Embroidered Wire Dipole Antennas Using Novel Copper Yarns

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Abstract—This letter presents a method of fabricating wearable antennas by embroidering novel fine copper yarn. In this work, fine copper wires are first twisted together to create a physically strong and yet flexible thread. A digital embroidery machine was used to create dipole antennas. The dc resistance of the antenna arms along with the return loss, radiation patterns, and efficiency of the antennas have been measured. The results are compared to embroidered dipoles using commercially available conductive threads and etched copper antennas.

Index Terms—Copper wire, embroidered antennas, fabric antennas, wearable electronics.

I. INTRODUCTION

MANY industries are seeking to enhance their technological capabilities by integrating wireless functionality into clothing and textiles. Specific applications include military, aerospace, search and rescue, telemedicine, fashion, etc. [1]–[4]. Wearable antennas have been constructed from a range of materials and using different fabrication methods [5]. Digital embroidery using conducting threads is a promising technique as the antennas can be integrated into clothing in an aesthetically pleasing manner, and as no glue, masks, or etching are required, it is suitable for single bespoke designs or mass manufacturing.

Previous research showed that the performance of microstrip patch antennas was dependent on the conductivity of the thread, the stitch direction, and stitch spacing [6], [7]. Higher efficiencies were achieved by stitching conducting threads in a direction parallel to the current flow. Therefore, embroidering two-dimensional structures (e.g., microstrip antennas) creates extra challenges compared to one-dimensional antennas such as dipoles.

The effects of stitch direction and density have also been considered for embroidered dipole antennas [8]. In that work, SHIELDEX commercial thread was used, which consists of interwound conducting and nonconducting filaments that were

then plated in silver. The paper considered the read range of radio frequency identification (RFID) devices and did not examine the efficiency directly. However, simulations indicated that the effective conductivity was less than 4000 S/m.

Flexible conductors constructed from silver–coated p-phenylene-2, 6-benzobisoxazole (PBO) have been used to embroider antennas [9]. The polymer core provides the mechanical strength essential to the embroidery process. Bundles of "several hundred" 15-μm-thick silver-coated threads are twisted together. A double-layer embroidery technique was used to improve the effective conductivity by minimizing the gaps between the threads. However, this inevitably reduces the flexibility of the device. Gain values within 1 dB of the etched copper equivalent were achieved, and the paper reported the antenna was robust to flexing and washing.

The same group has also embroidered antennas using Amberstrand commercial thread, which consists of a metallic coating on a polymer core [10]. The double thickness of embroidery stitches was used to increase the stitch density. Gain values within 0.6 dB of copper were achieved. However, the gain reduced above 4 GHz and also when curved around a cylinder as the stitch spacing was increased. Bending effects of nonembroidered antennas have also been considered [11], [12].

Ouyang and Chappell have investigated the performance of various monofilament and multifilament conducting threads at high frequencies using the waveguide cavity method [13]. These included silver-plated nylon and 60 40-μm-thick copper filaments. Composites of metallic and insulating threads are made by "wrapping 40 μm silver plated copper fibres around a nonconductive core." The insulating threads enhanced the physical durability of the resultant composite threads. The weaving threads were quite thick, which limited the thread spacing and resolution and would be less suitable for embroidery. Weaving gave better performance than knitting due to higher thread density. The threads made from fine copper and steel fibers had an effective conductivity of approximately 6000 S/m. The paper concluded that monofilament threads were better than the multifilament threads, and direct current (dc) measurements were only useful as an approximate indication of radio frequency (RF) performance. The seven threads examined all had a lower Q-factor than metal foil.

Previous papers have embroidered antennas using commercial threads. In this letter, a novel conducting yarn has been introduced. This was fabricated by twisting seven copper strands together. The thread is highly conducting and has the required physical properties to be suitable for embroidery. Dipole antennas have been made using this novel thread.
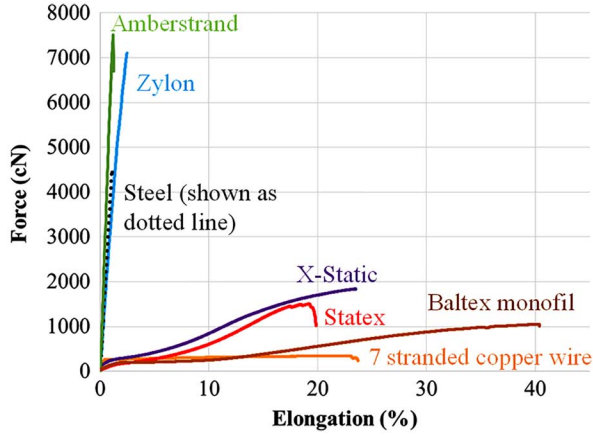
Fig. 1. Load extension graphs of the 7-filament copper thread compared to Amberstrand, steel, and other conductive threads.
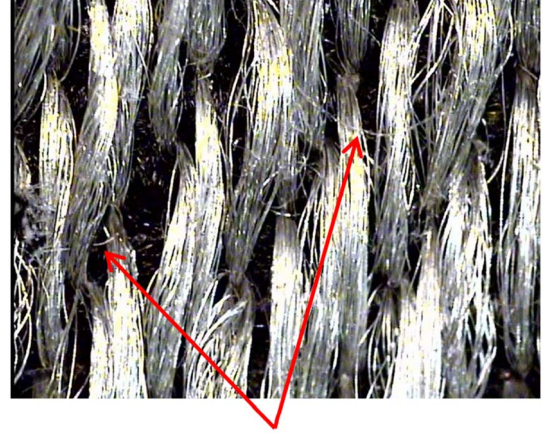

Fig. 2. Example of the filamenting of the Amberstrand thread seen under a microscope. Note the fine filaments running normal to the embroidered yarn.

Section II outlines the challenges of embroidering using metallic threads and introduces the novel twisted copper thread. Section III covers the dipole fabrication process. Measured results are discussed in Section IV. Finally, conclusions are in Section V.

II. COPPER THREAD FABRICATION AND EMBROIDERY CHALLENGES

Typically, metal yarns are not developed for use in embroidery and therefore do not have the desirable characteristics of a "normal" embroidery thread that is made from textile fibers. Metal yarns exhibit difficulty going around or through metal contact points (thread guides and needle eye, etc.) on the machine due to higher surface friction, especially at high speeds. The frictional drag would result in higher thread tensions, which often lead to breakages or fraying of the thread. There is also the issue that these contact points usually have a low radius of curvature resulting in higher pressure between contact surfaces according to a formula calculated by Pierre-Simon Laplace in 1805 to define the pressures applied on curved surfaces. Metal threads tend to exhibit poor recovery—this means that they keep their shape when deformed.

The copper wire used in this letter has been developed in collaboration with Luxion Technologies, Inc., Ltd. Fine copper filaments were drawn out by passing them through two sets of rollers rotating at different speeds—this is a very common process employed in spinning yarns, known as drafting. The copper threads used in this work are made by twisting seven very fine copper filaments using standard twisting machines. Investigation with different structures demonstrated that seven filaments was the optimum compromise between maintaining the flexibility to be embroiderable and the breaking strength under tension during the embroidery process. The load extension graph of the 7-stranded copper yarn compared to widely used conductive threads is shown in Fig. 1.

The multistrand copper wire behaves differently to stainless steel or Amberstrand. Based on breaking force, the copper thread was found to be 10 times weaker than other conductive threads. However, its extension at breaking point is similar to

conductive textile threads (i.e., 17%) except for the Amberstrand as shown in Fig. 1. The thread does not break excessively when embroidered. The Amberstrand thread is produced by using the strongest and the stiffest textile fiber "Zylon." The copper threads are ductile but not as strong as embroidery threads, which are generally made from synthetic fibers. Therefore, great care was taken to reduce the tension on the threads.

Unlike Amberstrand, the copper wire does not lead to filamenting or fuzzing; see Fig. 2, where broken filaments can be seen crossing the normal yarn direction.

III. DIPOLE FABRICATION

Dipole antennas were embroidered using Amberstrand and the novel copper yarn. The base material was a military clothing grade textile. It has been previously shown that using Teflon, which is a low-loss material, as the substrate in a patch antenna can improve the efficiency [14], [15]. Therefore, an additional layer of Teflon was included in two cases to create a total of four textile antennas; see Fig. 3.

The prototypes discussed in this letter were connected directly to a 100-mm-long, lightweight coaxial cable connected to a U-FL series ultra-miniature coaxial connector with a diameter of 1.32 mm. This connector is made up of two pressure-fitted parts, namely a tiny receptacle (inner core) and a plug (outer core/ground plane). The receptacle and the plug were soldered to opposite arms of the dipole. The dipole was then embroidered onto a denim layer. For the Amberstrand dipoles shown in Fig. 3(a) and (b), the soldering was on the top side of the dipole, while for the copper wire dipole, the connection is not visible since the soldering was performed on the underside of the dipole arms.

IV. RESULTS

Measured S_{11} values for the antennas are shown in Fig. 4. Other measured results are shown in Table I. The results indicate a measured gain of 4–6 dBi, which is higher than one would expect for a dipole antenna. Further investigation indicated that this was due to the positioner [16]. When the simulated antenna included the positioner, the gain increased to 4.54 dBi. The simulated positioner cylinder had a 72-mm diameter and
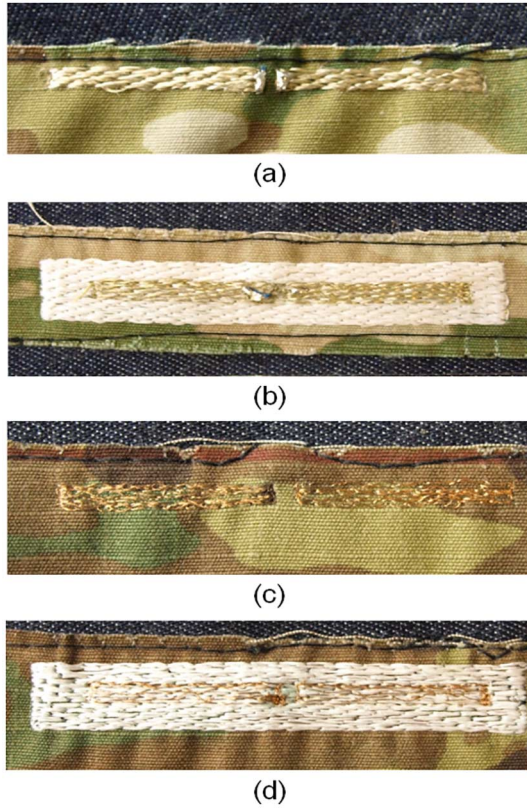
Fig. 3. Embroidered dipoles: (a) Amberstrand, (b) Amberstrand on Teflon, (c) copper yarn, and (d) copper yarn on Teflon.
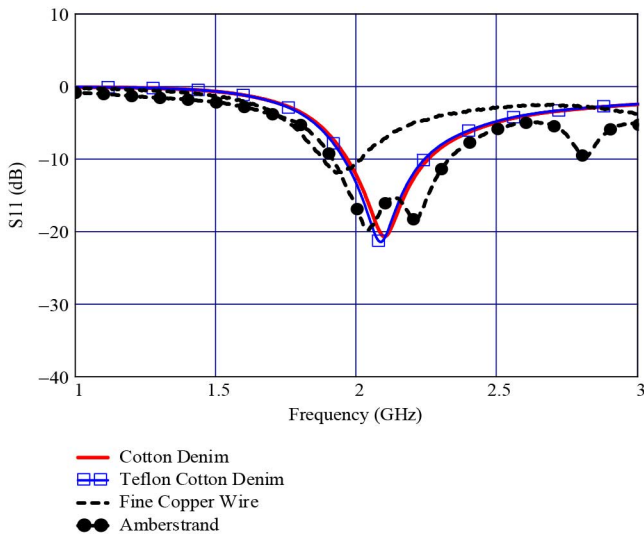

Fig. 4. Measured reflection coefficients of continuous copper-layer dipoles on different substrates, fine copper wire dipole on cotton denim, and full fabric Amberstrand on denim antenna.
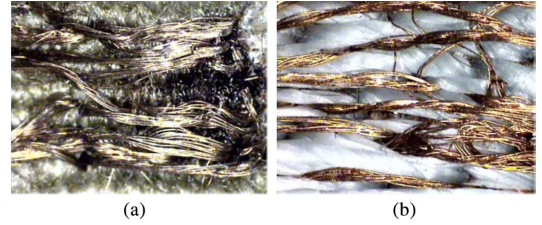

Fig. 5. Microscope images: (a) copper wire; (b) copper wire with Teflon.

TABLE I
MEASURED AND SIMULATED RESULTS OF ETCHED COPPER ON FR4, AMBERSTRAND (AM), AND COPPER (CU) WIRE

	Sim, with posi- tioner	FR4	AM	AM	Cu wire	Cu wire
Teflon layer	N	N	N	Y	N	Y
Length (mm)	57	57.25	60.70	56.48	55.11	54.43
Width (mm)	3.00	3.00	3.42	4.30	3.12	3.19
R_DC of arms (Ω)		0.2; 0.2	0.2; 0.2	0.2; 0.2	0.7; 1.0	0.9; 0.7
Freq (MHz)	1864	1748	2025	1966	1955	1940
RL (dB)	39.31	13.04	16.15	14.59	12.54	19.49
10dB BW (MHz)	256	195	413	425	306	253
Gain (dBi)	4.47	3.90	4.83	3.47	4.43	4.09
Directivity (dBi)	4.54	3.98	6.07	5.14	5.50	5.38
Eff. (%)	98.4	93.2	73.3	65.6	78.1	73.5

etched copper version on a low-loss FR4 substrate. However, the copper wire had a larger dc resistance than the Amberstrand dipole arms. The embroidered antennas exhibited a wider bandwidth than the etched and simulated antennas. However, this was at the expense of reduced efficiency.

The results in Table I indicate that adding a Teflon layer reduced the antenna efficiency. Visible inspection showed that the Teflon layer increased the spacing between the conducting threads; see Fig. 5. The copper wire dipoles had a higher efficiency than the embroidered Amberstrand versions. These efficiency results show that the dc resistance is only an approximate but not a reliable indicator of RF performance. Some resonant frequency variations were noted between simulated and measured etched copper dipoles. It is felt that these are caused by production uncertainties and variation in the physical properties of the FR4 substrate.

A. Radiation Patterns

The radiation patterns for the Amberstand and copper yarn dipoles (without the Teflon layer) are shown in Fig. 6 at the relevant resonant frequencies.

The cross-polarization component increases significantly compared to the etched copper version (not shown for space constraints). The cross-polarization components were reduced with the Teflon layer.

B. Gain on Body

The four antennas were also placed on the upper arm of a volunteer. Therefore, the antennas were bent around the arm

was composed of Acrylonitrile Butadiene Syrene (ABS), with a relative permittivity and loss tangent ($\tan\delta$) of 2.91 and 0.025, respectively. Simulations were performed using Empire XCcel finite-difference time-domain (FDTD) software.

The fabricated geometry of the dipole arms indicates that it is challenging to embroider dipoles with precision better than 1 mm and the arms were of slightly different lengths. The Amberstand dipoles exhibited comparable dc resistance to the
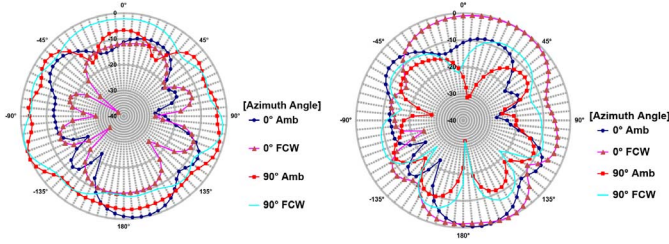
Fig. 6. Measured *(left)* E-Phi polarization gain (dBi) [elevation plane] and *(right)* E-Theta polarization gain [elevation plane] for Amberstrand and 7-stranded copper yarn (fcw). Dipole is horizontal in the plane of the paper.

Fig. 7. Horizontal copper wire dipole on Teflon placed on arm.

V. CONCLUSION

This letter has embroidered wearable antennas using a novel copper yarn. By twisting thin copper wire strands, a physically strong, flexible, and highly conducting thread has been created. The results indicate improved antenna efficiency compared to Amberstrand. The low-loss Teflon material decreased the gain—it was concluded that the extra thickness of the substrate led to greater problems for the embroidery process. The substrate material losses are less critical for dipoles compared to patch antennas as the fields are less concentrated in the substrate. It is hypothesized that these copper threads may have lower production costs than the current specialist threads such as Amberstrand, however it is difficult to estimate the relative costs at this stage. The copper wire is potentially less susceptible to physical damage. Furthermore, as the entire material is copper as opposed to just having a thin metallic cladding, the material may be more suitable for low frequencies where the skin depth becomes an issue.

TABLE II
GAIN OF AMBERSTRAND AND 7-STRANDED COPPER DIPOLE ANTENNAS ON THE BODY—HORIZONTAL DIRECTION (dBi)

	Amber-strand	Amber-strand	Copper wire	Copper wire
With Teflon?	N	Y	N	Y
T-shirt	−8.0	−7.0	−6.0	−8.0
T-shirt and shirt	−7.0	−6.0	−5.0	−7.0
T-shirt, shirt and jumper	−2.0	−2.0	−4.0	−4.0

TABLE III
GAIN OF DIPOLE ANTENNAS ON THE BODY—VERTICAL DIRECTION (dBi)

	Amber-strand	Amber-strand	Copper wire	Copper wire
With Teflon?	N	Y	N	Y
T-shirt	−10.0	−6.0	−3.5	−7.5
T-shirt and shirt	−5.0	−4.5	−2.5	−2.0
T-shirt, shirt and jumper	0.5	−2.0	−0.5	−1.5

when placed in the horizontal direction; see Fig. 7. Two horn antennas were placed 1.64 m apart in a semi-anechoic chamber. The gain of the dipoles, placed on the human body, was calculated by replacing one of the horn antennas and using the gain transfer method. The horizontal and vertical dipole results are shown in Tables II and III, respectively. Due to the variation in position and body movement, the results were only rounded to the nearest 0.5 dBi. The gain of the antennas was strongly dependent on the distance of the antenna away from the body and increased with additional layers of clothing. This distance is estimated to be between 1 and 6 mm depending on the clothing worn. Simulations of a dipole antenna close to a cuboid phantom yielded similar trends in gain to those measured at the different spacings (1 mm gave −6 dBi).

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