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Broadband Textile-Based Passive UHF RFID Tag Antenna for Elastic Material

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***Abstract*—We present a broadband textile-based UHF RFID tag antenna. Its wide bandwidth makes the tag less susceptible to objects and materials in the vicinity. Also high conductive textile material (E-fiber) is used to introduce elasticity, flexibility and mechanical strength. As a result the designed tag antenna can operate in a wide range of dielectric materials and various environments. By contrast, conventional RFID tag antennas have narrow bandwidth and must be designed for placement in different materials. The new tag is designed for implementing with elastic materials; as an example, the designed tags are tested on automotive tires. Experimental results show that the designed tag achieves much better performance compared with commercially available tags.**

***Index Terms*—RFID, tag antenna, textile, antenna design**

I. Introduction

RFID (Radio Frequency IDentification) technology has been implemented widely for item identification and inventory tracking. Recently there is also strong interest for integrating RFIDs with sensors to wirelessly monitor conditions of structures or devices while in service and possibly hostile environments [1-2]. Generally speaking, the RFID tag/sensor tag antenna is only designed for a given material to optimize impedance match and read range. However, a tag's performance deteriorates significantly when mounting location or nearby material changes. Therefore, it is desirable to design a broad impedance bandwidth RFID tag antenna for operation in a variety of material structures.

Broadband RFID tag antennas have been considered before, but primarily for covering multiple bands [3-5]. Here we focus on a broadband UHF RFID tag antenna delivering a bandwidth of 263MHz (free space) for the purpose of maintaining performance over a wide range of materials. Previous UHF RFID antennas have been designed for operation on metallic objects [6-7], extreme environments [8], and metallic/dielectrics [9]. However, there is no solution in the literature for UHF RFIDs that can operate in different dielectrics, including elastic materials.

Here, we present an RFID tag antenna constructed from conductive textiles for flexible and stretchable designs [10]. A single E-fiber thread is employed to embroider a stand-alone RFID wire antenna. This is an attractive approach since former technologies based on stretchable conductive wires (e.g., liquid metal [11], copper traces [12], silver nanowires [13], etc) are prone to fatigue and wear. Using the proposed textile wires, the RFID antenna exhibits excellent mechanical properties that favor its application in hostile environments.

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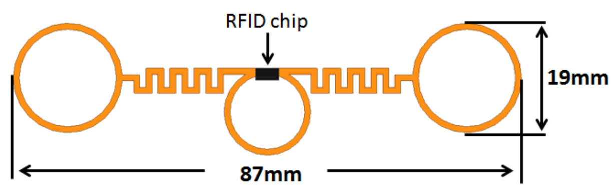

Fig. 1 Design of the proposed RFID tag antenna.

In this work, a textile-based broadband RFID tag antenna is presented. The proposed tag antenna is designed incorporating three aspects: 1) electrical properties: broad bandwidth and electrically small size; 2) mechanical properties: elasticity, flexibility, and mechanical robustness; and 3) fabrication complexity: low profile and easy to mass produce. The designed antenna achieves a wide frequency bandwidth making it functional over a wide range of materials. Various tags are fabricated with copper wire and E-fiber threads. Their performance is evaluated and compared with a commercial RFID tag for the tire application. Measurements indicate that the designed antenna achieves significant improvement as compared to a conventional one without loss of flexibility.

II. Proposed Tag Antenna

The antenna is designed and optimized based on the three key aspects described in the introduction, namely, 1) electrical properties, 2) mechanical properties, and 3) fabrication complexity. As illustrated in Fig. 1, the antenna is composed of three parts: the circular end-loading loops at both ends, the meander-line dipole arms, and a tuning loop in the center. Design optimization was performed using ANSYS HFSS™ software.

1) Electrical properties: The designed tag antenna is electrically small (87 mm × 19 mm) and broadband. As such, it is able to maintain tuned behavior over a wide range of mounting locations and nearby materials. Fig. 2 plots the power reflection coefficient between the RFID chip and antenna. Specifically, in Fig. 2, the red curve and the blue curve correspond to the power reflection coefficient of the antenna in free space and when mounted on a 4 mm-thick dielectric with

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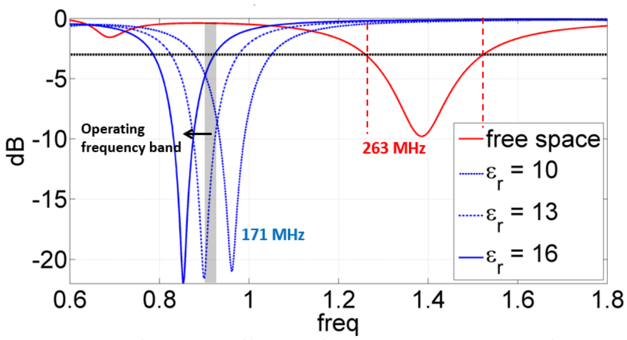
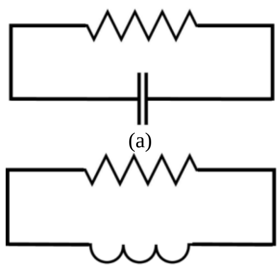


Fig. 2 Power reflection coefficient of the proposed antenna in free space and on a 4mm dielectric slab for 3 different permittivities.



(a)

(b)

Fig. 3 Equivalent circuit model for (a) the chip impedance, and for (b) the dipole antenna loaded with a short stub.

$\varepsilon_r = 10{,}13{,}16$, respectively. As seen, the tag antenna delivers a 3 dB bandwidth of 263MHz in free space. More importantly, it is tuned to maintain a good impedance match over the US RFID band (902-928MHz) with sufficient bandwidth (171 MHz $\varepsilon_r = 10$) to allow variability in the underlying or surrounding material. The impact of dielectric materials placed in the vicinity of the tag antenna and the need for a broadband antenna to mitigate these effects are discussed in [14] [15].

In the proposed antenna design the circular loop in the center is used to provide sufficient inductance for impedance matching to the RFID chip. A RFID tag consists of two parts, an antenna and a RFID chip. For maximum power delivery, it is necessary to match the antenna impedance to that of the chip. Therefore, we must minimize the power reflection coefficient given by [16]

$$|\Gamma(f)|^2 = \left|\frac{Z_c(f) - Z_a^*}{Z_c(f) + Z_a}\right|^2 . \tag{1}$$

Here, Z_c and Z_a refer to the complex impedances of the RFID chip and antenna, respectively. Generally speaking, the RFID chip does not incorporate a matching circuit. Its impedance is highly capacitive and can be modeled as a resistor and a capacitor in parallel shown in Fig. 3(a). Based on transmission line theory, the circular center loop can be viewed as a short stub, and therefore serves as a parallel inductor. The equivalent circuit model of the antenna and the center loop is provided in Fig. 3(b). We note that the length of the loop was optimized such that complex conjugate matching can be achieved at the desired frequency.

The meander-line structure was adopted to reduce the tag's size [17]. As compared with a straight dipole of the same length, the resonance frequency can be significantly reduced using meander-lining, typically at the expense of narrower bandwidth.

The circular end-loading wire loops are employed to increase the impedance bandwidth of the antenna. The end-loading (or top-loading) of the dipole serve to broaden its bandwidth [18]. Fig. 4 (a) compares the designed antenna with and without end-loading. As would be expected, the end-loading loops improve impedance bandwidth. Furthermore, the end-loading reduces the overall size of the antenna. As depicted in Fig. 4(a), the antenna with end-loading is 3mm shorter than the one without end-loading.

2) Mechanical properties: The tag antenna was designed to be mechanically robust. This implies that its physical integrity and electrical performance remain intact when the tag is subject to external forces. To do so, the shape of the meander-lines was optimized such that the tag's performance is preserved even if the antenna undergoes deformation. Importantly, the meander line structure enables stretching of the tag. Fig 4(b) compares the performance of the original antenna and the one stretched by 10% (overall length remains the same). As expected, the simulations show that the antenna's resonance is shifted downwards in frequency after stretching. However, its bandwidth still overlaps the operating frequency band. The end-loading circular loops also allow stretching in any dimension. Fig. 4(c) compares the antenna with the original and elongated loops. The elongated loops are of rectangular shape, but maintain the same perimeter.

3) Fabrication complexity: The designed tag antenna incorporates a low profile structure such that the fabrication complexity and manufacturing cost are reduced. Previous textile-based RFID tag antennas use densely stitched conductive textile to produce the surface of planar antennas. In this work, the tag antenna only requires a single thread of the conductive textile. This is because end-loading loops were used instead of patches in order to avoid rigid planar surfaces. The adoption of the loops was inspired by the observation that for end-loading patches, the current is primarily distributed on the edges. Fig. 4(d) compares the antenna when the end-loading is formed of loops and patches. The results show that the antenna with end-loading loops achieves equally good performance as that with patches. When fabricated using single textile threads, the circular loop is more attractive as it avoids sharp corners. That is, rectangular loops are challenging to fabricate. Therefore, circular loops were adopted to avoid sharp corners and increase fabrication accuracy. The meander-line does not require embroidering sharp edges either. As will be shown in the following section, the shape of the antenna could be preserved after cured with polymer material.

III. Textile Based Tag Antenna

To realize a flexible and stretchable version of the proposed broadband RFID tag, we used electrically conductive metal-polymer fibers (E-fibers) embedded in elastic polymer. Flexibility and elasticity are important for RFID tags that operate in hostile environments subjecting them to mechanical deformation. These E-fibers have already been validated for some textile antennas and sensors [10][19], indicating excellent mechanical strength, flexibility, low DC resistance (about 0.5-0.7Ω/m), and low loss at RF frequencies. They have been

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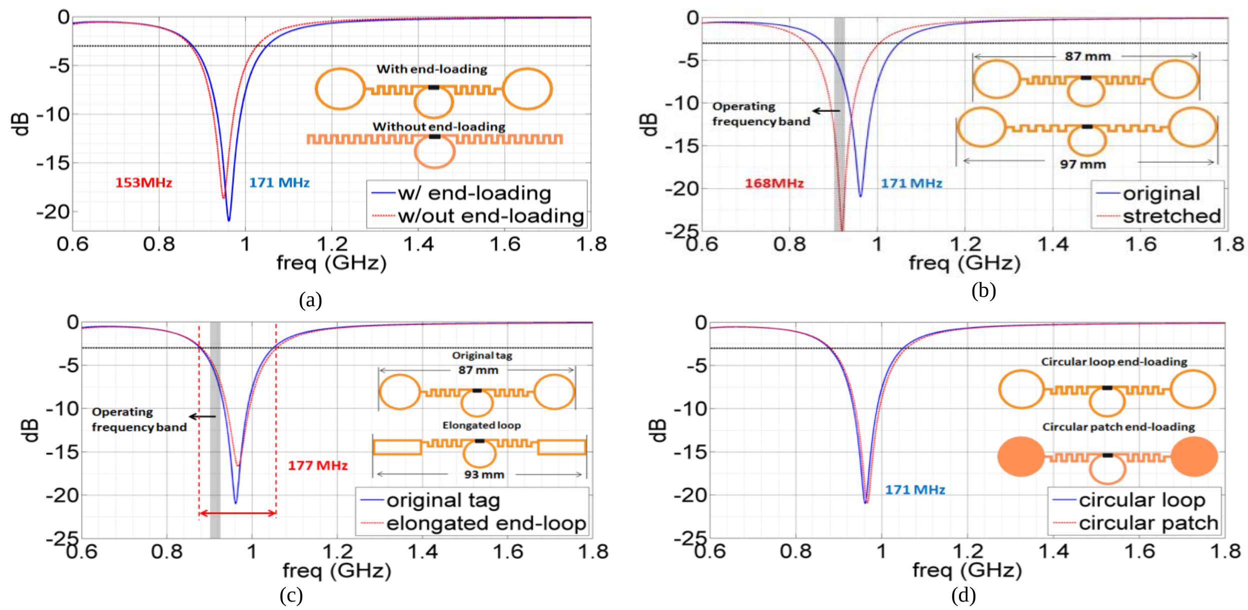

Fig.4 Power reflection coefficient of designed antenna: (a) with vs. without end-loading, (b) non-stretched vs. stretched by 10%, (c) with original vs. elongated end-loading loops, and (d) with end-loading loops vs. patches.

Fig. 5. Fabricated prototype of the flexible and stretchable textile RFID tag embedded in polymer.

Fig. 6. Copper wire version prototype embedded in polymer.

found to have comparable performance to their copper counterparts. Polydimethylsiloxane (PDMS) was employed as the polymer material (ε_r=3, tanδ<0.02) because it is flexible and allows for antenna elongation of about 10% of its original size.

The fabrication procedure may be summarized as follows: (a) convert the antenna CAD file into a digital stitching pattern, or, equivalently, needle path, (b) use a standard sewing machine to embroider the prescribed antenna pattern onto a polyester fabric (as an intermediate support), (c) solder the RFID chip to the antenna, (d) melt the non-stretchable polyester fabric via heating (melting point≈250^{o}C) without damaging the E-fiber (melting point≈600^{o}C), (e) pour 1-2mm thick liquid PDMS polymer on the RFID tag, and (f) cure the PDMS polymer by placing it on an elevated temperature (120^{o}C) hot plate. The resulting product is the flexible and stretchable E-fiber RFID prototype tag shown in Fig. 5.

The prototype was found to withstand repetitive flexing and stretching. The surrounding polymer also preserves the integrity of the E-fiber and protects it from corrosion.

IV. Experimental Results

Four versions of the designed antenna were fabricated and soldered to G2XM RFID chips (impedance: 16-148j) [20]: a copper wire antenna and an E-fiber antenna, each with and without being embedded in polymer. Shown in Fig. 6 is the copper wire version embedded in polymer. Thin (1-2mm) and low-permittivity (ε_r=3) polymer was used to support the mechanical integrity of the tag. The tags' performance was evaluated using read range and threshold power tests (the minimum reader output power required to detect the tag). An Impinj Speedway RFID reader [21] was used to collect data. All measurements were conducted in a large RFID lab.

A. Read Range Test

In this test the fabricated copper wire tag embedded in polymer and a commercially available RFID tag for tires (the Speedy Core) were tested and compared. The commercial tag has the same G2XM chip and its structure is shown in [22]. Both tags were measured on truck tires. Truck tires are constructed of multiple layers of rubber with different dielectric constants and thicknesses [14]. It is necessary to have a broadband antenna such that the RFID tag maintains good performance over a wide range of tires.

The measurement setup is shown in Fig. 7. The tag under test was mounted at the same position on the outer surfaces S1, S2, S3, and S4 of two truck tires. The space between the two adjacent tires is 15 cm, equal to the separation of dual tires on trucks. The output power of the RFID reader was set to be 30 dBm. The RFID reader antenna was moved away from the tires until the tag cannot be detected. The distance between the reader antenna and the tire on the left is the read range of the tag. Measurement results are shown in Table I.

As the table shows, the designed tag has much longer read range than the Speedy Core. More importantly, the designed tag was readable at all positions whereas the Speedy Core was not readable at positions S3 and S4.

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Fig. 7 Read range experiment setup.

TABLE I. READ RANGE TEST OF THE COPPER WIRE VERSION OF THE BROAD IMPEDANCE BANDWIDTH RFID TAG COMPARED WITH A COMMERCIALLY AVAILABLE TAG FOR TIRES, THE SPEEDY CORE.

Antenna/Surface	S1	S2	S3	S4
Commercial Tag for Tires (Speedy Core)	4ft	0.5ft	Cannot be read	Cannot be read
Copper wire antenna embedded in polymer	13+ft	8ft	4ft	4ft

B. *Threshold Power Test*

In this test all four fabricated tags were evaluated for threshold power sensitivity. The threshold power of a tag is the minimum reader output power required to detect the tag at a fixed range. A lower power indicates a better performing tag. The tags under test were placed in turn on surface S1of the tire (see Fig. 7). The reader antenna was fixed 5 feet from the tire. The results are given in Table II. The threshold power is nearly the same for all four versions of the tag. We may therefore conclude that all of the fabricated tags would outperform the commercial Speedy Core tag.

TABLE II. THRESHOLD POWER TEST OF PROTOTYPES

Copper Wire	E-fiber	Embedded copper wire	Embedded E-fiber	Speedy Core tag
20 dBm	21 dBm	21 dBm	20 dBm	27dBm

C. *Stretch Test*

The performance of the copper wire prototype was tested in an elongated condition. As the tags will be embedded in the sidewall of a tire during the manufacturing process, the tag antenna would suffer a certain amount of deformation along its longitudinal direction. Therefore it is very important that the tag antenna maintains its electrical properties after the embedding process. Threshold power measurements were carried out and listed in Table III. The designed tag achieved the same good performance after being stretched by nearly 10%.

TABLE III. STRETCH TEST OF THE COPPER WIRE TAG

Antenna	Length	Threshold power
Original	85 mm	20 dBm
Stretched	93 mm	20 dBm

V. CONCLUSION

In this work, a textile-based broadband elastic RFID tag antenna was designed, fabricated and tested. It was demonstrated that the designed antenna achieves a bandwidth of 263MHz in free space, and more importantly, it maintains its tuned behavior when placed on dielectrics with varying permittivity. Different versions of the designed tag antenna were fabricated and tested. Experimental results show that the designed tags achieve consistently better performance as compared to an existing commercial tag. Furthermore, the performance of the designed tag antenna does not degrade under mechanical deformation up to 10%, which makes it a good candidate for elastic and hostile environments.

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