High-Geometrical-Accuracy Embroidery Process for Textile Antennas With Fine Details

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(Invited Paper)

***Abstract*—An embroidery process with high geometrical accuracy is presented for antennas with fine details. Previous embroidery processes employed thicker threads, leading to resolution not better than 1 mm. Therefore, fine details (e.g., sharp corners) could not be realized, and geometrical accuracy was low, viz. $>$ 1 mm. To overcome these limitations, in this letter we: 1) employ much thinner E-fibers to enable the "printing" of sharp corners, and 2) increase embroidery density to boost surface conductivity. Two Liberator E-fibers were tested: 1) 40-strand (diameter $= 0.27$ mm), and 2) 20-strand (diameter $= 0.22$ mm). Embroidery density was optimized using double-layer stitching of 7 threads/mm. To validate our embroidery approach, we fabricated and tested a dipole antenna with intricate details operating at 2.4 GHz. This design could not be formerly "printed" on textiles. Both E-fiber (40/20-strand) prototypes exhibited excellent performance, comparable to that of copper antennas. The achieved geometrical accuracy was ~ 0.3 mm (viz. 3 times better).**

***Index Terms*—Conductive textiles, embroidered antennas, embroidery geometrical accuracy.**

I. Introduction

TEXTILE antennas were recently introduced for conformal applications that require flexibility, light weight, and mechanical strength [1]–[3]. Examples include textile body-worn antennas for wireless communications [4]–[7], textile RFID tag antennas [8], and textile medical sensors [9]. In the past, we demonstrated embroidery of metal-coated polymer fibers (E-fibers) [1] as a promising alternative to carbon nanotube impregnated fabrics [10], [11], conductive tapes adhered on fabrics [12], electrically conductive yarns [13], [14], screen–printed silver nanowires [15], and liquid metal alloys [16]. E-fibers were shown to provide better mechanical strength and tolerance to fatigue [1] and were fabricated using a standard sewing machine. The latter implies their fabrication was of low cost.

A challenge with previous E-fibers was their large thickness to achieve improved conductivity. However, this compromised geometrical accuracy. Specifically, our former embroidery process employed: 1) 664-strand (diameter $=$ 0.53 mm) Amberstrand E-fibers [17], and 2) double–layer stitching of 2 threads/mm [1]. In doing so, the embroidered surface conductivity was close to that of copper [1], [4]. However, these thick E-fibers could not enable the sewing or "printing" of fine details (e.g., sharp corners). Concurrently, accuracy was low, viz. $>$ 1 mm. Therefore, miniature antennas and/or antennas with fine geometrical complexities could not be "printed" using the previous textile embroidery approach [1], [4].

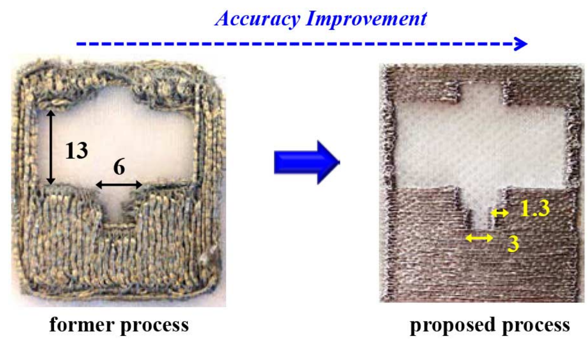

Fig. 1. Proposed versus former [1] embroidery process for "printing" textile antennas with fine details.

In this letter, we present a new embroidery process with high geometrical accuracy for E-fiber antennas. The proposed process improves geometrical accuracy by a factor of 3 and has a resolution of $\sim$ 0.3 mm (see Fig. 1). This significant improvement is achieved by employing much thinner E-fibers. The latter exhibit low embroidery tension and high flexibility and can, therefore, lead to more accurate shapes. To account for tradeoffs in conductivity, the stitching pattern is also modified. Specifically, the embroidery density is increased to minimize physical discontinuities and, thus, boost the surface conductivity. Two Liberator E-fibers are used for improved accuracy: 1) 40-strand (diameter $=$ 0.27 mm), and 2) 20-strand (diameter $=$ 0.22 mm). We note that this is the first time that Liberator E-fibers are used in textile antenna embroidery. To ensure good conductivity using these thinner E-fibers, the embroidery density was increased to 7 threads/mm (as compared to 2 threads/mm using the thicker E-fibers [1], [4]).

Validation of the new embroidery process was carried out by testing a dipole antenna with intricate details operating at 2.4 GHz. This design could not be formerly embroidered using textiles. Both E-fiber (40/20-strand E-fibers) prototypes were found to exhibit excellent performance, comparable to that of their copper counterpart.

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II. Embroidery Process with High Geometrical Accuracy

The E-fiber threads used for the proposed embroidery process are multi-strand metal-clad Liberator E-fibers [17]. Specifically, two E-fibers were tested: 1) Liberator-40 (40 strands, diameter = 0.27 mm), and 2) Liberator-20 (20 strands, diameter = 0.22 mm). These E-fibers have advantages over traditional conductive wires in terms of flexibility, weight savings, mechanical strength, and durability, all being crucial for microwave applications. Each strand is composed of a ~ 23 μm thick liquid crystal polymer (LCP) Vectran fiber core and is coated with two metal coatings, viz. copper (inner layer) and silver (outer layer). Before embroidery, these E-fibers were twisted with a twist per inch of TPI = 4.5. These highly twisted threads were then employed in a sewing machine to realize textile surfaces (without a need for braiding). By contrast, the former Amberstrand-664 E-fibers (664 strands, diameter = 0.53 mm) were twisted at TPI = 1.7. This lower TPI implied that the E-fibers could potentially get untwisted during embroidery and clog the sewing machine. Thus, they had to be braided prior to embroidery. This latter step was often time-consuming.

As would be expected, the drawback in employing thin E-fibers versus our former thick E-fibers is lower conductivity. Specifically, the dc resistance of Amberstrand-664, Liberator-40, and Liberator-20 is 0.7, 1, and 2 Ω/ft, respectively [17]. To address this inevitable degradation in conductivity, we increased the embroidery density. Denser embroidery reduced physical discontinuities in the "printed" surfaces. However, in practice, denser embroidery is more challenging since it may lead to sewing needle breakage. Also, embroidery software tools may have stitching density limitations. Therefore, it is important to optimize embroidery density versus conductivity and geometrical accuracy. This was done by fabricating and testing several 50-Ω transmission lines (TLs) as depicted in Fig. 2. These textile prototypes were placed on a polydimethylsiloxane (PDMS) polymer ($\varepsilon_r = 3$, $\tan\delta < 0.01$) substrate, 1.5 mm thick [18]. The embroidery density was finally chosen to be double-layer stitching of 7 threads/mm. For comparison, our former embroidery process employed double-layer stitching of Amberstrand-664 at a much sparser density of 2 threads/mm [1].

Fig. 2 shows four TL prototypes with TLs and ground planes made of: (a) copper tape, (b) Amberstrand-664 with double-layer stitching of 2 threads/mm (former embroidery process), (c) Liberator-40 with double-layer stitching of 7 threads/mm (proposed embroidery process), and (d) Liberator-20 with double-layer stitching of 7 threads/mm (proposed embroidery process). The S-parameter performance of these prototypes is given in Fig. 3. As seen, the Liberator-40 threads lead to TLs having conductivity and loss similar to those achieved by our former threads and embroidery process. As expected, Liberator-20 threads have better geometrical accuracy but lead to a slightly lower conductivity. This is because the latter are associated with lower conductivities.

In brief, the proposed embroidery process achieves good RF performance up to ~ 3.5 GHz, as was the case with our former embroidery process [1], [4]. However, it provides much improved geometrical accuracy. This is demonstrated next.

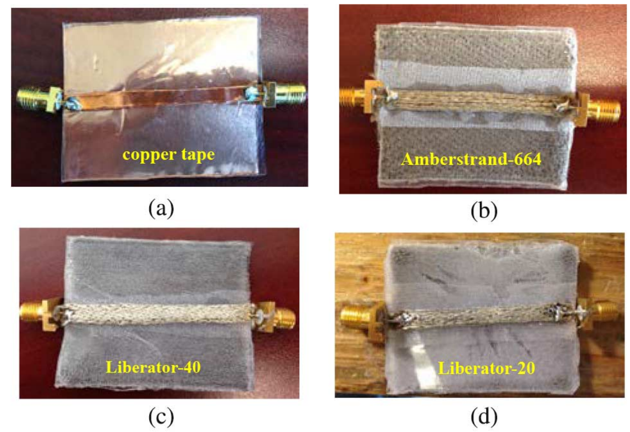

Fig. 2. TL prototypes used to optimize the embroidery density: (a) copper tape, (b) Amberstrand-664 with double-layer stitching of 2 threads/mm (former process), (c) Liberator-40 with double-layer stitching of 7 threads/mm (proposed process), and (d) Liberator-20 with double-layer stitching of 7 threads/mm (proposed process).

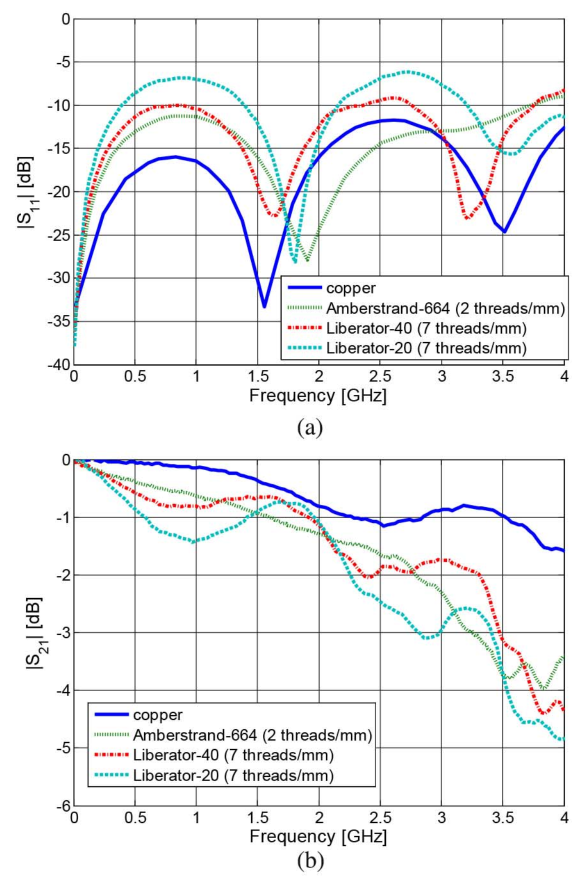

Fig. 3. Measured S-parameters of the TL prototypes shown in Fig. 2: (a) reflection coefficient, $|S_{11}|$, and (b) transmission coefficient, $|S_{21}|$.

III. E-Fiber Antennas With Fine Details

We proceed to validate the proposed embroidery process for textile antennas with fine details. To do so, we fabricated and tested two E-fiber antenna prototypes (40/20-strand Liberator

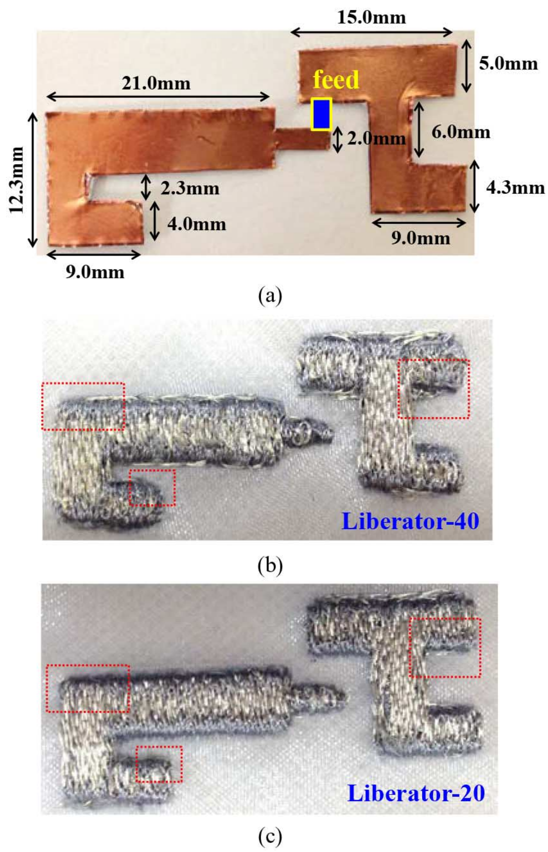

Fig. 4. Antenna prototype used to validate the proposed embroidery process [19]: (a) copper tape, (b) Liberator-40 with double-layer stitching of 7 threads/mm, and (c) Liberator-20 with double-layer stitching of 7 threads/mm (areas marked in red indicate superior performance using the Liberator-20 in printing sharp corners).

threads). We used 7 threads/mm and double-layer embroidery for these prototypes. The antenna is the 2.4-GHz dipole in Fig. 4 (39.0×18.8 mm^2 in size), a modified version of the one presented in [19]. This dipole was selected because of its geometrical complexities, i.e., miniature size, sharp corners, slots, and required accuracy of 0.3 mm. We note that this antenna could not be "printed" using our former embroidery process. For comparison, the copper tape counterpart of this antenna was also fabricated and tested.

As seen in Fig. 4, both antenna prototypes were accurately "printed" using E-fibers. Notably, the 2.3-mm-wide slot and 4.3/12.3-mm-wide arms were accurately embroidered, indicating geometrical "printing" feasibility down to 0.3 mm. As would be expected, the Liberator-20 E-fibers were found to be slightly superior in "printing" sharp corners (areas marked in red in Fig. 4). The measured reflection coefficient ($|S_{11}|$) data of the E-fiber and copper antennas are shown in Fig. 5, indicating excellent agreement. The measured antenna patterns at 2.4 GHz are also given in Fig. 6. These exhibit very good agreement as well.

From the data in Figs. 5 and 6, the Liberator-40 prototype was found to perform nearly the same as its copper counterpart. However, the Liberator-20 prototype exhibited ~ 0.6 dB lower gain, on average. This is attributed to the lower conductivity of the Liberator-20 embroidered surface (see Section II). Therefore, we may conclude that Liberator-20 E-fibers should be selectively employed for only those antenna portions that exhibit challenging geometrical complexity.

The proposed embroidery process can be applied to "print" any desired geometry on E-fibers. For example, Fig. 7 shows Archimedean, sinusoidal, toothed, and trapezoidal geometries

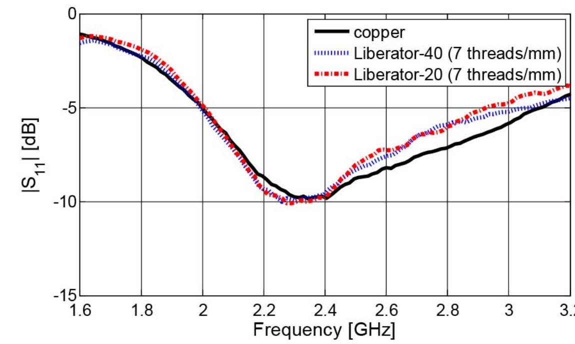

Fig. 5. Measured reflection coefficient, $|S_{11}|$, of the dipole antenna prototypes shown in Fig. 4.

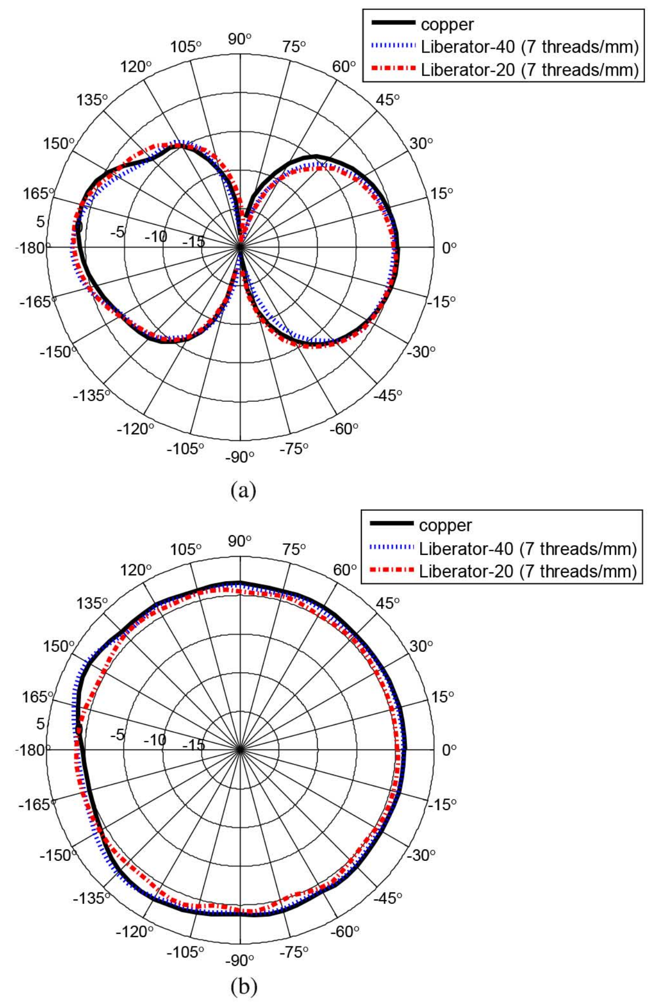

Fig. 6. Measured radiation pattern at 2.4 GHz of the dipole antenna prototypes shown in Fig. 4: (a) E–plane and (b) H–plane (gain values are given in dBi).

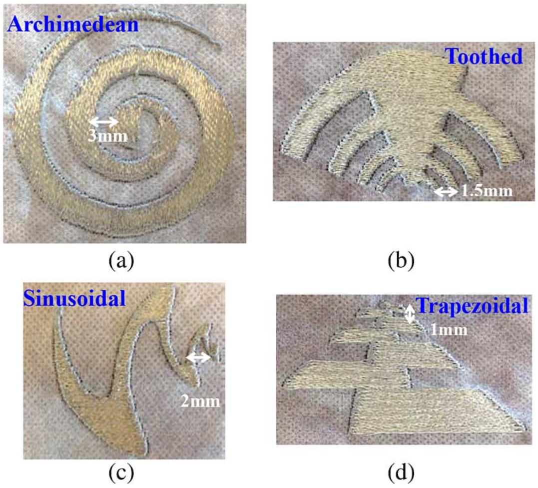

Fig. 7. Example complex geometries "printed" on E-fibers using the proposed embroidery process: (a) Archimedean, (b) toothed, (c) sinusoidal, and (d) trapezoidal.

"printed" on textiles. These are example prototypes showing the flexibility of the E–fiber "printing" process.

IV. Conclusion

A new embroidery process with high geometrical accuracy was presented for antennas with fine details (down to $\sim$ 0.3 mm accuracy). This was done by employing: 1) very thin E-fibers: 40- and 20-strand Liberator E-fibers, and 2) double-layer embroidery using 7 threads/mm stitching density to boost surface conductivity. For the first time, miniature antennas and/or antennas with fine geometrical complexity were realized on textiles with accuracy down to 0.3 mm. These fabricated E-fiber antennas exhibited excellent agreement in terms of reflection coefficient, gain, and pattern data as compared to their copper counterparts. Concurrently, they have remarkable flexibility, mechanical strength, and tolerance to fatigue. Liberator-20 threads were found to be slightly superior in "printing" sharp corners, but exhibited $\sim$ 0.6 dB loss in realized gain. As such, the Liberator-20 E-fibers can be selectively employed to embroider only those antenna portions that exhibit the finest geometrical complexity.

Such embroidered antennas are mechanically strong and robust, yet comfortable, flexible, lightweight, and attractive for inconspicuous daily wearing [2], [20]. Therefore, they can be integrated into daily garments to realize wireless wearable devices for a wide range of applications (medical, body-worn, sports, space, etc.). Future work will involve: 1) more accurate modeling of the textile surface to predict performance of the embroidered antenna using the electrical properties of E-fiber threads, and 2) radiation efficiency measurements.

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