Fabrication of Textile Antennas and Circuits With 0.1 mm Precision

Asimina Kiourti, *Member, IEEE*, Cedric Lee, *Student Member, IEEE*, and John L. Volakis, *Fellow, IEEE*

***Abstract*—We present a new selection of E-fibers (also referred to as E-threads) and associated embroidery process. The new E-threads and process achieve a geometrical precision down to 0.1 mm. Thus, for the first time, accuracy of typical printed circuit board (PCB) prototypes can be achieved directly on textiles. Compared to our latest embroidery approach, the proposed process achieves: 1) 3× higher geometrical precision; 2) 24× lower fabrication cost; 3) 50% less fabrication time; and 4) equally good RF performance. This improvement was achieved by employing a new class of very thin, 7-filament, Elektrisola E-threads (diameter $\approx$ 0.12 mm, almost 2× thinner than before). To validate our approach, we "printed" and tested a textile spiral antenna operating between 1–5 GHz. Measurement results were in good agreement with simulations. We envision this textile spiral to be integrated within a cap and unobtrusively acquire neuropotentials from wireless fully-passive brain implants. Overall, the proposed embroidery approach brings forward new possibilities for a wide range of applications.**

***Index Terms*—Conductive textiles, E-fibers, E-threads, embroidered antennas, embroidery geometrical precision, flexible antennas, spiral.**

I. Introduction

TEXTILE antennas and circuits are becoming attractive for applications that require conformality, flexibility, and ruggedness [1]–[3]. Example applications include but are not limited to: RFIDs [4], [5], medical sensors [6], wearable electronics [7], [8], etc. However, a challenge in reported embroidery processes [1], [4], [9], [10] is the achieved geometrical precision. This is very important for antennas and circuits with intricate details [11].

Recently, we developed an embroidery process that achieved precision down to 0.3 mm [10]. This process employed 20-filament Liberator E-fibers [12] (diameter $\approx$ 0.22 mm) with automated double-layer embroidery of 7 threads/mm. Yet, higher precision is still desired. In this regard, we note that the typical geometrical precision of printed circuit board (PCB) prototypes is 0.1 mm.

In this letter, we present an embroidery process that achieves geometrical precision down to 0.1 mm, viz. 3× better than that reported in [10]. Concurrently, and as compared to [10], the proposed process leads to: 24× lower fabrication cost, 50% less time required for fabrication, and equally good RF performance. To obtain this remarkable improvement (see Fig. 1), we employed a new class of very thin (diameter $\approx$ 0.12 mm), 7-filament, Elektrisola E-threads [13]. We note that this is the first time that Elektrisola E-threads are used for this class of applications. The density of the embroidery was optimized as single-layer stitching of 7 threads/mm. Validation of the proposed embroidery process was carried out for a textile spiral antenna at 1–5 GHz. This textile spiral is intended for integration into a cap to unobtrusively acquire neuropotentials from wireless fully-passive brain implants [14]. Overall, the proposed embroidery process brings forward a new capability for a wide range of applications.

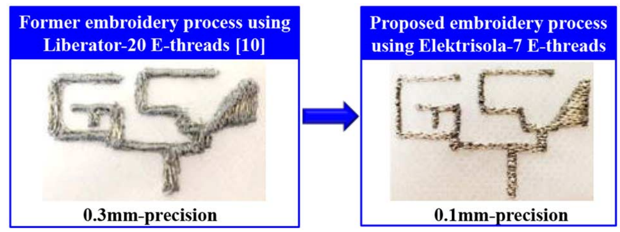

Fig. 1. Former [10] versus proposed embroidery process for achieving geometrical precision down to 0.1 mm.

II. Embroidery Process

The proposed embroidery process is shown in Fig. 2. Specifically, computer-aided design (CAD) files were exported to a Brother embroidery software toolset and converted into digitized stitching patterns (needle paths). An automated embroidery process was then applied using a programmable sewing machine. The conductive textile surfaces were realized using 7-filament silver-plated copper Elektrisola E-threads, 0.12 mm in diameter [13]. The latter exhibit very low dc resistance of 1.9 Ω/m. For comparison, our former embroidery process [10] employed 20-filament Liberator threads that: 1) were 2× times thicker; 2) exhibited 3.5× higher dc resistance; and 3) cost 12× more.

The thinner Elektrisola-7 threads imply lower embroidery tension and higher flexibility and can lead to geometrical precision down to 0.1 mm, viz. 3× better than [10]. Also, lower dc resistance implies that single-layer embroidery can now be employed to realize highly conductive textile surfaces. Previously in [10], we employed double-layer stitching, embroidering a second layer right atop the first layer, to increase conductivity. In both cases, the embroidery density was optimized as single-layer stitching of 7 threads/mm. Same as in

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The authors are with the ElectroScience Laboratory, Electrical and Computer Engineering Department, The Ohio State University, Columbus, OH 43212 USA (e-mail: kiourti.1@osu.edu; lee.6256@osu.edu; volakis.1@osu.edu).

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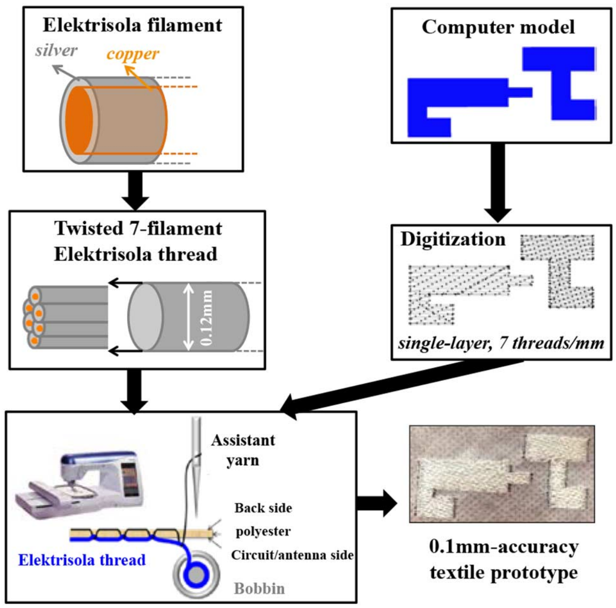

Fig. 2. Proposed embroidery process to achieve 0.1 mm geometrical precision.

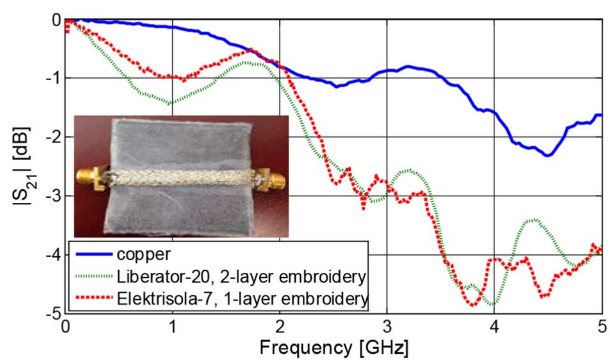

Fig. 3. Measured transmission coefficient, $|S_{21}|$, for a transmission line prototype with TLs and ground planes made of: (a) copper, (b) Liberator-20 E-threads with double-layer stitching and 7 threads/mm (former embroidery process [10]), and (c) Elektrisola-7 E-threads with single-layer stitching and 7 threads/mm (new embroidery process).

[10], optimization was performed by "printing" and testing several 50-Ω transmission lines (TLs). The latter employed a 1.5-mm-thick polydimethylsiloxane (PDMS) polymer ($\varepsilon_r = 3$, $\tan\delta < 0.01$) substrate.

As a proof-of-concept, the 50-Ω TL in Fig. 3 was fabricated and tested on: (a) copper; (b) Liberator-20 E-fibers with double-layer stitching and 7 threads/mm (former embroidery process [10]); and (c) Elektrisola-7 E-threads with single-layer stitching and 7 threads/mm (new embroidery process). As seen, the proposed process leads to TLs having RF performance close to that achieved in [10]. Concurrently, 50% less time is now required to "print" the desired prototype (single- versus double-layer embroidery). Also, overall cost is reduced by 24× (2× because of single- versus double-layer embroidery, and 12× because of the reduced E-thread cost, as noted above). More importantly, geometrical precision is now 3× better than [10].

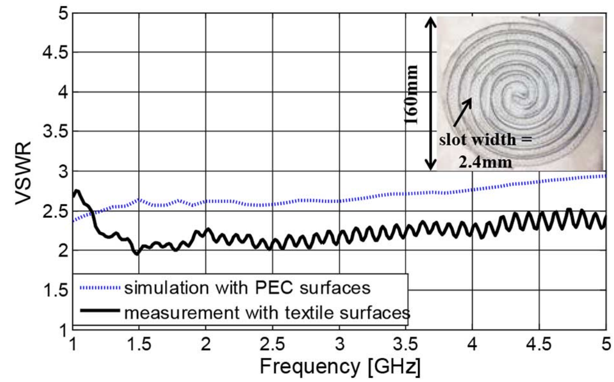

Fig. 4. VSWR of the fabricated textile spiral used to validate the proposed embroidery process.

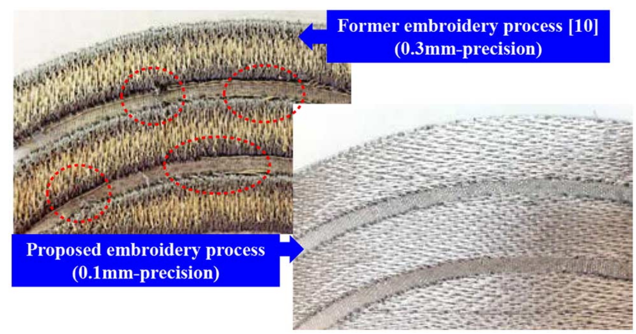

Fig. 5. Precision improvement achieved by the proposed versus our former [10] embroidery process in printing the textile spiral antenna.

III. Validation of the Proposed Embroidery Process for a Textile Spiral Antenna

To validate the proposed embroidery process, we proceeded to "print" and test a textile spiral antenna at 1–5 GHz. The inset of Fig. 4 shows the fabricated prototype using Elektrisola-7 E-threads with single-layer stitching (proposed embroidery process). It is a 160-mm-diameter Archimedean spiral having a slot width of 2.4 mm and a strip width of 8.5 mm. Fig. 5 clearly illustrates the improved geometrical precision achieved by the proposed embroidery process versus our former process reported in [10].

The measured versus simulated voltage standing wave ratio (VSWR) is shown in Fig. 4. As seen, measurement results agree well with simulations assuming perfect electric conductor (PEC) surfaces. The lower measured VSWR values were likely due to loss in the textile surface.

Simulated versus measured boresight realized gain results are shown in Fig. 6(a). Both right-hand circular polarization (RHCP) and left-hand circular polarization (LHCP) gains are given. As seen, measurements agree very well with simulations assuming PEC surfaces, for frequencies up to around 3 GHz. At higher frequencies, the textile prototype exhibits lower realized gain as compared to simulations. This was expected and can be attributed to losses from roughness and imperfect metallization of the textile surface. We remark that a similar deterioration in RF performance at higher frequencies is also observed in Fig. 3. Example measured versus simulated radiation patterns at 1.2, 2.4, and 4.8 GHz are shown in Fig. 6(b). Finally, as seen

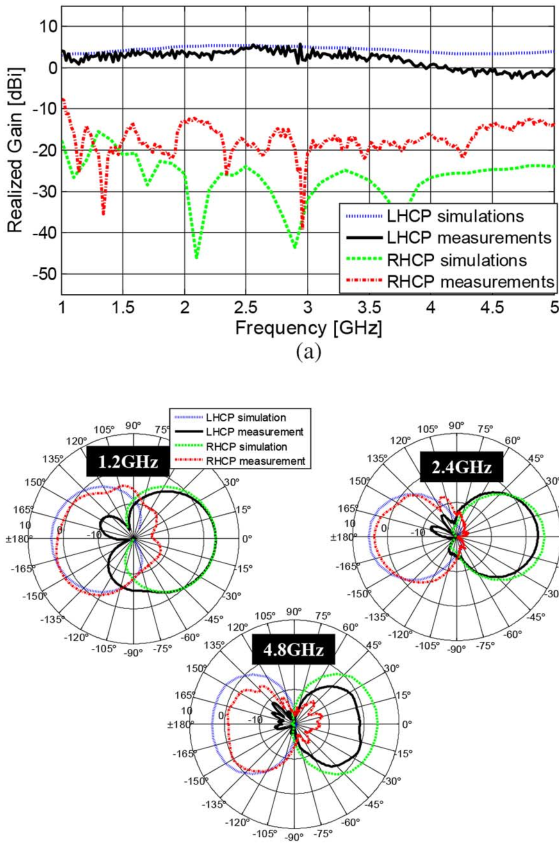

Fig. 6. Gain performance of a textile spiral antenna used to validate the proposed embroidery process: (a) Boresight realized gain vs. frequency, (b) Realized gain radiation patterns at 1.2, 2.4, and 4.8 GHz.

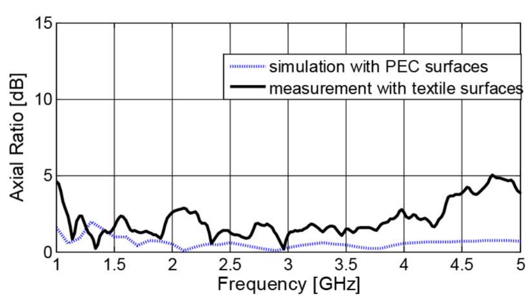

Fig. 7. Axial ratio of textile spiral antenna used to validate the proposed embroidery process.

in Fig. 7, an axial ratio of < 3 dB was measured across almost the entire frequency range of interest. Again, as would be expected, measurements show deteriorated performance at higher frequencies.

IV. Conclusion

A new selection of E-threads and associated embroidery approach was presented to achieve 0.1 mm precision in fabricating textile antennas and circuits with intricate details. Compared to our latest embroidery approach, the proposed process achieved: 1) $3\times$ higher geometrical precision; 2) $24\times$ lower fabrication cost; 3) 50% less fabrication time; and 4) equally good RF performance. These improvements are due to a new class of 7-filament Elektrisola E-threads, 0.12 mm in diameter. Automated embroidery was employed using a programmable sewing machine to fabricate or "print" the antenna. Validation was then carried out by "printing" and testing a textile spiral antenna at 1–5 GHz. We envision this antenna integrated within a cap to unobtrusively acquire neuropotentials from wireless fully-passive brain implants.

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