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Effect of Stitch Structure on the Reading Performance of Fabric-Based Embroidered UHF RFID Tags

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Abstract
As the demand for low-cost rapid preparation techniques for RFID (Radio Frequency Identification) fabric tags is increasing, embroidery technologists have attempted to fabricate tag antennas. However, the effects of stitch structures on the performance of tag antennas have rarely been studied. Since the structure of an embroidered stitch is related to the embroidering process parameters and embroidery thread, this study chose a common stitch trace type to prepare two sets of UHF RFID tag antennae by changing the embroidery thread structure and stitch length, and then the electrical and gain properties of these antennas were analyzed. And again, the reading performance of the corresponding tag was evaluated. The results showed that the antennas embroidered with copper/PET wrapped yarns have higher energy transfer efficiency than those with single copper wire yarns. When the stitch length increases from 0.9 to 5 mm, the read range of the embroidered tag firstly increases and then decreases, due to the large embroidering process deviation of the tag antenna geometry, and the optimal stitch length for the read range is 1.7 mm, where the read range is 12.95 m. When the stitch length is 5 mm, the read range is minimum – 9.56 m. In summary, this study determined the embroidered thread structure and the process design of the stitch length in terms of the performance of a fabric-based embroidery antenna for an RFID tag as well as the read range.

Key words: *embroidery, stitch structure, RFID, conductive yarn, antenna.*

Introduction

Due to the endless application potential for wearable radio frequency identification (RFID) tags in identification, monitoring and sensing, they are gradually getting people's attention. Among them, the UHF RFID antenna of a T-matched structure is particularly widely used because of its simple structure and good performance. However, the manufacturing techniques for all kinds of T-match UHF RFID antenna are still being developed, particularly when it comes to features such as low cost, wearability and washability. Therefore, some techniques have been explored to decrease the amount of conductive material as the main cost of T-match tags, to fabricate the antenna structure from textile fibres, and to use the mature textile manufacturing process [1, 3].

To decrease the amount of conductive material, the geometrical structure of the T-match antenna has been simplified on the basis of the dominant distribution of the radiated current in the outer edge of the antenna conductor [2], and only the boundary portion of the original antenna conductor is retained, as shown in ***Figure 1***. The UHF RFID tag with simplified topology has a 10% reduction in the read range compared to a fully printed tag, while ink consumption has been reduced by nearly 50%; and comparably the embroidered conductive yarn will have a similar reduced consumption.

The aim of the present study was to fabricate a tag antenna from textile fibres with increased wearability as well as washability, Nicolas [3] used conductive yarn to embroider the topology-simplified T-match antenna, shown in ***Figure 1.b***. The fabrication of the tag not only has low cost and effective time, but also it has a comparable read range to that of the embroidered full-topology antenna, i.e. 8.0 m. Obviously, the topology-simplified T-match antenna has the advantage of low-cost manufacturing, and the performance of the embroidered T-match antenna demonstrates the feasibility of fabrication from fibrous materials. And also, due to the processing compatibility of embroidery with various textile substrates and the technical maturity in the textile industry, it is one of the preferred techniques for the low cost and rapid manufacturing of fabric-based antennas.

According to embroidery process technology and antenna theory, the fabric substrate and stitch structure of the antenna conductor will affect the read performance of T-matched tags. Previous works have determined the following factors for fabric-based antennas [4]: good dielectric properties of the substrate, low and stable resistance of the conductor, and uniform thickness. In terms of the embroidery process, the stitch structure directly affects the signal transmission path formed by the integration of conductive yarn into the fabric substrate, thereby affecting the performance of the embroidery tag antenna.

According to ISO 4915:1991, Stitch types – Classification and terminology, a stitch is a unit formed by one or more stitches, which are intralooping, interlooping, or interlacing on or through a seam material. In this paper, the form of interlacing was adopted, that is, a thread loop with one thread passing through another. And the stitch structure is mainly determined by the embroidery process and conductive embroidery yarn during the antenna manufacturing process, as illustrated in ***Figure 2***. The embroidery process parameters mainly include the stitch type, stitch spacing and stitch length [5-7].

In the case of the geometry-simplified T-matched antenna, its conductor can consist of single conductive yarn, intrinsically forming a continuous object and improving the efficiency; thus, the embroidery process parameters are mainly the stitch length (Ls) and the embroidery yarn when the stitch type and embroidering tension are stabilised. The working principle of the computer embroidery machine is shown in ***Figure 3***. According to the input embroidery pattern, the computer embroidery machine fixes the pattern by tangling the bottom thread and upper thread. The upper thread is drawn out from the external spool of the embroidery machine, and a certain tension is applied through the tension device to make it pass through the needle hole of the thread take-up lever and the embroidery needle, and finally through the embroidery foot. The bottom thread is drawn from the internal spool of the embroidery machine. Generally, the bottom thread does not appear on the front of the fabric. The stitch length affects the electrical impedance of the transmission line [5] and the return loss of the antenna [8]. However, few works have deeply discussed its effect on the performance of the UHF RFID tag antenna.

Previous works used plated silver thread to embroider a T-match antenna [9], but this kind of thread has low stretchability and its plated film easily cracks under the embroidering tension. Moreover, thin copper wires are used as the embroidery yarn, but this kind of metal wire easily breaks once twisted, which makes the embroidery process difficult and the antenna tensile endurance poor.

On the other hand, according to the principle of embroidery and the length of the actual embroidered tag antenna conductor, it is difficult to control the first falling position of the needle, as illustrated in ***Figure 4***, so that each segment of the antenna conductor is regular and the topol-

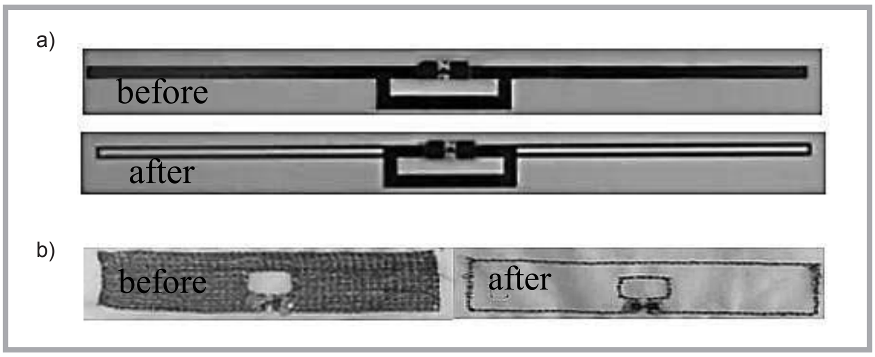

Figure 1. *Topology structure of two T-match antennas before and after simplification: a) print, b) embroidery.*

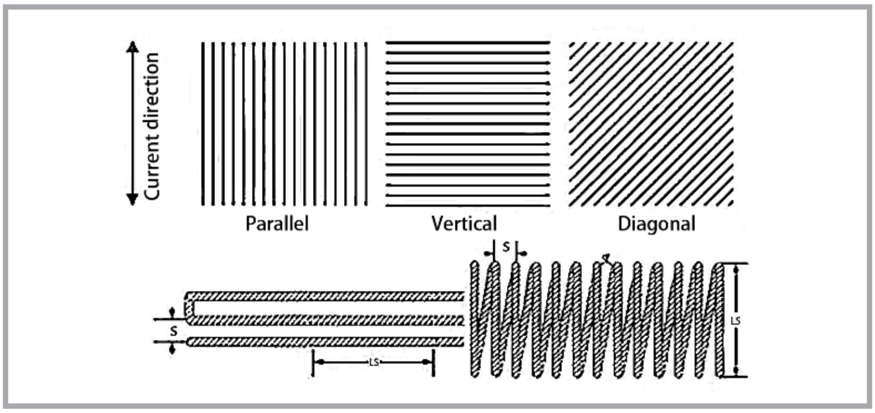

Figure 2. *Stitch type (top), stitch spacing (s) and stitch length (LS).*

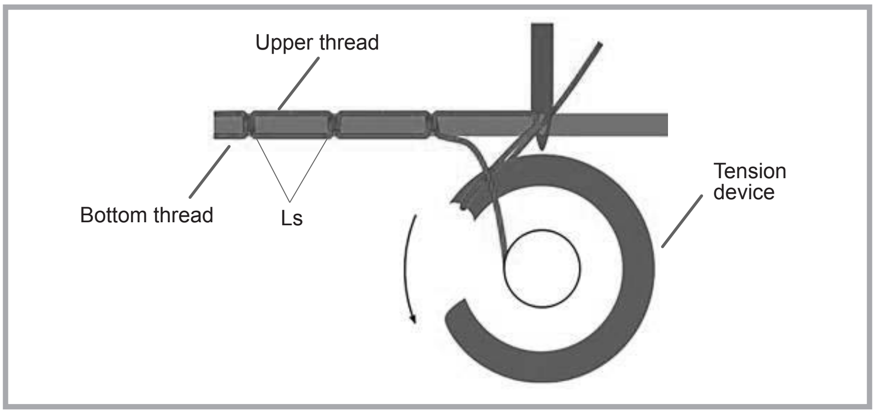

Figure 3. *Working principle of computer embroidery machine.*

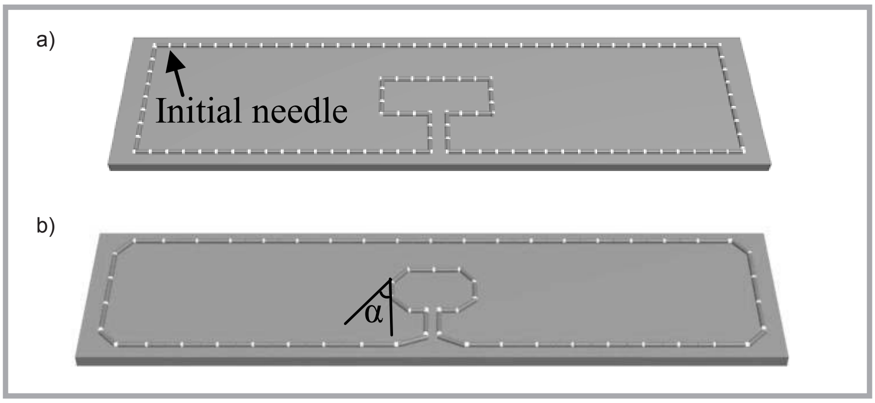

Figure 4. *Illustration of the antenna designed and embroidered: a) structure of T-match antenna designed, b) embroidered structure of T-match antenna.*

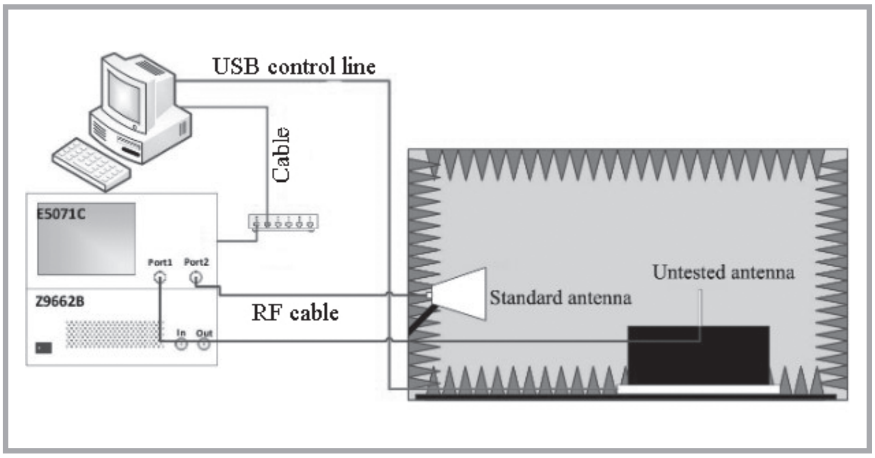

Figure 5. *Measurement of antenna gain.*

Table 1. *Parameter design of embroidered tag antenna with different stitch lengths.*

	1#	2#	3#	4#	5#	6#	7#	8#	9#	10#
Stitch length, mm	0.9	1.1	1.3	1.5	1.7	1.9	2.1	3	4	5
Deviation angle	–	–	–	–	–	5°	8°	15°	20°	30°

ogy geometry does not deviate from the design. This kind of geometry difference is commonly used to change the radiation of the antenna. In this sense, it is pertinent to discuss the inevitable geometry deviation of the T-match tag antenna due to the embroidering process.

In summary, although the embroidery process has been widely used to fabricate RFID tag antennas and fabric-based flexible electronics, little attention has been paid to the process of embroidering an RFID antenna with a single conductive yarn nor to the influence of embroidery process deviations on the performance of the antenna for a RFID tag. In view of this, this study focused on the embroidery stitch structure of the geometry-simplified T-match antenna, that is, the effect of the structure of the embroidery conductive yarn and the stitch length on the geometrical size deviation and performance of the tag antenna.

Experiments

Materials

Tags were fabricated on polyester non-woven fabric, with a mass weight of 79 g/m^2 and thickness of 0.73 mm. The relative dielectric constant measured at 900 MHz was 1.13 ± 0.01, and the dielectric loss was 0.00118 ± 0.02. During embroidering, the bottom line was made of conductive yarn and the top line of polyester sewing thread (40S/2). The tag chip was a higgs-4 series RFID IC with a wake-up power of −18 dBm. The flip-chip method was used to attach the IC to the antenna with anisotropic conductive silver epoxy.

Structure of conductive yarn

The antennas were embroidered with conductive yarns made of copper/polyester wrapped yarn. The twist of the conductive yarn is 50 twists per 10 cm. In copper/polyester wrapped yarn, copper wire is wrapped around textured polyester multi-filaments, so that the conductive wrapped yarn has good stretchability and maintains constant conductivity after certain stretching. For comparison, copper wire with the same diameter to that wire of wrapped yarn was used as the embroidery thread. The comparison results show that the tag with pure copper wire had a gain of 1.08 dBi and a read range of 12.78 m, while for the tag with spiral wrapped yarn the gain was 1.21 dBi and the reading range – 13.32 m. When the chip was attached to the antenna, a part of the distributed capacitor was usually introduced. And this spiral copper wire in the wrapped yarn introduced an inductive reactance, thereby cancelling the capacitive reactance in the equivalent circuit [10]; thus, the maximum energy transfer was achieved. Hence, copper wire wrapped yarn was selected to embroider the tag antenna in the subsequent experiment.

Design of stitch length

The stitch length (Ls) was the distance between two stitch tips along the direction of the stitch movement, which is illustrated in ***Figure 3***. According to the actual embroidery situation, a set of antennas was embroidered with different stitch lengths at the same embroidery tension level. Their stitch length and regularity, which is mainly expressed by the deviation angle (α, shown in ***Figure 4***) of the embroidered antenna's structure, are listed in ***Table 1***. The deviation angle refers to that between the vertical direction and deviation direction of the yarn. The test was repeated three times and the average value obtained.

Resistance measurement of antenna

The linear resistance of the conductor of the tag antenna was tested with reference to "Determination of in conductive textiles – Textiles – linear resistance of wires (EN16812:2016)". Three tags were prepared for each of the stitch lengths, and the average and dispersion of their resistance were calculated. The subsequent experimental tests and data statistics methods were similar.

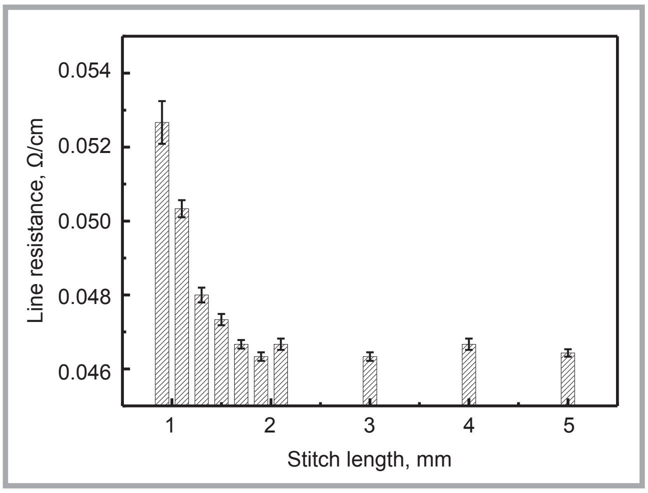

Figure 6. *Resistance values of embroidered tag antennas with different stitch lengths.*

Impedance measurement of antenna port

In order to maximise the energy and read range, it was necessary to evaluate the degree of matching between the port impedance of the antenna and that of the chip. An impedance analyser (IM7585) was used to measure the impedance of the antenna and the chip. By analysing the signal measured, the impedance of the component measured at different frequencies was obtained. This paper mainly analysed the RF signal at 860-960 MHz.

Gain measurement of antenna

A network analyser was used to test the gain of the UHF RFID embroidered tag [11]. The gain directly affects the maximum read range of the tag. The test system setup is shown in ***Figure 5***, and the entire test process was performed in an anechoic chamber.

Results and discussion

Resistance of embroidered antenna conductor

As shown in ***Figure 6***, the stitch length has a significant influence on the conductor resistance of the UHF RFID embroidered antenna. And the conductor resistance of the tag antenna gradually decreases in the range of the stitch length from 0.9 to 1.7 mm. When the stitch length exceeds 2 mm, the line resistance of the antenna conductor approaches a stable level. In order to deeply analyse the reason why the resistance exhibits this change with the stitch length, the topological structure of the antenna at different stitch lengths is characterised and compared.

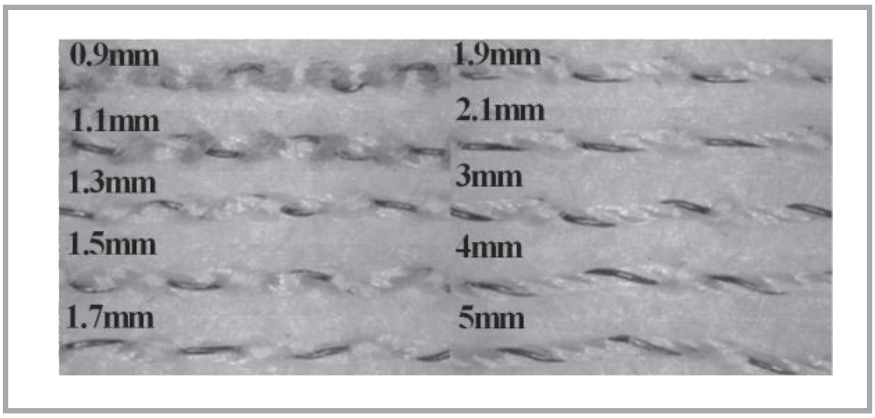

Figure 7. *Conductive yarn morphology at different stitch lengths.*

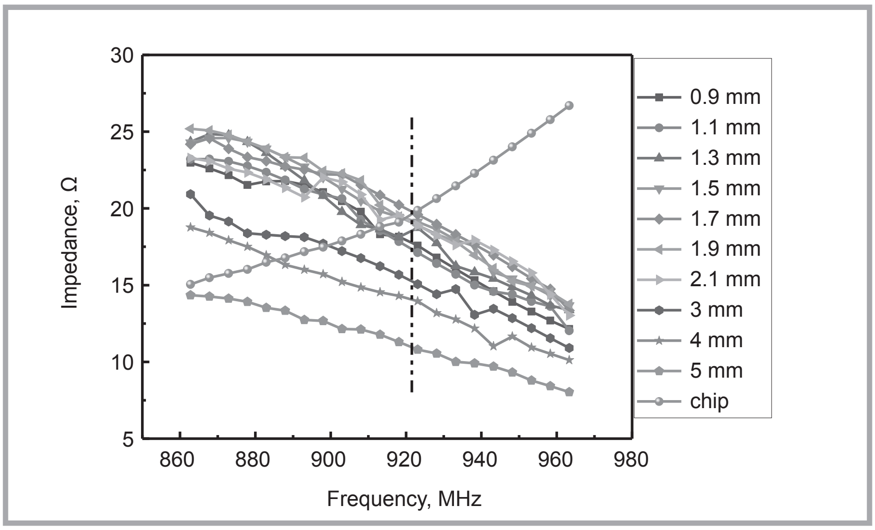

Figure 8. *Comparison of port impedance between the UHF RFID tag antenna and chip with different stitch lengths.*

As can be seen from ***Figure 7***, when the stitch length is between 0.9 and 1.5 mm, the conductive yarn exhibits a different pitch of twist. And as the stitch length increases, the twist pitch of the copper wire becomes bigger. Consequently, the wire resistance of the antenna conductor per unit length decreases. When the stitch length is over 1.7 mm, the twist pitch of the copper wire in the conductive wrapped yarn is so big that the copper wire is nearly straight. In this sense, the length of the the copper wire in the antenna conductor per unit length is near-

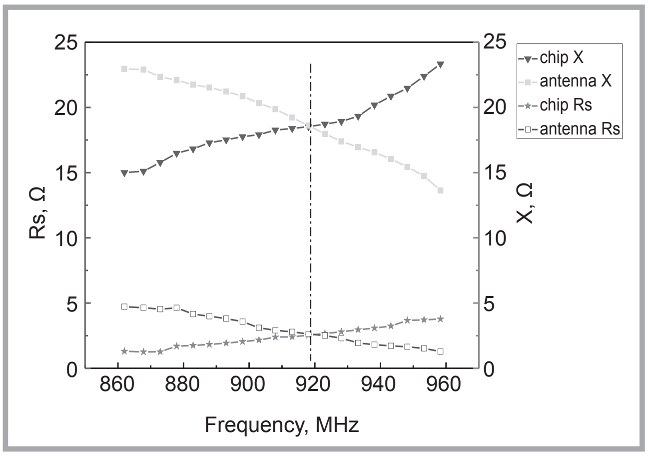

Figure 9. *Antenna and chip resistance and reactance at 1.7 mm.*

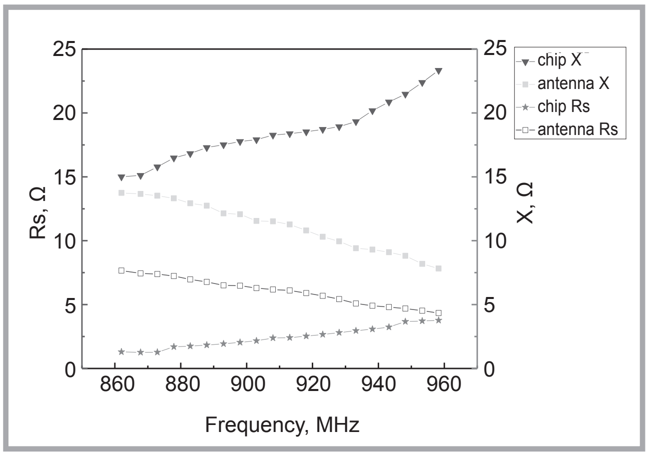

Figure 10. *Antenna and chip resistance and reactance at 5 mm.*

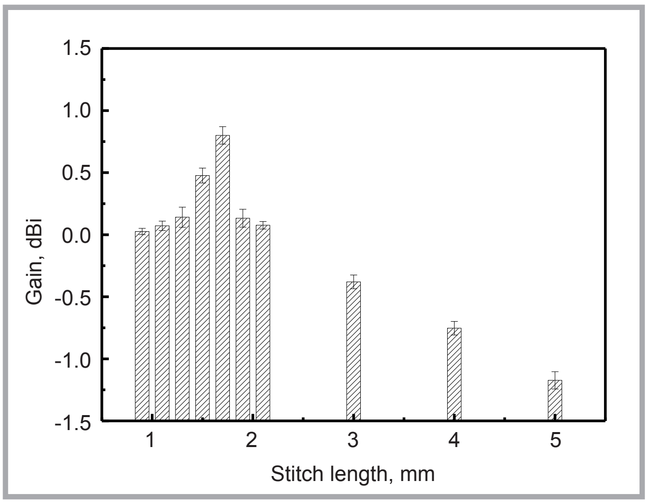

Figure 11. Maximum gain of UHF RFID embroidered tag at 915 MHz.

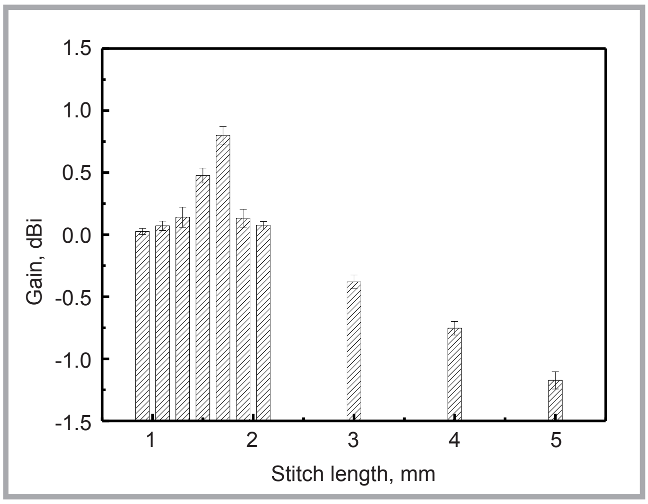

Figure 12. Read range of the corresponding tags for the embroidered antenna of different stitch lengths.

ly same; therefore, there is no significant difference in resistance.

Impedance of UHF RFID embroidered antenna

In ***Figure 8***, the impedance of the chip and antenna varies with the frequency, and the intersection of them is the impedance matching frequency. When the stitch length is 1.7 mm, the matching frequency between the embroidered antenna and the chip impedance is around 920 MHz. Moreover, at a frequency of 860-960 MHz, when the stitch length is 5 mm, there is almost no intersection between the frequency-impedance curves of the embroidered antenna and the chip; that is, the impedance matching between the antenna and the chip is poor, and thus the energy loss increases.

In order to further understand the variation in the real and imaginary parts of the impedance at different stitch lengths, two kinds of stitch length samples with good and poor impedance matching of the above antenna ports were selected. In addition, the real and imaginary parts of the impedance were further analysed. Here, the two stitch lengths are 1.7 mm and 5 mm, respectively, the impedance components of which are shown in ***Figure 9*** and ***Figure 10***, respectively.

It can be seen from ***Figure 9*** that the intersection of the reactance of the antenna and the chip as well as the resistance are both around 920 MHz, which is consistent with the results shown in ***Figure 8***. However, ***Figure 10*** shows that there is almost no intersection of resistance and reactance between the antenna and the chip in the range of 860-960 MHz, which shows a very poor port impedance match between the antenna and the chip. And the energy loss is high.

Besides the varying spiral twist of the copper wire in conductive wrapped yarn when the stitch length is 0.9-1.5 mm, the embroidery process deviation of the tag antenna geometry size can also cause changes in the antenna resistance and impedance when the stitch length is 1.9-5 mm. Especially, when the stitch length is 5 mm, the impedance change is the largest.

Gain of UHF RFID embroidered antenna

In ***Figure 11***, in the range of the stitch length of 0.9-5 mm, the gain first increases and then decreases. When the stitch length is 1.7 mm, the impedance matching between the antenna and the chip is good, so that the energy loss is the smallest and the gain reaches the maximum value of 0.81 dBi.

Reading performance of UHF RFID embroidered tag

The read range of the fabric-based UHF RFID tag is a basic indicator for determining the success of the antenna manufacturing and antenna-chip attaching process. The specific test results are shown in ***Figure 12***.

In the range of the stitch length of 0.9-5 mm, the read range first increases and then decreases, and the read range is the farthest when the stitch length is 1.7 mm. The impedance matching between the antenna and the chip is good at this time and the energy loss is small. The gain of the antenna is large, therefore the reading distance is the largest – 12.95 m, which exceeds 50% of the earlier research results (8 m) [2]. Within the range of 1.9-5 mm, the deviation of the antenna's embroidery structure gradually appears: 5-30°. When the stitch length is 5 mm, the deviation of the antenna structure is serious, with a deviation angle of 30°. Here, the antenna energy loss is high. Therefore, when the deviation angle of the antenna structure exceeds 30°, the performance of the tag will be greatly affected.

Conclusions

This work selected and demonstrated a kind of copper/PET wrapped yarn to overcome the low stretchability of common metal or metal-plated conductive yarn and to strengthen the performance of the embroidered tag antenna. On basis of this kind of wrapped conductive yarn, it was discovered that the stitch structure has a significant effect on the reading performance of fabric-based UHF RFID embroidered tags due to the embroidery process deviation of the antenna geometry. Furthermore, the stitch length has a parabolic effect on the maximum antenna gain and maximum tag read range. Moreover, the impedance matching and reading performance of the tag is optimal when the stitch length is 1.7 mm and the maximum read range – 12.95 m, which exceeds the earlier reported value by 50% [2]. Generally, these results will improve the antenna fabrication efficiency of fabric-based UHF RFID tags. In the future, we will further uncover the statistical distribution of the effect of the process deviation of the antenna geometry on the read performance.

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