Characterization of the High Frequency Properties of Electrotextiles

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***Abstract* — A waveguide based cavity method is discussed to measure the high frequency properties of electrotextiles. The effects of patterning, textile spacing, material choices, etc… can be determined using this method. Two half cavities are used in two separate steps in order to characterize the electrotextile. The unloaded Q of the cavity is determined to characterize the loss of the material and the external Q is determined in order to characterize the ability of the material to shield propagating waves.**

I. INTRODUCTION

Electrotextiles are unique in their ability to mimic clothing or other fabric based applications while also performing electrical functions [1]. However the high frequency properties can be vastly different than the low frequency properties. Textile pattern construction as well as fiber construction can have a large role in determining the properties of the materials. There is to date not much if any data of high frequency performance of the electrotextiles. We present details of a method for determining the textile's high frequency performance while interpreting the results in terms of the material construction.

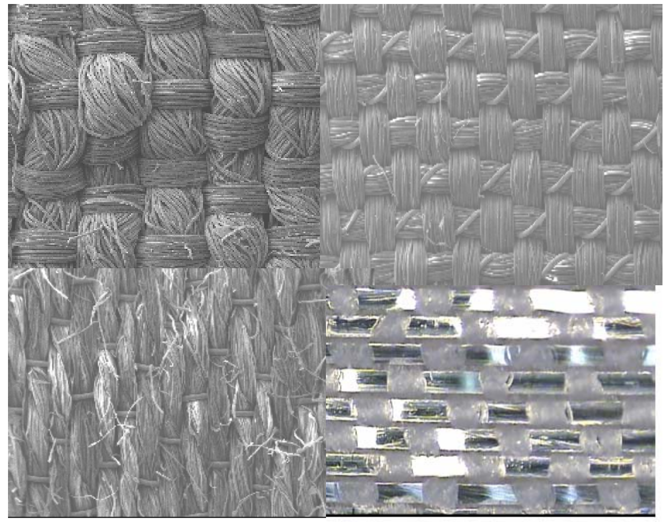

Fig. 1: SEM figures showing details of different electrotextile materials. Plated yarns woven together are shown in the top left. Metal woven within a textile shown in other pictures.

The simplest high frequency application of the electrotextiles is for flexible shielding materials. More advanced applications include the creation of flexible or body worn antennas. The requirements for shielding applications are different than for antenna applications; however they both prefer low loss materials which block energy. A means to simultaneously characterize the shielding capabilities and the loss characteristics of the material is desired for picking the correct material for each application. A process which allows for both the shielding capabilities and the loss to be characterized is presented in this paper. Moreover, a smaller amount of material is needed in order to characterize the performance than in free space measurements, which can require an impractically large amount of material particularly for new, prototype materials.

II. OVERVIEW OF ELECTROTEXTILE

In general there are two main methods followed for rendering a textile material electrically conductive: (a) by applying a conductive coating on the surface of a non-conductive textile after it is formed, (b) by incorporating conductive fibers (e.g. via interweaving or via embroidery) into the textile structure. Any textile structure, including knitted, woven or nonwoven textiles, can be thus made electrically conductive. The choice of the textile structure and of the conductive mechanism determines the efficiency of the textile as an equivalent electroconductive material and assures its durability for its intended lifetime. The state-of-the art in conductive fibers are highly conductive metal wires or plated fibers. Inherently, conductive polymers are becoming closer in performance to that of metallic conductors and may be suitable for the next generation of applications in electrotextiles.

As an example of the need to characterize these materials at high frequencies, one means of metallizing a fiber is to sputter a thin layer of metal on the outside of an insulating core. The current crowding on the thin layer of metal will produce loss at low frequencies, while the skin depth will make this fiber similar to bulk metal wires at the same frequencies. The discrepancy in the high frequency and low frequency data requires that the high frequency materials are accurately measured. Similarly, the shielding ability needs to be directly measured at high frequency. Towards this end, a waveguide based measurement system has been developed to simultaneously measure loss and shielding capabilities for a class of electrotextiles.

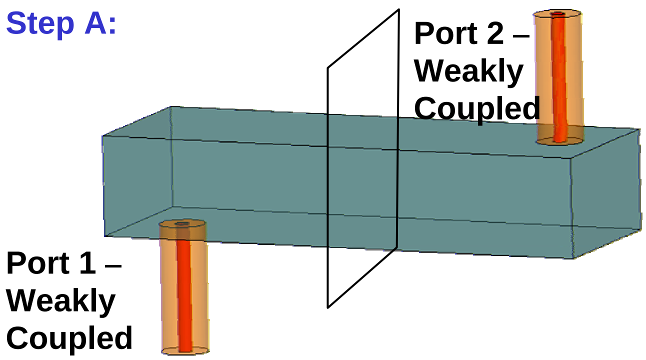

Fig. 2 Step A: Waveguide Cavity Measurement Setup for Calibration

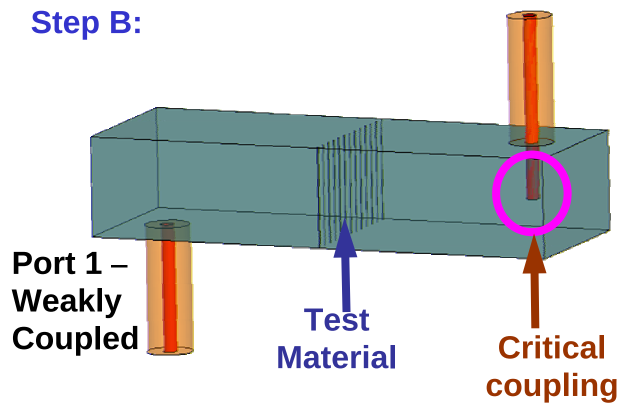

Fig. 3 Step B: Waveguide Cavity Measurement Setup for Characterizing the Electrotextile

III. IMBALANCED CAVITY ELECTROTEXTILE MEASUREMENT – THEORY AND DETAILS

Traditionally, waveguide measurements have been successfully used in order to determine material properties. Nearly all of these processes rely on a change in quality factor, Q, and the resonance frequency to determine the loss tangent and the dielectric constant of the material [2]. Most, if not all, processes assume that the waveguide has symmetric port feeds that are weakly coupled in order to easily extract out the unloaded Q of the cavity, from which the loss of the material under test can be extracted.

$$Q_u = \frac{Q_l}{1 - S_{21}} \quad (1)$$

This formula isolates the losses in the cavity by eliminating the losses through the ports of the resonator, namely by removing the parallel external Q's, Q_{ext}, but assumes that the input and output coupling mechanisms are identical. The effects of the feeds are removed in order to look at the resonator in isolation (without the loss associated with the energy escaping to the measurement ports).

Alternatively, in this research, we are looking to both quantify the losses in the material under test and also determine the ability of the material to shield energy from penetrating through it. This can be done by allowing an asymmetric coupling into the waveguide resonator by using the material under test as one of the coupling sections. This scheme allows for isolating the Q of the resonator to characterize the loss in the sidewalls, as well as the external coupling to the resonator to indicate shielding. Using the electrotextile as a means of coupling into the resonator allows for the quantification of the loss in the material as well as the material's ability to reflect energy. The details for this measurement are presented below. As shown in Fig. 2, one metal waveguide cavity (15.8mm×7.9mm×47mm) is split into two half cavities (15.8mm×7.9mm×23.5mm) at the symmetry line as shown. The first step (step A) is to use both halves to calibrate the system; a second step (step B) uses a resonance in a half cavity to characterize the electrotextile.

Step A: Weakly couple to both half cavities (with short coupling probes in the coax feed that are of the same length for both half cavities) and align them together to form one metal waveguide cavity as in Fig. 2. This cavity is twice the size of that in the following stage (stage B) in which only one half cavity is used. Measure the loaded Q (Q_l) and S_{21} at the second resonant frequency (the TE_{201} mode) and calculate unloaded Q (Q_u) and external Q (Q_{ext}) at each port. Since the coupling at both ports is symmetric at this point, we can use (1) and (2) to calculate Q_u of the cavity and Q_{ext} at each port [3].

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$$Q_{ext} = \left(\frac{1}{Q_l} - \frac{1}{Q_u}\right)^{-1} \times 2 \quad (2)$$

Step B: Change the coupling of the second half metal cavity (the right half in Fig. 3) to critical coupling. This is done by extending the coupling probe from the coax feed of port 2 such that the reflection coefficient from this transition is minimized. Next, insert the test material between the two half cavities and measure the loaded Q (Q_l) and S parameters at the first resonant frequency (the TE_{101}). Because the coupling at port 1 and port 2 is asymmetric, we use (3) to calculate the unloaded Q (Q_u) of the waveguide resonator.

$$Q_u = \frac{1-S_{11}^2}{1-S_{11}^2-S_{21}^2}\left(\frac{1}{Q_l}-\frac{1}{Q_{ext1}}\right)^{-1} \tag{3}$$

where $Q_{ext1} = Q_{ext}/2$ due to the change in the resonant mode as explained below.

Because the field distribution for the TE_{102} mode for the full cavity in step 1 is the same (and at the same frequency) as the TE_{101} mode of the left half cavity in step 2, the amount of power lost through port 1 will be equal. Since power stored is twice for the TE_{102}, the Q_{ext1} in step 2 is half of the Q_{ext} in step 1 [4]. In step 2, since the output port is critically coupled, S_{21} can be used to determine the amount of energy leaking through the electrotextile. Moreover, because there is no resonance in the right cavity, the wave amplitudes is much smaller than in the left cavity. Therefore, we can assume that the conductive loss in the metal walls in the right cavity is negligible and the energy leakage through the e-textile into the right cavity equals the energy transmitted at port 2. From the definition of Q and energy conservation in the system, we derive (4) which relate the Q_{ext2} with Q_u. Equation (3) which derives the critical value Q_u is determined by combining (4) and (5) below.

$$Q_{ext2} = \frac{1-S_{11}^2-S_{21}^2}{S_{21}^2}Q_u \tag{4}$$

$$\frac{1}{Q_l} = \frac{1}{Q_u}+\frac{1}{Q_{ext1}}+\frac{1}{Q_{ext2}} \tag{5}$$

From the Q_u of the left half cavity in step 2, we can calculate the conductive loss in the electrotextile and thus the effective surface resistance and conductivity of the test electrotextile. The process for finding surface resistance from the unloaded Q for a cavity waveguide with solid sidewalls can be found in many standard textbooks [5]. We use steel for the sidewalls of the metal cavities and solve for the conductivity of the textile face. The consequence of using this calculation is to homogenize the material into a solid sidewall of effective conductivity in order to compare materials with each other. Moreover, the isolation of the cavity from the waveguide at port 2 is a measure of the shielding effectiveness of the material. Specifically, Q_{ext2} is directly related to the ability of the electrotextile to shield energy from the critically coupled, since it relates the power inside the cavity to the power coupled through port 2. From the textile interface and therefore can be used to determine the quality of shielding for this material.

Alternatively, the ability of the material to shield can be determined by the reflection coefficient of a single reflection from the electrotextile in a waveguide. The single reflection from the waveguide is however quite sensitive, since these materials acts very much like a short and reflect a large majority of the signal. Therefore the single pass measurement is extremely sensitive. However, by treating the resonator as a half wave transmission line resonator, we can fit the reflection coefficient at the output of resonator to the extracted external Q at port 2 through the formula:

$$\Gamma_{\text{interface}} = \frac{1-\frac{2}{\pi}Q_{ext2}}{1+\frac{2}{\pi}Q_{ext2}} \tag{6}$$

IV. IMBALANCED CAVITY MEASUREMENTS ELECTROTEXTILE FIBERS - RESULTS

In order to characterize the conductive property of various conductive fibers, a fiber fixture for the waveguide cavity measurement was created. With the fiber fixture, conductive threads were arranged parallel to each other with controllable equal space over the aperture of the waveguide in our measurement setup. In this way, the effective surface resistance of different classes of conductive threads can be evaluated at high frequency without the pattern affecting the result. There are seven conductive threads tested in our measurement setup. 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 as shown in Fig. 4. The x-static thread (Fig. 4a) is formed by twisting many thin elastic silver plated nylon fibers together. The 100% stainless steel thread (Fig. 4b) is composed of numerous stainless steel fibers with diameter of 12 µm. The Litz wire sample in our test (Fig. 4c) contains 60 copper threads with diameter of 40 µm. The polyester/stainless steel sample (Fig. 4d) is a mixture of polyester fibers and thin stainless steel threads. For equal comparison of these conductive threads, we fix each of the threads on the fiber fixture with the same spacing. In Table 1, three conductive threads are tested at the density of 36 ppi. The silver plated copper threads (monofilament, diameter 0.159

mm) are orders of magnitude better than other two conductive threads, x-static in 4.a (70-xs-34x2 Textured), and Polyester/Stainless steel in Fig. 4.d (an 80/20 ratio), in both effective surface resistance and conductivity. Because the Litz wire (Fig. 4c) and 100% stainless steel (Fig. 4b) samples are too thick to be mounted on the fiber fixture at the density of 36 ppi, we used a 20 ppi fixture instead for these two samples. From Table 2, it is also confirmed that the monofilament threads in our test are orders of magnitude better than other multifilament samples. There are two reasons that the silver plated copper wire references are better than the multifilament samples. First, the conductivity of the silver coating on the copper wires is higher than that of stainless steel in (b) and (d), copper in (c) and coated silver on the surface of nylon fibers in (a). Secondly, the multiple conductive fibers in the multifilament threads substantially increase the effective surface and lead to higher conductive loss and also forces the current to flow in the directions of the wires (not always perfectly straight) increasing the total distance traveled.

V. CONCLUSIONS

We show a means of characterizing electrotextiles using a unique waveguide measurement using imbalanced coupling. The measurement process was detailed and preliminary results are provided. A comparison of numerous types of textiles is shown. We believe that this is a first step towards understanding the effects of textile features on their high frequency performance.

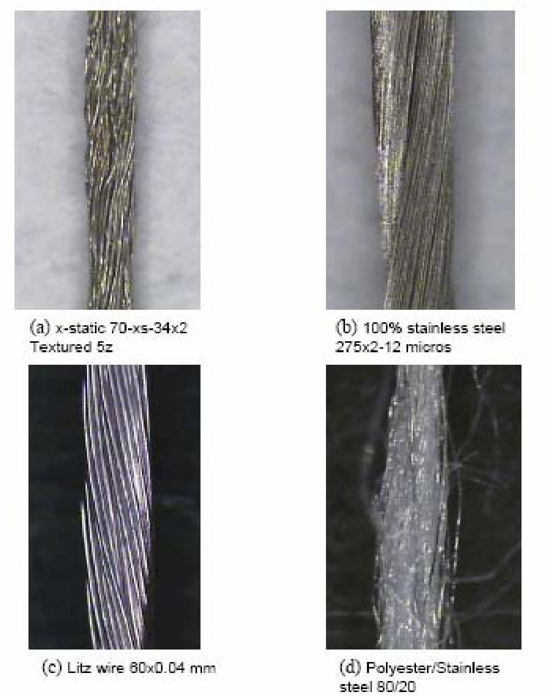

Figure 4 – Different Fibers Tested Using the Imbalanced Cavity Technique

Acknowledgements – We would like to thank Stacey Burr with Textroniks Corporation and Invista Corporation for supporting this project.

REFERENCES

[1] P. O. Salonen, et al, "Dual-Band Wearable Textile Antenna ," *2004 IEEE Antennas and Propagation Society International* Symposium, Monterey, California, USA, vol. 1, pp. 463-466

[2] D. Kajfez and E. J. Hwan, "Q-Factor Measurement with Network Analyzer," IEEE Trans. Microwave Theory Tech., vol. MTT-32, pp.666 – 670, Jul. 1984.

[3] Andy Brown, "High-Q Integrated Micromachined Components for a 28 GHz Front-end Transceiver," PhD thesis, University of Michigan, 1991.

[4] Simon Ramo, John R. Whinnery, and Theodore Van Duzer, *Fields and Waves in Communication Electronics*, New York: J. Wiley & Sons, 1993.

[5] David M. Pozar, *Microwave Engineering*, Second Ed., New York:John Wiley & Sons, Inc., 1998.

Table 1: Comparison of different conductive threads at 11.4 GHz (thread density 36 ppi)

Sample	Diameter (mm)	Q_u	Rs (Ω/m)	Conductivity (S/m)
silver plated copper wire	0.159	5156	0.093	5.2E+06
(a) x-static 70-xs-34x2 Textured 5z	N/A	1966	1.162	3.3E+04
(d) Polyester/Stainless steel 80/20	N/A	519	5.959	1.3E+03

Table 2: Comparison of different conductive threads at 11.4 GHz (thread density 20 ppi)

Sample	Diameter (mm)	Q_u	Rs (Ω/m)	Conductivity (S/m)
silver plated copper wire	0.08	4419	0.197	1.2E+06
silver plated copper wire	0.04	2844	0.611	1.2E+05
(c) Litz wire 60x0.04mm	N/A	1029	2.730	6.0E+03
(d) 100% stainless steel 275x2-12 micros	N/A	992	2.853	5.5E+03