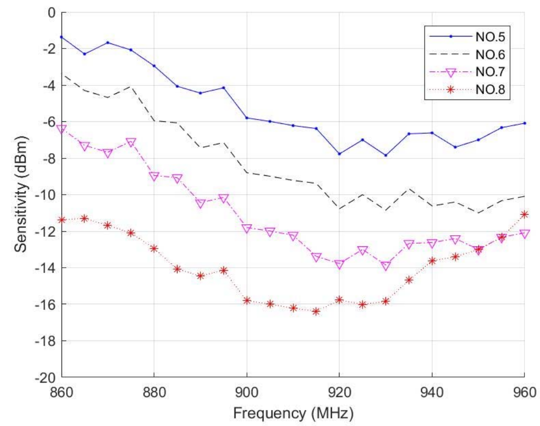


Fig. 8. Sensitivity comparison of a set of RFID antennas.

Furthermore, using the Friis Equation, we can estimate the reading range of these RFID labels based on their sensitivities. The reading range of the RFID Label No. 8 is illustrated in Fig. 9.

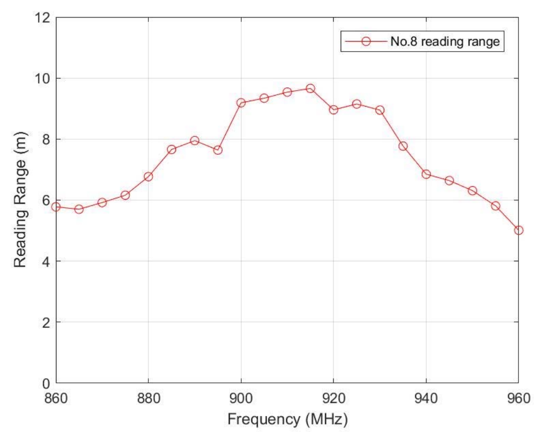


Fig. 9. Estimated reading range of No. 8 antenna.

V. Conclusion

In this paper, a set of embroidered RFID antennas are designed and fabricated. Their feasibilities are verified by simulation and measurement results, and their electromagnetic performances are comparable with the metallic counterparts. Although this work is an initial feasibility study of embroidered RFID antennas, it suggests that antenna and other EM components with conformal shapes can be seamlessly embedded into clothing or textiles and find their applications in wireless body area networks. Future work will focus on embroidery antenna on various fabrics, investigating the effects of deformation on antenna performances and further use of the antenna as a sensing terminal in wearable sensors.

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