Conformal Load-Bearing Spiral Antenna on Conductive Textile Threads

Jingni Zhong, *Student Member, IEEE*, Asimina Kiourti, *Member, IEEE*, Tom Sebastian, *Member, IEEE*
Yakup Bayram, *Senior Member, IEEE*, and John L. Volakis, *Fellow, IEEE*

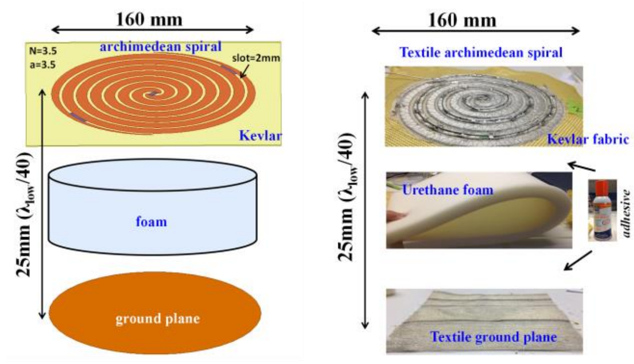
***Abstract*—We present a novel load-bearing spiral antenna on conductive textile threads (E-threads) for conformal applications. The textile spiral exhibits a nearly 10:1 bandwidth (0.3–3GHz) with circularly polarized gain of 6.5dBi across the 1–3GHz bandwidth. Such performance is unique for textiles and flexible surfaces. An important aspect of this paper is the demonstration of repeatable performance for this textile spiral antenna. Also, mechanical tests for the spiral showed no appreciable changes in performance, even after 300 flexing cycles. The spiral is a cavity-backed configuration with its ground plane also embroidered using very thin (diameter=0.12mm) Elektrisola E-threads. These threads can achieve geometrical precision down to 0.1mm. To enhance robustness, high-strength Kevlar fabric was employed as the substrate. Overall, the proposed spiral is very attractive for several wideband, conformal, and load-bearing applications, such as airborne and wearables.**

***Index Terms*—Archimedean spiral, conductive textiles, embroidered antenna, Kevlar fabric, mechanical testing repeatability testing.**

I. INTRODUCTION

BROADBAND antennas are highly attractive for airborne [1] and wearable [2] applications. However, antenna design for such applications is challenging due to requirements for conformality, flexibility, and robustness. To address these challenges, textile antennas were recently introduced based on automated embroidery of conductive textile threads (E-threads) [3]-[5]. These E-threads exhibit much better mechanical strength [3], [6] than other approaches, such as conductive tapes [7], screen–printed silver nanowires [8], and liquid metal alloys [9].

In the past, we demonstrated a conformal spiral antenna based on embroidered Amberstrand® E-threads [1], [10]. That spiral was fabricated with an integrated microstrip planar textile balun as in[11], and placed upon a polydimethylsiloxane (PDMS) flexible substrate. However, the realized gain of this spiral dropped to < 0 dBi at frequencies greater than 2 GHz. This was due to losses associated with the textile balun. Also, the PDMS substrate was susceptible to tears/breaks under mechanical stresses. As an alternative, in this paper we introduce a textile spiral antenna weaved on Kevlar fabric. The latter is suitable for more extreme temperature and stretching or bending situations [12]. Additionally, using Kevlar as the substrate, we carry out the first ever repeatability and mechanical tests of this textile technology. The spiral and ground plane were embroidered using a new class of well-tested Elektrisola E-threads [13], [14]. These threads are very thin (diameter = 0.12 mm), and can achieve geometrical precision as high as 0.1mm. Concurrently, they are highly flexible, for comfortable and unobtrusive integration into garments and other conformal surfaces [3], [6], [13].



(a) (b)

Fig. 1. Proposed spiral antenna: (a) design, and (b) fabricated prototype (antenna has 3.5 turns, expansion coefficient a=3.5, and slot width of 2mm).

To reduce losses at high frequencies, the spiral was fed by a thin coaxial cable wound on top of its surface. This thin coaxial cable does not impact the flexibility of the spiral. Key features of the proposed antenna are: 1) conformality and flexibility, 2) excellent mechanical performance, 3) nearly 10:1 VSWR bandwidth from 0.3 to 3 GHz, and 4) near consistent circularly polarized gain of 6.5 dBi over the 1 to 3 GHz band. We remark that this is the first time we show design and fabrication of broadband antennas using the proposed textile technology with a surface accuracy as high as 0.1mm. As opposed to other flexible antenna fabrication methods, such as inkjet printing, the proposed technology provides for robust and load-bearing conformal antennas with repeatable performance after many bents. Repeatability and mechanical tests for textile antennas

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J. Zhong, A. Kiourti and J.L. Volakis are with the ElectroScience Laboratory, Department of Electrical and Computer Engineering, The Ohio State University, Columbus, OH 43212 USA (e-mail: zhong.181@osu.edu, kiourti.1@osu.edu, volakis.1@osu.edu). T. Sebastian and Y .Bayram are with the PaneraTech,Inc. Chantilly, VA 20151 USA (e-mail: tom.sebastian@paneratech.com, yakup.bayram@paneratech.com)

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are presented for the first time as well. These tests provide confidence for future uses and applications.

The paper is organized as follows. Section II presents the antenna design and fabrication. In Section III, we show measurements of the antenna performance along with repeatability tests. In Section IV, mechanical testing is carried out.

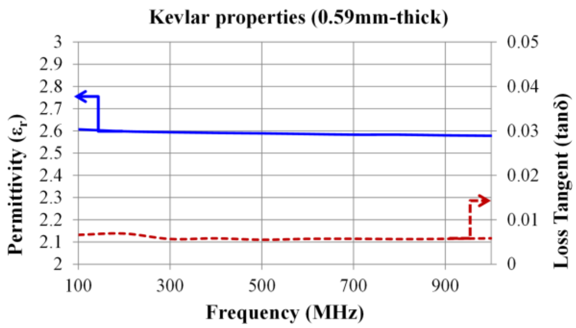


Fig. 2. Measured permittivity and loss tangent of the Kevlar fabric used as substrate for weaving the E-threads.

II. Antenna Design and Fabrication

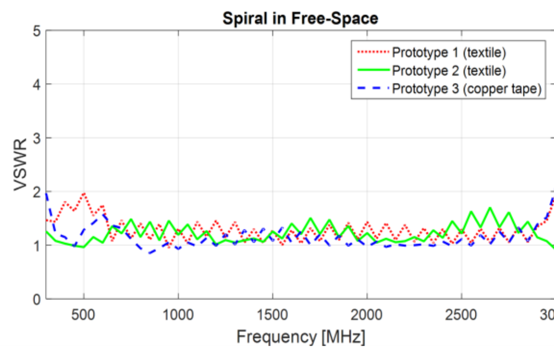
The proposed antenna is a 160mm-diameter Archimedean spiral [11], [13], [15] with the ground plane placed 25mm below the antenna aperture. This spiral has 3.5 turns, an expansion coefficient a=3.5, and a slot width of 2mm. It is depicted in Fig.1 and was designed to operate from 0.3 GHz to 3 GHz. To realize unidirectional radiation a shallow reflecting cavity was employed. Specifically, the reflecting cavity was placed at a distance of λ_{low}/40 from the spiral surface, where λ_{low} refers to the wavelength at the lowest operational frequency (in this case, 0.3 GHz) [15]-[17].

The fabricated spiral prototype is shown in Fig. 1(b). The spiral and ground plane were both textile surfaces, and were weaved using 7-filament silver-plated copper Elektrisola E-threads [14]. These 0.12mm-diameter E-threads exhibit excellent mechanical strength and flexibility, low DC resistance of 1.9 Ω/m (for comparison, the DC resistance of a 0.12mm-diameter copper wire is 1.36 Ω/m), and allow for geometrical precision down to 0.1 mm. An automated embroidery process was employed by programming the embroidery machine, as described in [13]. As already noted, for enhanced robustness, the spiral surface was weaved on a 0.59mm-thick Kevlar substrate. This Kevlar fabric had a permittivity of ε_r=2.6 and a low loss tangent of tanδ=0.006. The actual measured ε_r and tanδ are given in Fig. 2 from 0.1GHz to 1 GHz frequency band. We note that Kevlar is a lightweight, low-loss, abrasion and heat-resistant material, making it suitable for extreme and flexible applications.

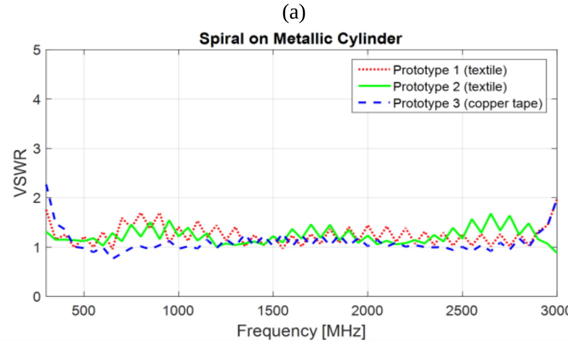
The spiral was fed at its center via a differential feed and using a thin coaxial cable wound along one arm of the spiral, as depicted in Fig. 3(a). When the cable reached the spiral center, the center conductor was exposed and crossed the feed gap. It was then soldered on the other arm [17]. As in [11], two 180 Ω resistors were soldered at the spiral ends to suppress wave

(a) (b)

Fig. 3. (a) Planar spiral surface showing the feeding coaxial cable, and (b) curved spiral placed on a metallic cylinder.



(a)



(b)

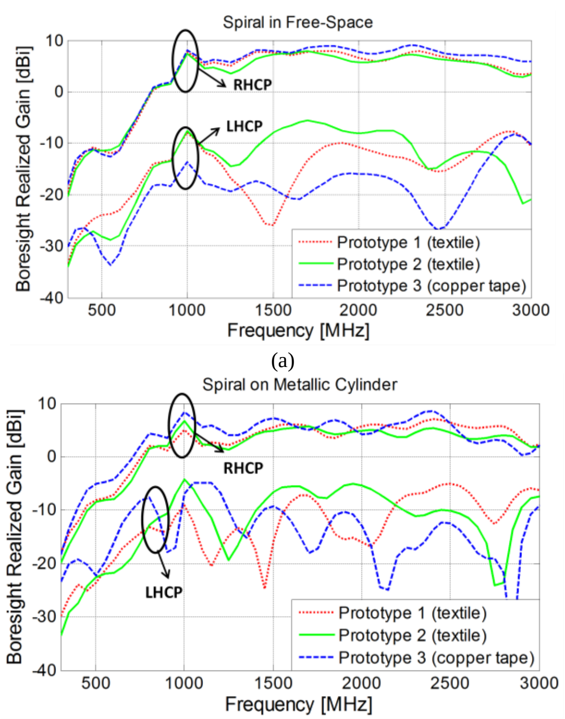
Fig. 4. VSWR of the textile vs. copper tape spiral antennas: (a) planar spiral in free-space, and (b) curved spiral on metallic cylinder.

reflections. Urethane foam was used to fill the reflecting cavity for stability.

III. Antenna Performance

Two measurement scenarios were considered: a) planar spiral in free-space (see Fig. 3(a)), and b) curved spiral while placed on a metallic cylinder (see Fig. 3(b)). A critical issue to be addressed is the repeatability of the employed fabrication approach. To assess repeatability, we fabricated and tested two planar spiral textile prototypes (namely prototypes 1 and 2). For comparison, a copper tape counterpart of the proposed spiral antenna was also fabricated and tested (namely prototype 3).

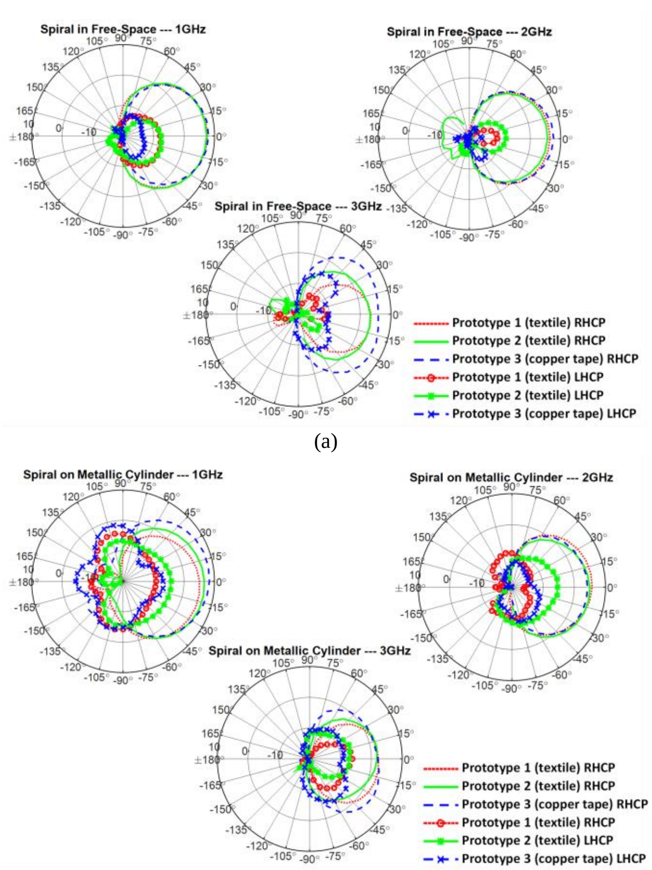
The measured voltage standing wave ratio (VSWR) for all 3 prototypes is given in Fig. 4. As seen in Fig. 4, the planar spiral exhibited a 10:1 bandwidth (VSWR < 2), operating from 0.3 to 3 GHz. When curved as in Fig. 3(b), the spiral retained its wideband performance. Importantly, prototypes 1 and 2 were found to perform nearly the same, confirming the repeatability of our fabrication approach. The measured VSWR of the textile



(a)

(b)

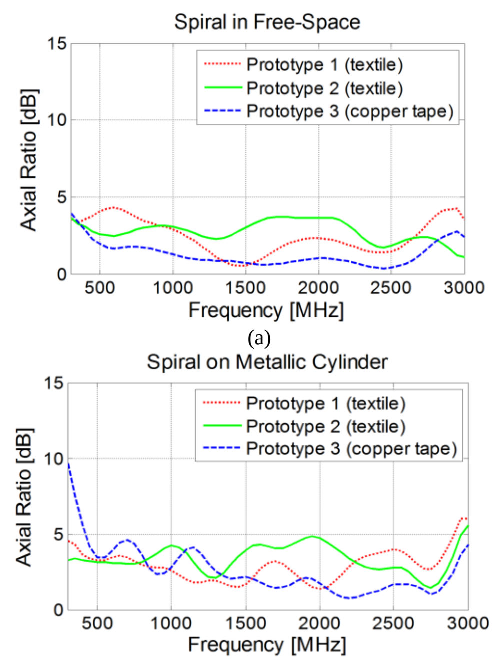
Fig. 5. Boresight realized gain of the textile spiral compared and in comparison to its copper counterpart. (a) planar spiral in free-space, and (b) curved spiral on a metallic cylinder.



(a)

(b)

Fig. 6. Measured radiation patterns at 1 GHz, 2 GHz, and 3GHz of the textile spiral vs. copper counterpart: (a) metal-backed planar spiral in free-space, and (b) curved spiral on a metallic cylinder.



(a)

(b)

Fig. 7. Axial ratio of the textile vs. copper tape spiral antennas: (a) planar spiral in free-space, and (b) curved spiral on metallic cylinder.

prototypes was also in excellent agreement with the copper tape antenna.

The measured boresight realized gain is given in Fig. 5. Both the Right Hand Circular Polarization (RHCP) and Left Hand Circular Polarization (LHCP) gain are given. As depicted, the RHCP gain is close to 6.5dBi across the 1 to 3 GHz band and this value is comparable to [11]. The LHCP gain (cross pol.) was suppressed out. As a result, a low axial ratio was maintained. When curved, see Fig. 5(b), the spiral retained its broadband, high-gain, performance. Further, we note that the performance of the textile prototypes was in good agreement with their copper tape equivalent. Example radiation patterns at 1 GHz, 2 GHz, and 3 GHz are given in Fig. 6.As seen in Fig. 6, the textile antenna patterns remain similar across the band. As expected, the curved spiral's pattern has larger beam width than that of the planar configuration.

Our measurements indicated that the free space spiral has an axial ratio of < 4 dB across almost the entire 10:1 bandwidth, see Fig. 7(a) [18]. For the curved spiral, the measured axial ratio was always < 5dB (see Fig. 7(b)). Again, these measurements confirmed the repeatability of the employed fabrication approach. The slightly lower axial ratio as compared with the copper counterpart is due to losses and surface roughness associated with the E-threads and the spiral itself.

IV. Mechanical Testing

To assess the mechanical performance of the proposed textile spiral, we proceeded to carry out three point flexing tests. The experimental set-up for flexing the spiral is shown in Fig. 8. Specifically, the antenna was placed flat upon two supporting pins at a distance of 160 mm. A third pin was then lowered from above at a speed of 50 mm/min to bend the

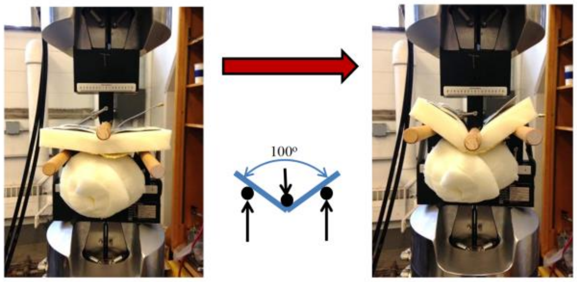


Fig. 8. Three point flexing test of the spiral using wooden rods

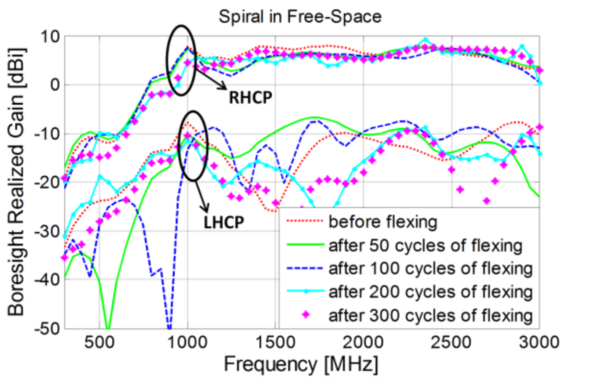
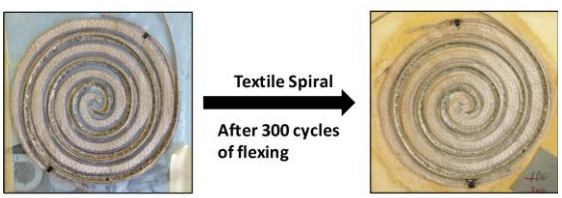
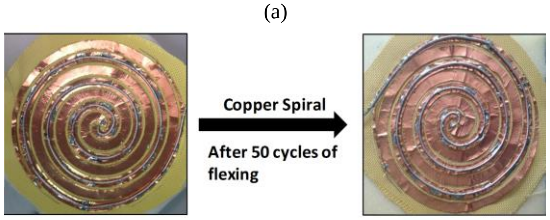


Fig. 9. Boresight realized gain of the textile spiral before and after 50, 100, 200 and 300 cycles of flexing (see Fig.8).



(a)



(b)

Fig. 10. (a) Textile antenna before and after 300 bending cycles, and (b) copper tape antenna before and after 50 bending cycles.

antenna. The maximum bending angle was 100°. Fig. 9 shows the measured boresight realized gain of the textile spiral after 50, 100, 200, and 300 bending cycles. Both RHCP and LHCP gains are provided. From the gain curves in Fig. 9, we conclude that the performance remains nearly the same even after 300 bending cycles.

For comparison, the realized gain of the copper tape antenna dropped by about 2 dB after only 50 bending cycles. No further mechanical tests were performed for the copper tape prototype as it became brittle. That is, as shown in Fig 10, the copper spiral had breaks in its surface making it not usable. These tests demonstrate the mechanical robustness of our textile technology, and make our design highly attractive for several conformal and load-bearing applications.

V. Conclusion

A novel textile spiral antenna was designed and tested for conformal and load-bearing applications. The antenna and its ground plane were embroidered using a new class of Elektrisola E-threads that can achieve geometrical precision as high as 0.1mm. The antenna performance was assessed when: a) planar in free-space, and b) curved upon a metallic cylinder. In both cases, the textile spiral was found to exhibit a nearly 10:1 bandwidth (0.3–3 GHz) with near consistent circularly polarized gain of 6.5dBi. Such performance has never before been achieved on textiles and flexible surfaces. Importantly, the spiral showed non-appreciable changes in performance, even after 300 flexing cycles. Repeatability of our textile fabrication technology was also confirmed for the first time. The proposed spiral is very attractive for several wideband, conformal, and load-bearing applications, such as airborne and wearables.

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