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Article

Colorful Textile Antennas Integrated into Embroidered Logos

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Abstract: We present a new methodology to create colorful textile antennas that can be embroidered within logos or other aesthetic shapes. Conductive threads (e-threads) have already been used in former embroidery unicolor approaches as attributed to the corresponding conductive material, *viz.* silver or copper. But so far, they have not been adapted to 'print' colorful textile antennas. For the first time, we propose an approach to create colorful electronic textile shapes. In brief, the embroidery process uses an e-thread in the bobbin case of the sewing machine to embroider the antenna on the back side of the garment. Concurrently, a colorful assistant yarn is threaded through the embroidery needle of the embroidery machine and used to secure or 'couch' the e-threads onto the fabric. In doing so, a colorful shape is generated on the front side of the garment. The proposed antennas can be unobtrusively integrated into clothing or other accessories for a wide range of applications (e.g., wireless communications, Radio Frequency IDentification, sensing).

Keywords: conductive textiles; e-threads; embroidered antennas; colorful textile antennas; logo antennas; dipole antenna; wireless communications; RFIDs; sensing

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1. Introduction

Wearable devices are of growing interest for several applications, including wireless communications, Radio Frequency Identification (RFID), sensing, *etc.* [1–5]. As would be expected, these wearable devices require antennas that are flexible, conformal, and robust to withstand daily wear and repetitive washing/drying. In the past, we demonstrated embroidery of conductive threads (e-threads) to realize textile antennas that address the aforementioned challenges [6–8]. The employed e-thread consists of a twisted bundle comprised of 7–600 metal-coated polymer filaments. This implies that the e-threads are unicolor as attributed to the corresponding conductive material. That is, they are silver-colored if the conductor coating is silver, and copper-colored if their conductor coating is copper. Thus, they cannot be employed to 'print' colorful textile antennas.

Of course, integration or 'printing' of wearable antennas into colorful logos or other aesthetic shapes would significantly enhance their unobtrusive nature and consequently their wider usage. In [9], authors discussed antenna designs focusing on aesthetic qualities relating to geometry and shaping (see Figure 1a). In this case, logo-type antennas were fabricated by etching copper on rigid substrates. Thus, they were not suitable for body-worn applications. In [10], logo-based RFID antennas were realized via manual cutting of copper tape adhered to the fabric (see Figure 1b). Also in [10,11] conductive inks were used to 'print' antennas on fabrics and temporary tattoo inkjet paper, respectively (see Figure 1c). However, these approaches may lead to delamination and ink surface rupture when flexed. In [12], conductive fabrics were employed to create shapes by a cutting plotter to mimic company logos (see Figure 1d). Again, the realized prototypes were detaching from the conductive fabrics after several washings and flexing.

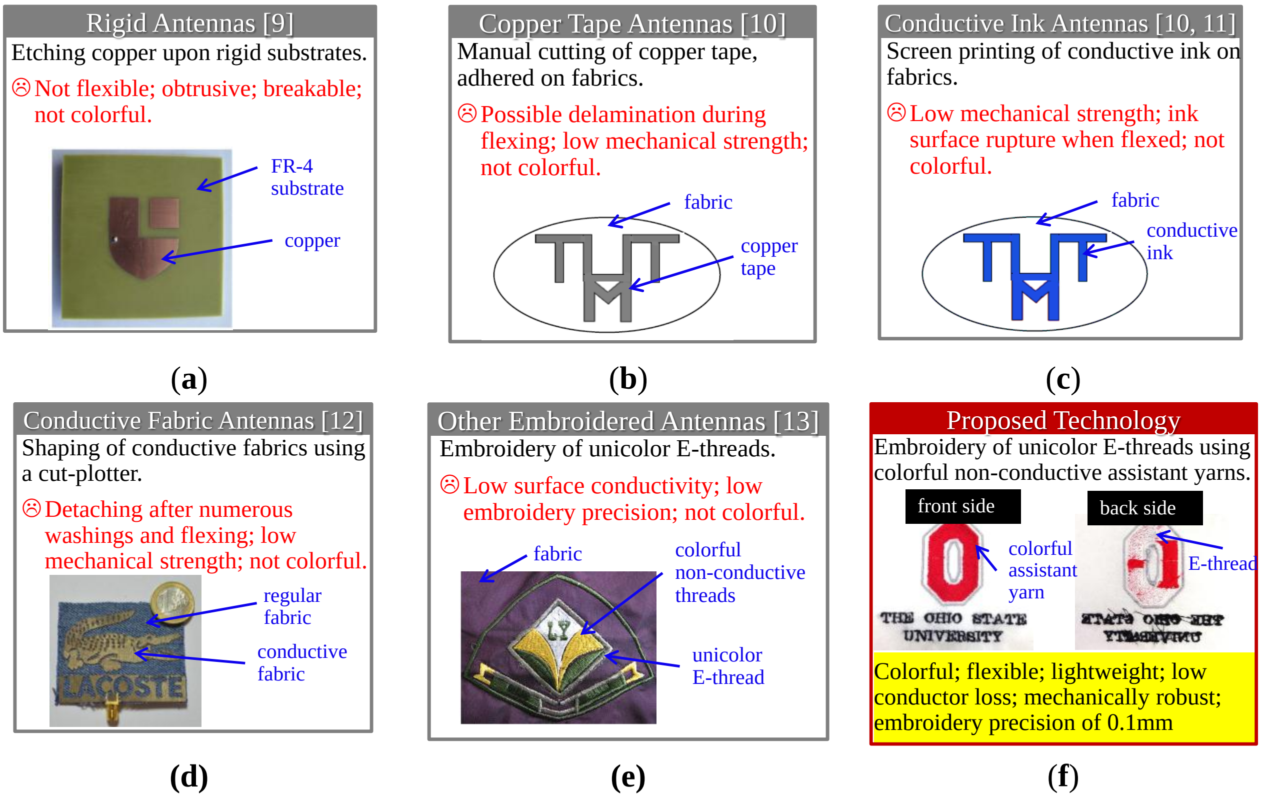


Figure 1. Former technologies used to realize wearable logo-shaped antennas: (**a**) rigid antennas © John Wiley and Sons [9]; (**b**) copper tape antennas [10]; (**c**) conductive ink antennas [10,11]; (**d**) conductive fabric antennas © IEEE [12]; (**e**) other embroidered antenna © IEEE [13]; *versus* (**f**) proposed technology.

To address the aforementioned concerns, a logo-shaped antenna was proposed in [13] using embroidered e-threads (see Figure 1e). However, color was only placed in the embroidered area that surrounded the antenna. The actual embroidered antenna did not incorporate any color (grey color in Figure 1e).

In this paper, we propose a new approach for realizing colorful textile antennas based on automated embroidery of conductive e-threads. As seen in Figure 1f, the developed textile antennas are colorful, highly flexible, conformal, lightweight, mechanically robust, and exhibit similar performance to their copper counterparts. Concurrently, the shape precision or resolution via our embroidery process can be as high as 0.1 mm. Section 2 describes the proposed embroidery process. Subsequently, Section 3 provides validation of a textile dipole antenna embroidered via this process.

2. Embroidery Process for Colorful Textile Antennas

A new approach is proposed to create colorful textile antennas that can be embroidered within logos and other aesthetic shapes. In brief, the embroidery process uses an e-thread in the bobbin case of the embroidery machine to 'print' the antenna on the back side of the garment. Concurrently, a colorful assistant yarn is threaded through the needle of the embroidery machine and used to secure or 'couch' the e-threads onto the fabric. In doing so, a colorful shape is generated on the front side of the garment. This embroidery process is depicted in Figure 2, and can be summarized as follows:

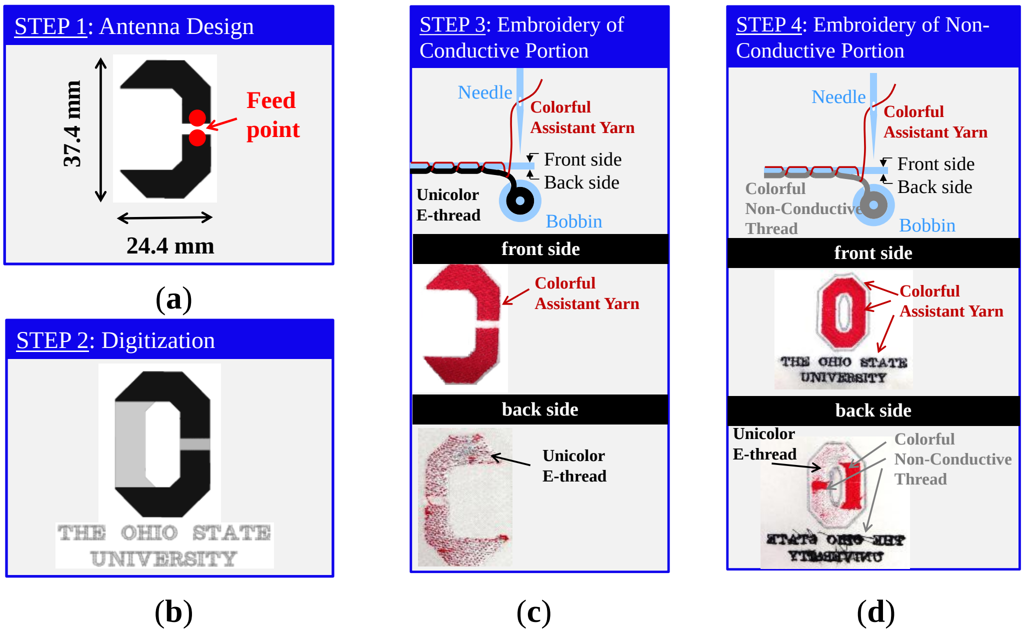


Figure 2. Proposed technology for colorful logo antennas: (**a**) STEP 1: antenna design; (**b**) STEP 2: digitization; (**c**) STEP 3: embroidery of conductive parts; (**d**) STEP 4: embroidery of non-conductive parts.

1) *Antenna design*. An antenna design is developed to satisfy pre-specified performance criteria, including gain, bandwidth, size and operational frequency. This can be done via any desired computational or analysis method (see Figure 2a).

2) *Digitization*. The desired logo or aesthetic shape, and the back-side antenna are digitized and put into the embroidery machine's format for loading. Referring to Figure 2b, the black color indicates the conductive portion of the logo (*viz*. the antenna), while the grey color indicates the non-conductive section (*viz*. the portion that surrounds the antenna to form the desired shape). The Computer Aided Design (CAD) file imported into the embroidery machine software contains the identification of the front and back side of the pattern in digital format.

3) *Embroidery of conductive part*. After loading the CAD file, the automated embroidery process is executed to 'print' the conductive parts of the logo; that is the antenna shown in black color in Figure 2b. To do so, the e-thread is placed inside the bobbin case of the embroidery machine. Concurrently, a colorful assistant yarn is threaded through the needle of the embroidery machine and used to 'couch' the e-thread on the fabric (see Figure 2c). As a result, the conductive portion of the logo becomes part of the colorful front side of the fabric. But in effect, the unicolor antenna formed by the conductive e-thread lies on the back side.

4) *Embroidery of non-conductive part*. The automated embroidery process is subsequently repeated for embroidering the non-conductive part of the logo. In this case, a non-conductive thread is placed inside the bobbin case of the embroidery machine. The colorful assistant yarn is used to 'couch' this non-conductive thread onto the fabric (see Figure 2d). Again, the colorful yarn appears in the front side of the fabric, while the non-conductive thread lies on the back side. This implies that the non-conductive thread fills in the design area not covered by Step 3. That is, Steps 3 and 4 complement each other to embroider the conductive and non-conductive parts of the entire logo.

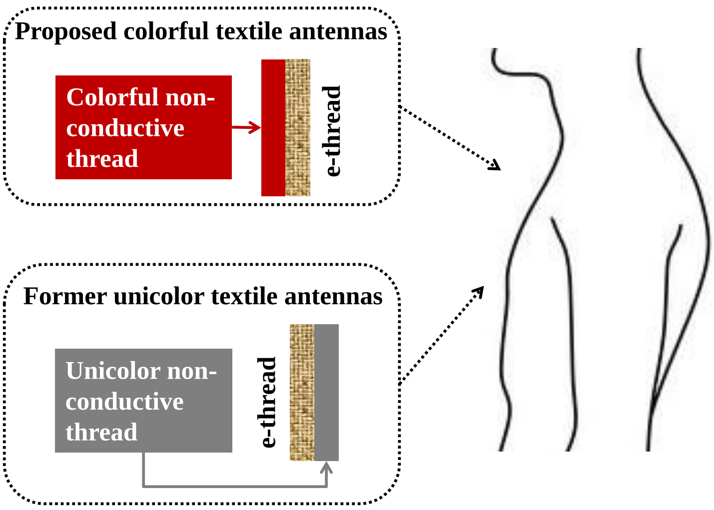


Figure 3. Side view of proposed colorful vs. former unicolor textile antennas.

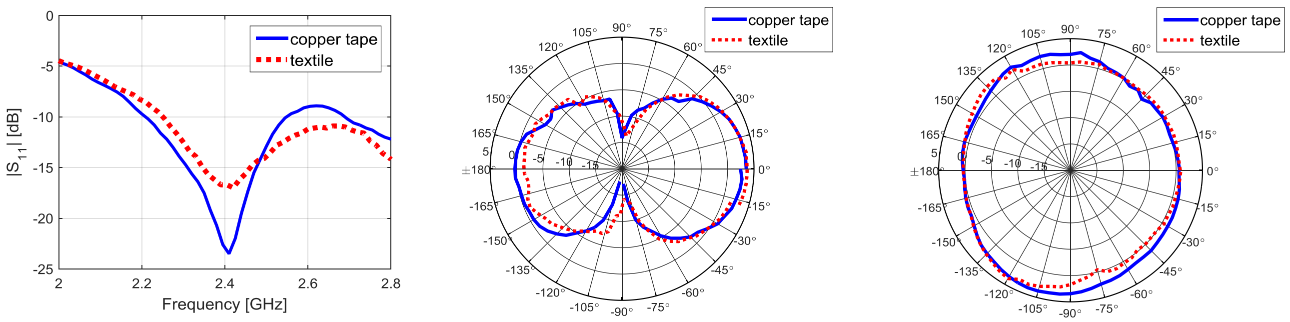
Figure 3 shows side views of the proposed colorful antennas vs. our former unicolor antennas. As seen, both technologies employ non-conductive threads to secure the e-threads onto the fabric. In the proposed antenna, the non-conductive threads are colorful and facing outward of the body. In our former antenna, the non-conductive threads were unicolor and were facing towards the body. Nonetheless, as noted in [6–8], the non-conductive threads behave pretty much like free-space, and do not affect the antenna performance in any way. Therefore, antennas 'printed' using either of these two approaches will perform the same way. As will be illustrated in the next section, the radiation pattern of the proposed colorful dipole is nearly omnidirectional, and similar to our former unicolor textile dipole in [7]. When placed upon the human body, these two dipoles will perform in the exact same way, *viz*. they will radiate outwards. Of course, extra care is necessary so that the conductive portion of the colorful textile antenna is not in direct contact with the skin, which can be conductive and will short-circuit the antenna. Fabrics or thin polymer coatings can be placed between the antenna and the skin tissue to avoid such direct contact.

3. Validation of a Colorful Textile Dipole Antenna as Part of the OSU Logo

To validate the proposed embroidery process, we proceeded to fabricate and test a 2.4 GHz colorful textile antenna. The antenna design is shown in Figure 2a, and is a portion of the Ohio State University (OSU) logo. It forms a wide width dipole geometry that occupies 37.4 mm length × 24.4 mm width. This conductive portion of the OSU logo was embroidered using 7-filament Electrisola e-threads, each being 0.12 mm in diameter. This e-thread exhibits high flexibility and low DC linear resistance (1.9 Ω/m), and its embroidery was optimized as single-layer stitching using 7 e-threads/mm. Importantly, these e-threads and process were recently shown to achieve a geometrical precision down to 0.1 mm [14]. The antenna was 'printed' on organza fabric. For comparison purposes, the copper tape counterpart of this antenna was also fabricated and tested.

The measured reflection coefficient, $|S_{11}|$, of the textile and copper antennas is given in Figure 4a, indicating good agreement. The corresponding measured realized antenna gain patterns at 2.4 GHz are shown in Figure 4b (E-plane) and Figure 4c (H-plane). As seen, excellent agreement is achieved.

We may conclude that the colorful textile antenna prototype achieves excellent performance as compared to its copper counterpart. Concurrently, it is flexible, lightweight, and mechanically robust. Thus, it can be unobtrusively integrated into clothing or other accessories (e.g., T-shirts, caps, backpacks, shoes).



(**a**) (**b**) (**c**)

Figure 4. Measured performance of the textile and copper tape dipole prototypes: (**a**) reflection coefficient, $|S_{11}|$; (**b**) E-plane realized gain radiation pattern at 2.4 GHz; (**c**) H-plane realized gain radiation pattern at 2.4 GHz.

4. Conclusions

A new embroidered approach was presented to realize colorful textile antennas that can form part of embroidered logos or other aesthetic shapes. The resulting textile antennas are flexible, lightweight, and mechanically robust to withstand daily wear and repetitive washing/drying. Such prototypes can be unobtrusively embroidered onto all sorts of clothing and accessories for a very wide range of applications (e.g., wireless communications, RFIDs, sensing). To validate our technology, we fabricated and tested a 2.4 GHz colorful textile dipole antenna, integrated as part of an embroidered OSU logo. Reflection coefficient, gain, and pattern data indicate excellent agreement between the textile prototype and its copper counterpart. Future work will involve: (a) radiation efficiency measurements, (b) performance evaluation of colorful textile antennas placed upon the human body, and (c) performance evaluation of colorful textile antennas after washing and stressing.

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Author Contributions

A. Kiourti and J.L. Volakis conceived the idea and wrote the paper. A. Kiourti performed the fabrication and measurements. J.L. Volakis mentored this work.

Conflicts of Interest

The authors declare no conflict of interest.

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