High Frequency Properties of Electro-Textiles for Wearable Antenna Applications

Yuehui Ouyang, *Student Member, IEEE*, and William J. Chappell, *Member, IEEE*

***Abstract*—A systematic study of the high frequency electrical properties of electro-textiles is presented in this paper. First, conductive thread characterization is completed with a waveguide cavity method. The effect of conductive thread density and comparison of several different types of conductive threads are included. Second, comparisons of knitted patterns and weave patterns are made in terms of effective electrical conductivity through a microstrip resonator method. The effect of various weave patterns on conductive and dielectric loss is detailed. Finally, the relevance of the high frequency characterization of the electro-textile materials is shown through electro-textile patch antenna fabrication and measurements. The efficiency of the fully fabric patch antenna is as high as 78% due to the use of low loss electrotextiles characterized in this paper.**

***Index Terms*—Conducting materials, electro-textile, materials testing, microwave resonators.**

I. Introduction

THE tradeoff presented by the decreasing form factor of wireless devices and the need for efficient wireless connections is increasingly difficult to manage, in part because of inherent performance limitations of electrically small antennas. To address this tension in the design, wearable wireless receivers have been proposed. Military applications for hands free operation have been demonstrated [1], and biomedical applications for health monitoring have been discussed [2], [3]. Each of these applications, as well as the need for generally better communication channels, requires the integration of antennas seamlessly into clothing. In addition, the increased space on human clothing can be utilized to maximize antenna diversity gain [4].

Electro-textiles are conductive fabrics constructed by interpolating conductive metal/polymer threads with normal fabric threads or conductive threads. These fabrics are considered a strong candidate to be integrated into clothing for distributed body-worn electronics because they are washable, durable and flexible [5]. While the use of metallic threads in clothing dates back to ancient times for protective armor and for decoration [6], their use for electrical functions is a relatively new concept. However recent advances have demonstrated wearable electrical systems that are mainly unobservable to the end user. Conductive fabrics were first used as an electromagnetic shielding material in the 1980s [7]. Microwave protective suits were created and evaluated for shielding effectiveness [8]. Since 1997, wearable fabric antennas have become a popular topic in research institutions and textile industry. Numerous papers have been published about the design, fabrication and applications of fabric antennas [9]–[18]. Some of these developments are highlighted below. In 2001, a GSM fabric PIFA (planar inverted F antenna) antenna for mobile phones was demonstrated for integration into clothing [12]. The effects of antenna bending on antenna gain, resonant frequency and impedance bandwidth were discussed in [14], [17]. In 2006, both textile patch antennas and textile UWB antennas were reported with detailed discussions of manufacturing process [9], [15]. In [16], the effects of human proximity on wearable antennas including SAR were analyzed. These initial findings point to a potential market for these novel materials.

Though electro-textiles have been demonstrated for the application of wearable antennas, very few works have been done on the characterization of the electrical properties of the electro-textiles in microwave frequency, which are quite different than the dc characteristics. In [10], [11], the effect of different conductive fabrics and insulation fabrics on antenna performance were briefly discussed. However a systematic study indicating the effects of the different material features has not been presented. In this paper, we demonstrate a systematic study of the construction of electro-textiles for high frequency applications and furthermore how to control the design parameters of conductive fabrics to achieve optimum performance. Effective conductivity of $1\mathrm{E}+6\ \mathrm{S/m}$ and higher is achievable for some of the best conductive threads as proven in a Ku-band waveguide cavity test. In direct comparison with solid copper laminates in a microstrip resonator test, 6% reduction in the unloaded resonant Q was found for the best electro-textiles, which indicates an effective conductivity of $2\mathrm{E}+7\ \mathrm{S/m}$. As a result, a highly efficient fully fabric antenna (see Fig. 1) was fabricated and tested with the optimum material elected from the material characterization.

In Section II, we introduce various conductive threads and different construction structures of electro-textiles. In Sections III and IV, we present and discuss measurement results of a variety of parameters in conductive fabrics and insulation fabrics. In Section V, electro-textile patch antennas were fabricated and evaluated to demonstrate the relevance of the characterization. In Section VI, we summarize and give conclusions based on the findings of the paper.

II. Overview of High Frequency Electro-Textiles

A. Conductive Fibers

There are three methods of creating conductive fibers [5]:

1) the filling of fibers with carbon or metal particles;
2) the coating of fibers with conductive polymers or metal;
3) the use of fibers that are completely made of conductive material.

Manuscript received January 21, 2007; revised on September 19, 2007. This work was supported in part by Textronics, Inc., Wilmington, DE and in part by Tellab Research Fellowship, Center for Wireless System Applications, Purdue University, West Lafayette, IN.

The authors are with the Electrical and Computer Engineering Department, Purdue University, West Lafayette, IN 47907 USA (e-mail: ouyangy@purdue.edu; chappell@purdue.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TAP.2007.915435

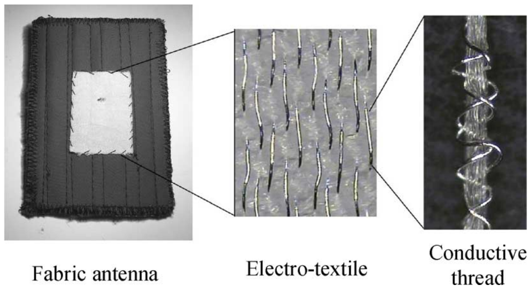


Fig. 1. Fully fabric antenna constructed from electro-textiles.

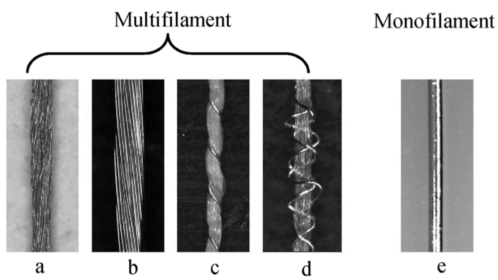


Fig. 2. Various conductive threads.

The state-of-the-art conductive fibers are highly conductive metal wires and plated fibers, which are superior to other alternatives in terms of conductivity [5]. Many alternatives in the construction of the fibers exist, however silver plated nylon fibers and thin silver plated copper fibers are the main focus of this paper.

B. Conductive Threads

Conductive threads are created from single or multiple strands of conductive and nonconductive fibers. As shown in Fig. 2, there are two categories of conductive threads: multifilament threads [see Fig. 2(a)–(d)] and monofilament threads [see Fig. 2(e)]. Each has different electrical properties as well as wearability and reliability characteristics. The monofilament conductive thread shown in Fig. 2(e) is composed of single silver plated copper fiber (diameter 40 μm). The X-static thread (Fig. 2(a), Sauquoit Industries Inc., Scranton, PA) is formed by twisting many thin elastic silver plated nylon fibers together. The Litz wire [see Fig. 2(b)] contains 60 copper fibers, each of which has a diameter of 40 μm. The threads in Fig. 2(c) and (d) are composite threads of insulating and metallic fibers. Both composite threads are created by spinning 40 μm silver plated copper fibers around a nonconductive core which is composed of multiple nonconductive fibers. The strong nonconductive fibers can protect the thin fragile conductive fibers from external tension, which makes the conductive threads more mechanically robust and still maintaining the electrical functionality. When elastic nonconductive core is used as in Fig. 2(d), the conductive thread becomes stretchable which is a desirable feature for wearability and the fabric takes on the feel of a traditional material. The effective conductivities of various conductive threads in the absence of the creation of a fabric were measured and compared at high frequencies in Section III.

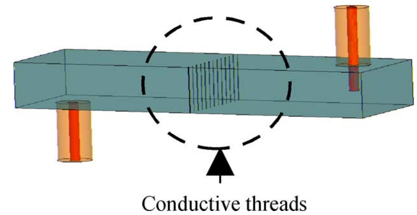


Fig. 3. Measurement setup for conductive thread characterization.

C. Conductive Fabrics

Electro-textiles are generally created by incorporating conductive threads into fabrics by means of weaving and knitting. The choice of the conductive threads and of the textile structure determines the efficiency of the textile as an equivalent electro-conductive material and assures its durability. In knitted fabrics, the threads meander through and create interlocking loops, while in woven fabrics the threads are straight in two orthogonal directions. Conventionally, conductive threads are used in both directions in conductive woven fabrics. In this paper, we study the application of woven fabrics which have conductive threads in only one direction and nonconductive threads in the other direction. This arrangement adds to the wearable feel of the fabric, while affecting the electrical parameters. The detailed studies of the electrical properties of various electro-textiles are presented in Section IV.

III. Conductive Thread Characterization

A. Waveguide Cavity Method

By forming part of the conductive metal walls in a rectangular resonant cavity with the test conductive material, the surface resistance of the material under test can be determined by the unloaded Q of the metal cavity [19]. By arranging conductive threads parallel to each other with controllable equal space over the waveguide aperture (Fig. 3), the effective surface resistance of different classes of conductive threads can be evaluated at high frequency before constructing a fabric from the conductive threads under test, which allows for a fair comparison of thread conductive losses independent of fabric patterns. Detailed measurement procedure and formula to calculate effective surface resistance were presented in [20], while the extensive measurement results and analysis are presented for the first time herein.

B. Measurement Results

Seven conductive threads were tested in this study. Three of them are monofilament threads: silver plated copper threads with diameter of 40 μm, 80 μm and 159 μm. The others are multifilament threads. The X-static thread [see Fig. 2(a)] is formed of thin elastic silver plated nylon fibers. The polyester/stainless steel thread is a mixture of polyester fibers and thin stainless steel fibers. The Litz wire [see Fig. 2(b)] contains 60 copper threads. The 100% stainless steel thread is similar to the Litz wire and composed of numerous stainless steel fibers, each of which has a diameter of 12 μm. For fair comparison, these conductive threads were mounted on the fiber fixture with the same spatial density.

TABLE I
COMPARISON OF DIFFERENT CONDUCTIVE THREADS AT 11.4 GHZ (THREAD DENSITY: 36 PPI)

Conductive thread	Diameter (μm)	Q_u	R_s (Ω/m)	Conductivity (S/m)
a) silver plated copper thread	159	5156	0.093	5.2E+06
b) silver plated copper thread	40	4105	0.259	6.7E+05
c) X-static® thread	~270	1966	1.162	3.3E+04
d) polyester/stainless steel thread	~320	519	5.959	1.3E+03

TABLE II
COMPARISON OF DIFFERENT CONDUCTIVE THREADS AT 11.4 GHZ (THREAD DENSITY: 20 PPI)

Conductive thread	Diameter (μm)	Q_u	R_s (Ω/m)	Conductivity (S/m)
a) silver plated copper thread	80	4419	0.197	1.2E+06
b) silver plated copper thread	40	2844	0.611	1.2E+05
c) Litz wire	~500	1029	2.730	6.0E+03
d) 100% stainless steel thread	~550	992	2.853	5.5E+03

In Table I, four conductive threads were tested at the density of 36 ppi (picks/threads per inch). The effective surface resistance and conductivity of the monofilament threads (silver plated copper threads, diameter 159 $\mu\mathrm{m}$ and 40 $\mu\mathrm{m}$) are orders of magnitude better than those of the other two multifilament threads [(c) X-static and (d) polyester/stainless steel]. Because the Litz wire [Fig. 2(b)] and 100% stainless steel threads are too thick to be mounted on the fiber fixture at the density of 36 ppi, we used the 20 ppi fixture instead for these two samples. Both densities were used to measure a reference monofilament sample, silver plated copper thread, as to make a fair comparison of all the threads. In Table II, the monofilament threads in this test were confirmed to be orders of magnitude better than other multifilament samples. This is hypothesized that more conductive loss in multifilament threads is partially the result of longer conductive paths in the spiral-like structure of individual conductive fibers.

For silver plated copper threads with various diameters, the thicker thread (larger diameter) has higher effective conductivity as shown in both Table I (the comparison of 159 $\mu\mathrm{m}$ and 40 $\mu\mathrm{m}$ thick threads) and Table II (the comparison of 80 $\mu\mathrm{m}$ and 40 $\mu\mathrm{m}$ thick threads). This is expected as we examine the current distribution in the conductive structure. For each cylindrical conductive wire in the one-dimensional periodic array, the thicker threads end up with distribution of the electrical current that is more spread over the surface area (less current crowding) and thus lower conductive loss.

In order to study the effect of thread density, we tested the effective surface resistance and conductivity of the silver plated copper thread (diameter 80 $\mu\mathrm{m}$) at various spatial densities. As shown in Table III, the effective surface resistance decreases from 0.197 Ω/m to 0.095 Ω/m as the thread density increases from 20 ppi to 75 ppi. It is worth noting that the amount of decrease in resistance is not as expected as in a dc analysis. The dc surface resistance is inversely proportional to the conductive thread density. However, the RF surface resistance decreases more slowly with the increasing thread density. This is due to the complicated current distribution around the surface of the conductive threads at RF frequencies as compared to the uniform current distribution inside the conductive threads in dc. As the conductive threads are placed closer together the region that the current flows is decreased. At one extreme, the conductive threads are tight enough that the surface looks like a sheet of metal and the surface resistance converges to the value of a metal plate with the thickness defined by the skin depth in the traditional microwave analysis. Therefore, the mutual interaction of the conductive threads dictates that the surface resistance does not follow the trends defined by a dc analysis.

TABLE III
THE EFFECT OF CONDUCTIVE THREAD DENSITY AT 11.4 GHZ: SILVER PLATED COPPER THREAD (DIAMETER: 80 MICROMETER)

Thread Density (ppi)	Q_u	R_s (Ω/m)	Conductivity (S/m)
20	4419	0.197	1.2E+06
40	4662	0.163	1.7E+06
51	4880	0.132	2.6E+06
75	5152	0.095	5.0E+06

In Table III, the effective conductivity increases from $1.2\mathrm{E}+06\ \mathrm{S/m}$ to $5.0\mathrm{E}+06\ \mathrm{S/m}$ as the thread density increases from 20 ppi to 75 ppi. In conclusion, higher conductive thread density in the electro-textile results in lower effective surface resistance and higher effective conductivity. By increasing the thread density in the woven fabric, we can achieve higher electrical conductivity while increasing the manufacturing cost dramatically by consuming much more relatively costly conductive threads (compared to normal fabric threads). A reasonable tradeoff can be found in the correlation of thread density and achievable electrical performance.

In summary, the choice of conductive threads has the major effect on the effective conductivity relative to the thread density by comparing the orders of magnitude difference in Tables I and II to the minor variance in Table III. In terms of effective conductivity, the monofilament silver plated copper threads are the best choice in this test set, and this higher effective conductivity leads to minimized conductive loss in electro-textile resonators, antennas, transmission lines and any other microwave devices with planar structures. In the following section, we will compare the electrical performance of the monofilament silver plated copper threads with some other composite multifilament threads such as those in Fig. 2(c) and (d) with consideration of both conductive and dielectric loss associated in the planar structures.

IV. CONDUCTIVE FABRIC CHARACTERIZATION

A. *Microstrip Resonator Method*

In addition to the waveguide cavity characterization method, we utilized another measurement technique for characterizing the electro-textiles based on the microstrip resonator. In this measurement setup, the conductive fabric (electro-textile) is

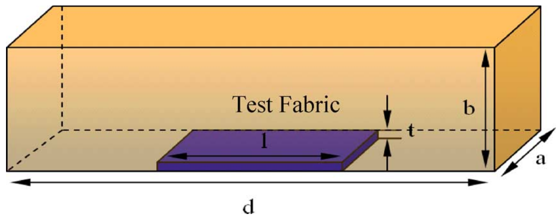


Fig. 4. Dielectric loaded waveguide cavity method setup.

TABLE IV
DIELECTRIC PROPERTIES OF THE TEST FABRIC SAMPLES.

Nonconductive Fabric	ε_r	tanδ
Cordura®	1.90	0.0098
cotton	1.60	0.0400
100% polyester	1.90	0.0045
Quartzel® Fabric	1.95	0.0004
Cordura/Lycra®	1.50	0.0093

used as the top layer of a microstrip resonator. Details of the measurement setup and numerical analysis can be found in [20]. The resonant frequency of the microstrip resonator is 2.6 GHz. The dielectric loss due to the nonconductive threads in the fabric affects the Q of the electro-textile microstrip resonator, as opposed to the waveguide cavity method where the dielectric losses are ignored due to the concentration of magnetic field around the material. The microstrip method therefore is suitable for characterizing the materials for applications in which both metal and dielectric losses are important.

B. Dielectric Properties of Normal Fabrics

To understand the dielectric properties of traditional nonconductive threads, we tested common fabric swatches by the dielectric loaded waveguide cavity method. In this method, a rectangular piece of the test fabric was placed in the waveguide cavity (Fig. 4) and the changes in resonant frequency and unloaded Q of the first resonant mode (TE110) were measured. The cavity is made in two halves with the seam following the current flow, which greatly increases repeatability of the resonator. By matching the measured changes due to dielectric loading with Ansoft HFSS (High-Frequency Structure Simulator) simulation, we can inversely find the dielectric properties of the test fabric.

The measurement results are listed in Table IV. Quartzel Fabric (Saint-Gobain Quartz, Louisville, KY) is produced from quartz crystal fibers. Cordura fabric (INVISTA, Wichita, KS) is highly resistant to abrasion and used widely in outdoor wears, backpacks, and suitcases. Quartzel Fabric and 100% polyester are the best in term of loss tangent while cotton is the worst. In the Sections IV-D, we will study the effect of dielectric loss due to the nonconductive threads in various weaving structures with electro-textiles, where it is explicitly shown the importance of the choice of fabric.

C. Comparison of Knitted and Woven Fabric

In Section II-C, we introduced two different fabric constructions: knit and woven. To identify the effect of the fabric construction, two sample fabrics were created with the same X-static conductive thread (supplied and fabricated by Textronics, Inc.) The measurement results are listed in Table V.

TABLE V
COMPARISON OF KNITTED AND WOVEN FABRIC

	Fabric Construction	Q_u
100% X-static® knit	Plain Jersey Pantyhose	8-16
X-static® woven	Satin 5	36.5/32.2

For the X-static woven fabric, the nonconductive thread used is Cordura/Lycra with density of 152 ppi and the conductive thread is the X-static thread with density of 76 ppi. Because of the construction of the conductive woven fabric, anisotropic conductive pattern is formed where conductive paths exist only in one direction (along the conductive threads). The unloaded Q measured for the woven fabric is 36.5 and 32.2 on different sides of the fabric when the conductive threads were aligned with the direction of the current (along the long side of the microstrip resonator). No resonance was found when the nonconductive threads were aligned with the long side of the microstrip resonator. This is expected since the desired current direction for this microstrip resonator is perpendicular to the conductive path (X-static threads) inside the material. The textile is therefore inherently polarization sensitive, an effect that can potentially be useful.

The unloaded Q for the knitted fabric is 8–16 depending on the orientation of the knit pattern with respect to the long side of the rectangular microstrip. This reduction in Q as compared to the woven fabric can be explained by the interleaving structure of the knitted pattern. Conductive paths exist in all directions through conductive threads and/or inter-contact points across threads. However, the conductivity of these current paths is not uniform in all directions since the point electrical connections across threads tend to be lossier than the electrical connections via conductive threads. Woven pattern is much more efficient in terms of electrical conduction than the knit pattern because the conductive paths in the woven pattern are better aligned with the current directions which minimize the conductive loss, assuming the directions of the threads in the weave pattern are in the intended direction for current flow.

D. Detailed Study on the Effect of Fabric Construction (Satin Weave Example)

As an example of a case in which the fabric construction is critical to the electrical properties of electro-textiles, a specific weave was evaluated focusing on asymmetrical fabric designs. In addition to the symmetric plain weave pattern (one-by-one interweaving between threads), there are fabrics with asymmetrical patterns on each side, termed satin weaves (Fig. 5). In Fig. 5, nonconductive threads (represented by vertical black rods) and conductive threads (represented by horizontal white rods) interweave with each other by certain ratio. For example, when the interweaving ratio of vertical and horizontal threads is 4:1 and the weave pattern is periodic every five thread, the weave pattern is called Satin 5 (Fig. 5). Satin weaves are asymmetric on both faces of the fabric. On the fabric face, there are more vertical nonconductive threads than horizontal

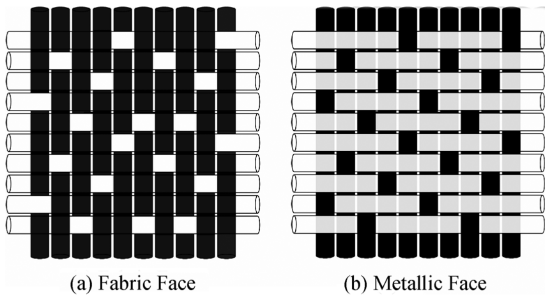


Fig. 5. Weave pattern of the Satin 5 weave.

conductive ones. On the metallic face (the reverse side of the fabric), there are more horizontal conductive threads than vertical nonconductive ones. This asymmetry on both faces of the satin-weave fabric leads to different Q in our microstrip resonator measurement when the conductive fabric is placed with the metallic face or the fabric face against the substrate. Therefore, we tested both cases for each satin-weave fabrics.

The difference in the Q_u of the microstrip resonators with different faces of satin-weave fabrics against the substrate is mainly due to the change in the amount of dielectric loss in the resonators. The loss tangent of the fabric materials ranges from 0.0004 to 0.04 (see Table IV) and thus the dielectric loss in electro-textiles is not negligible. To illustrate the dielectric loss mechanism, we plot the cross section of the resonator in Fig. 6. When conductive threads (indicated by the small circles) are underneath the nonconductive threads as in Fig. 6(a), most of the electric field is contained between the periodic conductive threads and the ground plane (laminated copper layer). Thus the dielectric loss in nonconductive threads is minimized. In the opposite case, when the conductive threads are on top of the nonconductive threads as in Fig. 6(b), extra dielectric loss is introduced due to the presence of strong resonant electric field in the region of the nonconductive threads. For instance, when the metallic side of a Satin 5 weave fabric is placed against the substrate [Fig. 6(c)], the metallic surface [as in Fig. 6(a)] dominates the electrical properties as compared to the fabric surface [as in Fig. 6(b)]. The occupation of the metallic surface versus fabric surface is 4 to 1. In contrast, when the fabric face is placed against the substrate [Fig. 6(d)], the fabric surface dominates. The domination of fabric surface results in more dielectric loss than in the opposite case.

In Fig. 7, the measured unloaded resonant Q of seven Satin 5 weave fabrics is plotted. For all the seven samples, the conductive threads are silver plated copper threads with diameter of 40 μm and the nonconductive threads are Cordura/Lycra with density of 152 ppi. There are noticeable differences in the measured Q_u of the electro-textile resonator when the metallic face or the fabric face is placed against the dielectric substrate. In short, it is proven that keeping metallic face against the dielectric substrate is preferred when constructing planar structures (microstrip line, patch antenna, etc.) for the sake of lowering electrical loss.

In addition, sample fabric with higher conductive thread density has higher unloaded Q on the metallic face and thus higher effective conductivity given the same construction of nonconductive threads. This confirms the conclusion drawn in Section III-B that higher conductive thread density leads to

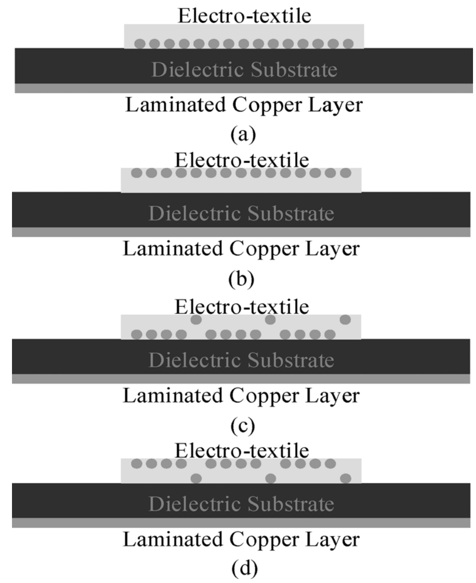


Fig. 6. Schematic cross section plot of satin weave fabric resonator. (a) When conductive threads are underneath nonconductive threads; (b) When conductive threads are on top of nonconductive threads; (c) When metallic face is against the dielectric substrate; (d) When fabric face is against the dielectric substrate.

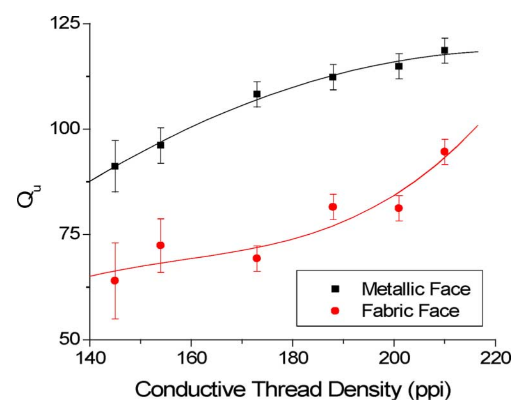


Fig. 7. Satin 5 construction: effect of conductive thread density. (Trend lines are added based on the measured data points.).

higher effective conductivity. Since the curve of the unloaded Q begins to level off as the conductive thread density exceeds 200 ppi and approaching the performance of solid metallic material, we find that the gain in the effective conductivity is limited as the thread density goes higher than 200 ppi. For reference, a strip of copper laminate (solid metallic material) was tested in the same test setup. The measured unloaded Q is 126.5. The highest Q_u of 118.6 was measured for the electro-textile with the highest conductive thread density of 210 ppi among the seven fabric samples. The 6% reduction in the unloaded resonant Q for this conductive fabric as compared to the Q for copper laminate indicates an effective conductivity of $2E + 7$ S/m [20].

Depending on the overlaying ratio of vertical and horizontal threads, there are different kinds of satin weave, such as Satin 4, Satin 5, Satin 10, etc., each indicating the ratio of asymmetry of the weave pattern. To compare different satin weave patterns, we tested four satin weave fabrics: Satin 5, Double Face Satin 4, Satin 10, and Satin 16. The Double Face Satin 4 is created

TABLE VI
EFFECT OF DIFFERENT WEAVE PATTERNS

Fabric Construction	Conductive Thread Density on Fabric (ppi)	Q_u (Metallic)	Q_u (Fabric)
Satin 5	210	118.6±3	94.6±3
Double Face Satin 4	254	98.6±3	99.8±3
Satin 10	335	100.5±3	68.1±3
Satin 16	496	68.6-95.7	62.3±3

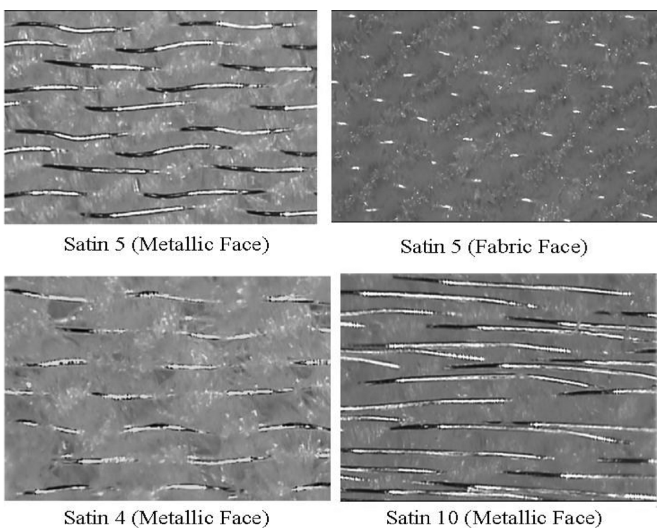


Fig. 8. Microscopic pictures of Satin fabrics.

such that it has a metallic face on both sides. The shiny metallic face is evident from each side of the fabric and therefore the Q_u under the Metallic and Fabric columns (Table VI) are expected to be the same value, which is verified by measurement. Based on previous discussion and the intuition developed, Satin 16 should have the lowest dielectric loss in the nonconductive threads when the metallic face is kept against the substrate and thus the highest resonant Q. In all the four fabrics, the conductive threads are silver plated copper threads with diameter of 40 μm and the nonconductive threads are Cordura/Lycra with the density of 152 ppi.

From Table VI, the Satin 5 sample shows the highest Q_u (118.6) on the metallic face among four satin fabrics though other fabrics have significantly higher conductive thread density which leads to higher Q_u as found in previous discussions. This is contrary to our initial expectation. From the microscopic pictures of the Satin fabrics (Fig. 8), we find that when the weaving ratio of conductive and nonconductive threads is increased, the threads become more loosely bound by each other. The irregularity in the pattern of conductive threads results in longer paths of conductive current and larger associated metal loss which lowers the effective conductivity of the electro-textiles and thus the Q_u of the electro-textile resonators. Therefore it is concluded that there is an optimum level of support of the conductive threads in the weave structure for minimum electrical loss.

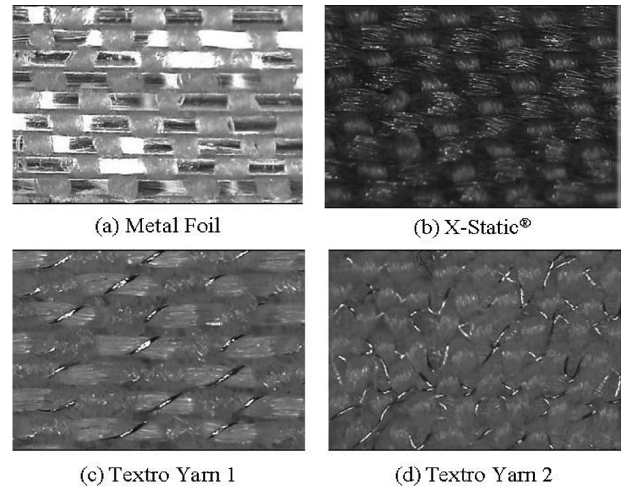


Fig. 9. Pictures of the Satin 5 samples: comparison of different conductive threads.

E. Comparison of Different Conductive Threads

To compare the performance of different conductive threads as in Section II-B, we tested seven Satin 5 fabrics with different conductive threads, in which the nonconductive threads are Cordura/Lycra with density of 152 ppi. Because of the elastic property of the nonconductive thread (Cordura /Lycra), the conductive thread densities of the seven samples are close but not exactly the same. During weaving process, some tension is placed upon the nonconductive threads. When the fabrics are taken off the weaving machine after being formed, the nonconductive yarns shrink by some extent, which increases the conductive yarn density. Thus, conductive thread densities on the weaving machine which can be well controlled are smaller than the resulting thread densities on the actual fabric.

The metallic Q_u of the seven test fabrics are plotted in Fig. 10. Metal Foil fabric is the best one in terms of metallic Q_u. The Q_u is 111.8 close to 126.5 for the reference copper laminate. As shown in Fig. 9(a), metal foils are used as conductive threads in this fabric and make it very close to the form of a metal sheet. Thus, less conductive loss is expected than other fabrics, however at the sacrifice of wearability and durability. Silver Plated Copper fabric, in which 40 μm silver plated copper threads are implemented, is the second in metallic Q_u. The Q_u of Textro Yarn 1 fabric (Fig. 9(c), Textronics, Inc.) is close to that of Silver Plated Copper fabric, because Textro Yarn 1 [see Fig. 2(c)] used in this fabric are composed of single 40 μm silver plated copper fiber and a nonconductive core. The use of Textro Yarn 1 increases the durability of the conductive fabric due to the mechanically strong nonconductive core in the conductive threads. Textro Yarn 2 fabric [Fig. 9(d)] is slightly worse than the Textro Yarn 1 fabric. Textro Yarn 2 as shown in Fig. 2(d), is elastic and composed of two 40 μm silver plated copper fiber and an elastic nonconductive core. Though both Textro Yarn 1 and Textro Yarn 2 contain the same silver plated copper threads, the pitch of the conductive fiber in Textro Yarn 2 is 300 μm, which is half the pitch in Textro Yarn 1. The smaller pitch increases the effective conductive loss by lengthening the current path in the

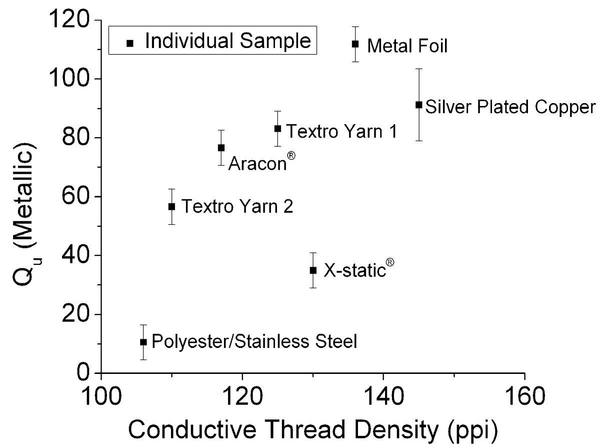


Fig. 10. Satin 5 construction: effect of different conductive threads.

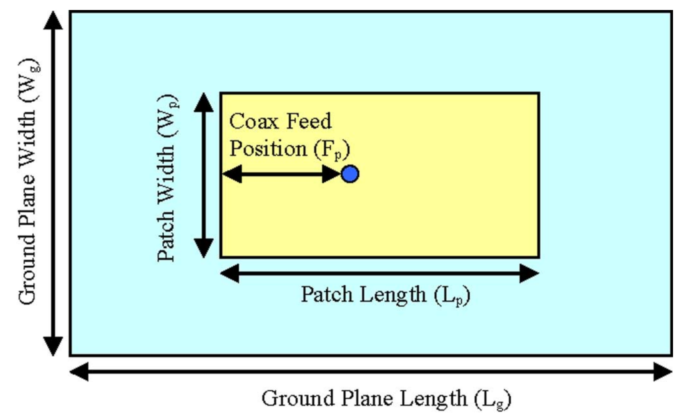


Fig. 11. Sketch of rectangular patch antennas.

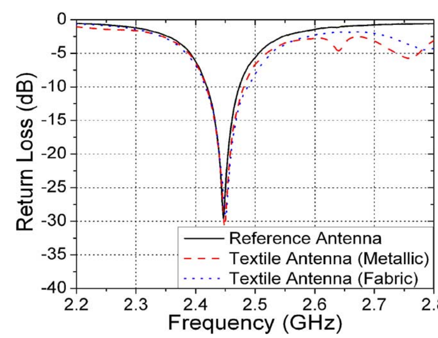


Fig. 12. S_{11} of the reference and electro-textile patch antennas.

thread. On the other hand, the use of Textro Yarn 2 further enhances the feel of the electro-textile by making it elastic as a whole, which defines a trade space between performance (electrical efficiency) and wearability (fabric-like feel). Therefore, Textro Yarn 1, Textro Yarn 2 and other similar types of conductive threads can be strong candidate for commercial/practical applications where the balance between durability, wearability and electrical efficiency is taken into consideration. The Aracon yarn used in Aracon fabric is comparable to the Textro Yarn 1 in terms of the metallic Q_u of the electro-textile resonators. The Aracon yarn is a DuPont brand product, which is made up of many very fine metal clad fibers (only 0.6 mils in diameter) twisted together. ARACON metal clad fibers are aromatic polyamides fibers with nickel, copper or silver coatings. X-static and Polyester/Stainless Steel are worse than those that contain copper fibers, which coincides with the results from conductive thread characterization in Section III.

V. Electro-Textile Patch Antenna

A. Test Electro-Textile Patch Antenna

To investigate the application of electro-textiles in antenna design, we fabricated and tested two electro-textile patch antennas using a Satin 5 woven fabric as the top layer, as well as a reference copper patch antenna, on the same dielectric substrate with thickness of 3.175 mm (Rogers Duroid 5880) [21]. Coax feeds from the back of the patch antennas was used (Fig. 11). Of the two electro-textile antennas, one is with the metallic face (the side with more conductive threads) facing against the substrate; the other one is with the fabric face (the side with more nonconductive threads) facing downwards. As discussed in Section IV-D, the asymmetry on both faces of the satin weave electro-textiles results in different dielectric loss in the fabric material depending on the placement of the fabric on the substrate. The same effect is expected on the antenna loss mechanism which relates to the efficiency of the patch antenna.

The dimensions for all three antennas (listed in Table VII) are very close to each other except for the ground plane which is sufficiently large. The resonant frequencies of three antennas

TABLE VII
Dimensions of Test Electro-Textile Patch Antennas [Millimeters]

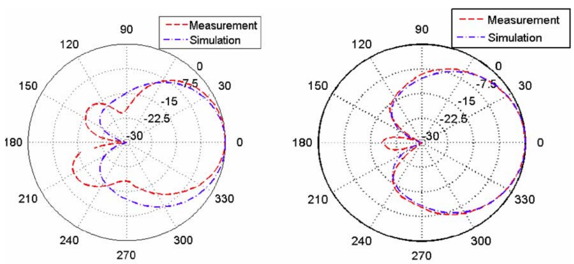
	L_g	W_g	L_p	W_p	F_p
Reference Copper Patch Antenna	102	63	40	26	15
Electro-textile Patch Antenna (metallic)	116	77	39	27	15.5
Electro-textile Patch Antenna (fabric)	116	77	38.5	27	15.5

match with each other (Fig. 12). This means that though electro-textiles have periodic conductive structure on microscopic scale, it behaves like continuous metal laminates with various effective conductivities as characterized in the material testing.

The antenna performance of the three antennas is summarized in Table VIII. The antenna efficiencies for the electro-textile patch antennas were derived based on the gain degradation compared to the reference copper patch antenna. From Table VIII, we find out that the efficiency of the electro-textile antenna increases from 79% (fabric face downwards) to 88% (metallic face downwards). The difference is mainly due to dielectric loss in the nonconductive threads in the satin weave fabric as expected from material characterization. More importantly, the high efficiency of the electro-textile antennas in direct comparison with the reference antenna made of copper laminates proves that electro-textile can be used as a replacement of traditional

TABLE VIII
TEST ELECTRO-TEXTILE ANTENNA PERFORMANCE (2.44 GHz) [21]

	Gain (dB)	Efficiency (%)	Bandwidth (%)
Reference Copper Patch Antenna	7.4	95	2.2
Electro-textile Patch Antenna (metallic)	7.1	88	2.6
Electro-textile Patch Antenna (fabric)	6.6	79	2.9



(a) E plane antenna pattern (b) H plane antenna pattern

Fig. 13. Antenna patterns of the fully fabric antenna at 2.44 GHz.

copper laminates with minimal amount of performance degradation in wearable applications such as body-worn patch antennas.

B. Fully Fabric Patch Antenna

While the Duroid substrate was used to be a stable base for the characterization of textile properties, flexible substrates are desired in the applications of wearable antennas. One fully fabric antenna was fabricated at 2.44 GHz (see Fig. 1). We used the same woven fabric used in previous test antennas as the top patch and the ground plane and we kept the metallic face inwards against the insulation layer on both sides. Eight layers of 100% polyester fabrics were stacked to form an insulation layer of about 4 mm. The dielectric constant of the polyester fabric is 1.9 and loss tangent is 0.0045 (see Section IV-B). Direct metal soldering is used to connect the top patch and ground plane to the SMA coax connector with local removal of a few nonconductive threads. The ground plane is 115 mm by 73 mm and the size of the patch is 48.5 mm by 28 mm.

As a reference, HFSS simulation was performed. In the simulation, laminated copper layers were used for the top and ground layer of the patch antenna and bulk dielectric material ($\varepsilon_r = 1.37$) was used in the insulation layer to equivalently represent multi-layer of polyester fabrics with approximately 40% of air (in volume) between layers. The measured and simulated radiation patterns of the fully fabric antenna are plotted in Fig. 13. Because the measured radiation patterns match well with the simulated ones, we are able to estimate the antenna efficiency based on the difference between the measured antenna gain and the one obtained from simulation. The measured gain of the fully fabric antenna at 2.44 GHz is 6.6 dB and the impedance bandwidth is 6.2% (VSWR < 2) (Table IX). This indicates that the fully fabric antenna can be used in smart clothes for WLAN communications with moderate antenna gain and impedance bandwidth larger than 4%.

TABLE IX
FULLY FABRIC ANTENNA PERFORMANCE AT 2.44 GHz

	Gain (dB)	Efficiency (%)	Bandwidth (%)
Reference Patch Antenna (HFSS™ simulation – ideal copper layer)	7.2	92	3.0
Fully Fabric Antenna (metallic)	6.6	78	6.2

VI. CONCLUSION

A comprehensive study of the high frequency properties of the electro-textiles was carried out in this paper. Various considerations and trade-offs in the choice of conductive threads and fabric constructions (woven/knitted, thread density, thread thickness, satin weave) were discussed in detail. A comparison of woven versus knitted fabric reveals that woven fabrics generally have better electrical properties. In both a microstrip resonator and a high frequency patch antenna, the electro-textile demonstrated Q performance with a few percent of a copper laminate. A demonstration of a flexible fabric antenna shows the utility of electro-textiles in the application of wearable microwave systems. In summary, the electro-textile materials can replace the solid metal sheets in wearable applications with minimal performance degradation while adding functionality through wearability.

ACKNOWLEDGMENT

The authors would like express their acknowledgment to Textronics, Inc., for their technical support and providing test materials for this study.

REFERENCES

[1] C. A. Winterhalter, J. Teverovsky, P. Wilson, J. Slade, W. Horowitz, E. Tierney, and V. Sharma, "Development of electronic textiles to support networks, communications, and medical applications in future U.S. military protective clothing systems," *IEEE Trans. Inf. Technol. Biomed.*, vol. 9, pp. 402–406, Sep. 2005.
[2] E. Jovanov, "Wireless technology and system integration in body area networks for m-health applications," in *Proc. IEEE-EMBS 27th Annu. Int. Conf.*, 2005, pp. 7158–7160.
[3] E. Wade and H. Asada, "Electrostatic analysis and design of a cable-free body area network of sensor nodes using 2D communication over conductive fabric sheets," in *Proc. IEEE/RSJ Int. Conf.*, 2005, pp. 3642–3647.
[4] Y. Ouyang and W. Chappell, "Distributed body-worn transceiver system with the use of electro-textile antennas," in *Proc. IEEE MTT-S Int. Microwave Symp.*, 2007, pp. 1229–1232.
[5] H. H. Kuhn and A. D. Child, "Electrically conducting textiles," in *Handbook of Conducting Polymers*, T. A. Skotheim, R. L. Elsenbaumer, and J. R. Reynolds, Eds., 2nd ed. New York: Marcel Dekker, 1998, pp. 993–1013.
[6] A. Zrebiec, L. Wolk-Simon, and S. W. Phyrr, "European 16th-19th centuries," *The Metropolitan Museum of Art Bulletin*, vol. 53, 1995–1996.
[7] K. H. Joyner, P. R. Copeland, and I. P. MacFarlane, "An evaluation of a radiofrequency protective suit and electrically conductive fabrics," *IEEE Trans. Electromagn. Compat.*, vol. 31, pp. 129–137, 1989.
[8] A. W. Guy, C. Chung-Kwang, J. A. McDougall, and C. Sorensen, "Measurement of shielding effectiveness of microwave-protective suits," *IEEE Trans. Microw. Theory Tech.*, vol. 35, pp. 984–994, 1987.

[9] I. Locher, M. Klemm, T. Kirstein, and G. Trster, “Design and characterization of purely textile patch antennas,” *IEEE Trans. Adv. Packag.*, vol. 29, pp. 777–788, 2006.
[10] P. Salonen, Y. Rahmat-Samii, H. Hurme, and M. Kivikoski, “Effect of conductive material on wearable antenna performance: A case study of WLAN antennas,” in *Proc. IEEE Antennas Propag. Soc. Int. Symp.*, 2004, vol. 1, pp. 455–458.
[11] P. Salonen, Y. Rahmat-Samii, M. Schaffrath, and M. Kivikoski, “Effect of textile materials on wearable antenna performance: A case study of GPS antennas,” in *Proc. IEEE Antennas Propag. Soc. Int. Symp.*, 2004, vol. 1, pp. 459–462.
[12] P. J. Massey, “GSM fabric antenna for mobile phones integrated within clothing,” in *Proc. IEEE Antennas Propag. Soc. Int. Symp.*, 2001, vol. 3, pp. 452–455.
[13] P. Salonen and L. Hurme, “A novel fabric WLAN antenna for wearable applications,” in *Proc. IEEE Antennas Propag. Soc. Int. Symp.*, 2003, vol. 2, pp. 700–703.
[14] P. Salonen and Y. Rahmat-Samii, “Textile antennas: Effects of antenna bending on input matching and impedance bandwidth,” *IEEE Aerosp. Electron. Syst. Mag.*, vol. 22, pp. 10–14, 2007.
[15] M. Klemm and G. Troester, “Textile UWB antennas for wireless body area networks,” *IEEE Trans. Antennas Propag.*, vol. 54, pp. 3192–3197, 2006.
[16] P. Salonen, Y. Rahmat-Samii, and M. Kivikoski, “Wearable antennas in the vicinity of human body,” in *Proc. IEEE Antennas Propag. Soc. Int. Symp.*, 2004, vol. 1, pp. 467–470.
[17] M. Tanaka and J. Jae-Hyeuk, “Wearable microstrip antenna,” in *Proc. IEEE Antennas Propag. Soc. Int. Symp.*, 2003, vol. 2, pp. 704–707.
[18] C. Cibin, P. Leuchtmann, M. Gimersky, R. Vahldieck, and S. Moscibroda, “A flexible wearable antenna,” in *Proc. IEEE Antennas Propag. Soc. Int. Symp.*, 2004, vol. 4, pp. 3589–3592.
[19] F. J. Tischer and F. Jalali, “Resonant cavities for the measurement of the surface resistance of conductors at millimeter wavelengths,” *Rev. Sci. Instrum.*, vol. 46, pp. 11–14, Jan. 1975.
[20] Y. Ouyang and W. Chappell, “Measurement of electrotextiles for high frequency applications,” in *Proc. IEEE MTT-S Int. Microwave Symp.*, 2005, pp. 1679–1682.
[21] Y. Ouyang, E. Karayianni, and W. J. Chappell, “Effect of fabric patterns on electrotextile patch antennas,” in *Proc. IEEE Antennas and Propag. Soc. Int. Symp.*, 2005, vol. 2B, pp. 246–249.

Yuehui Ouyang (S’03) was born in Nantong, China, in 1981. She received the B.S. degree in electrical engineering from the University of Science and Technology of China, Hefei, in 2003, and the M.S. degree in electrical engineering from Purdue University, West Lafayette, IN, in 2005, where she is currently working towards Ph.D. degree.

Her current research is focused on electro-textiles, wearable antennas, diversity design, wireless channel characterization and integrated RF front-ends.

William J. Chappell (S’98–M’02) received the B.S.E.E., M.S.E.E., and Ph.D. degrees from the University of Michigan at Ann Arbor, in 1998, 2000, and 2002, respectively.

He is currently an Assistant Professor at Purdue University, West Lafayette, IN, where he helps run the RF Advanced Packaging Laboratory. His research focus is on advanced applications of RF and microwave components. He has been involved with numerous DARPA projects involved in advanced packaging and materials processing for microwave applications. His research sponsors include HSARPA, ONR, NSF, the state of Indiana, CERDEC, ARO, as well as industry sponsors. His research group uses electromagnetic analysis, unique processing of materials, and advanced design to create novel microwave components. Specifically of interest are the application of very high quality and tunable components utilizing package scale, multilayer components.

Dr. Chappell was the recipient of the URSI Young Scientist Award, the Joel Spira Teaching Excellence award, and the Eta Kappa Nu 2006 Teacher of the Year at Purdue University.