

Characterization of Conductive Textiles for Wearable RFID Applications

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Abstract — Characterization based on wireless reflectometry of embroidered structures made of conductive threads is performed at the upper microwave ISM band (5.8 GHz). Obtained results are compared to the expected results based on DC conductivity measurements to highlight and discuss anisotropy effects

1 INTRODUCTION

Wearable RFID systems have attracted increased attention for healthcare applications [1, 2]. An integral component of wearable RFID systems is a wearable antenna which is required for wireless communications. Fabrication of wearable antennas is usually performed by using conductive fabric [3, 4], by the use of computerized embroidery machines [5] or by a combination of both [6–8]. The latter two options are attractive as complex geometries can be realized with high accuracy [9,10]. Consequently there is a large interest in characterizing the performance of embroidered conductive structures in relation to fabrication parameters such as stitch spacing, stitch direction and stitching patterns [11].

Early work into characterizing embroidered structures has shown that as the conductive threads take sinusoidal paths, a phase delay over a bulk material is observed with implications for setting a resonant frequency of operation [12]. Studies into embroidered patch antennas have shown that embroidered structures can be modeled as a homogeneous structure with an imaginary component for sheet resistance [13].

Given the complex microscopic structure that embroidery produces, modeling of embroidered structures can be quite challenging. One approach is to model the embroidered structures as meshes of finite conductivity [15] which has the advantage of taking into account current flow in the direction orthogonal to the desired current path.

Often the expected RF performance is based on extrapolating the DC parameters of the structures

which assumes that the material is isotropic. However this is not always true as embroidered structures show anisotropy [16].

Whilst there has been extensive work to understand the effect of fabrication parameters there has been less focus on the effect of anisotropy on embroidered structures in terms of embroidery density. This present work aims to answer this question. To this end, five embroidered conductive sheets are fabricated using varying embroidery densities and are characterized at the upper microwave ISM band using reflectometry under parallel and perpendicular polarizations, relative to stitching direction. The measured results are compared with the expected RF behaviour, and the anisotropic behavior of the samples is discussed.

2 Sample Fabrication

A computerized embroidery machine (Brother PR655c) was used to create linearly embroidered sheets of nominal dimensions 100 mm x 100 mm with a stitch spacing of 1 mm. All samples were prepared using Statex Shieldex 117/17 2Ply conductive yarn with a specified linear conductivity of less than 30 Ω /cm. A total of five samples were made, each with a different embroidered density obtained by varying the number of passes, as shown in Fig. 1. It was observed that after being stretched during the fabrication process, the samples would relax to average dimensions of 100 mm x 93 mm. Consequently, all simulations were performed with these dimensions.

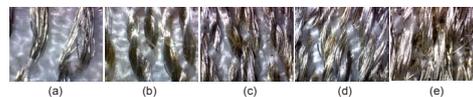


Figure 1: Fabricated samples under a microscope with different number of passes: (a) one pass, (b) two passes, (c) three passes, (d) four passes, (e) five passes.

3 DC Measurements

3.1 DC Conductivity

The DC sheet resistance of all samples was determined by a contactless conductivity measurement

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kit (Suragus EddyCus 2020). The measurement is based on measuring the magnetic field created by induced eddy currents. The induced eddy currents would take a circulating path through an homogeneous isotropic sample referenced to the center of the measurement device. Due to the anisotropy of the embroidered samples, the circular path is not possible especially for low wire densities.

3.2 Extrapolation to RF

Based on the measured DC sheet resistance, an effective RF sheet resistance can be extracted given $R_{\text{RFS}} = 1/\sigma_{\text{eff}}\delta$ where σ_{eff} is the effective conductivity and δ is the skin depth. For samples one to three, the effective RF sheet resistance can be assumed to be nearly the same as those measured at DC because the skin depth for these samples is greater than the thickness of the sample due to the high DC sheet resistance.

4 Scattering Experiments and Results

4.1 Experimental Setting

To determine the RF properties of the samples a scattering set-up was used as shown in Fig 2. The frequency range was chosen from 5.4 GHz to 8.2 GHz, to include the upper microwave ISM band (5.8 GHz). The samples were placed in an anechoic chamber and were then illuminated by an incident wave from a standard gain horn antenna (Narda Model 642) at an incidence angle of approximately $\theta = 8$ degrees. The scattered wave was detected from another similar horn antenna in the direction of specular reflection. An RF absorber block in between transmitter and receiver was used to minimize the coupling between the horns.

The reflection coefficient was determined using

$$|\Gamma| = \frac{|\Gamma_S - \Gamma_B|}{|\Gamma_C - \Gamma_B|}, \quad (1)$$

where Γ_S is the reflection coefficient of the sample, Γ_B is the reflection coefficient of the background environment and Γ_C is the reflection of a copper reference sheet of the same dimensions as the samples.

4.1.1 Simulation Setting

The reflection coefficient of the embroidered samples is calculated taking the ratio of the bistatic radar cross section (RCS) with the same incidence angle as in measurement to that of a perfect electric conductor plate of same dimensions. Simulations

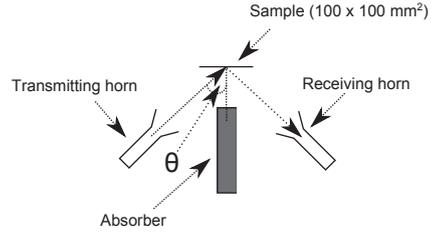


Figure 2: Reflectometry measurement set-up.

were performed with the effective RF sheet resistance. All simulations were performed using CST Microwave Studio.

4.1.2 Results

The measured results from the scattering experiments are shown in Figs. 3(a)–(e) for samples one to five. The solid blue and red lines represent the measured reflection coefficient for parallel and perpendicular polarizations, respectively. The results show, as expected, an obvious anisotropy. Comparisons of measured results to simulations, not shown here due to space constraints, revealed noticeable discrepancies – this is attributed to the DC measurement method which neglects anisotropy. Consequently to characterize the anisotropy, simulations were performed where the sheet resistance of samples was varied till an acceptable match was found to measured results for both polarizations.

The fitted sheet resistance values obtained by fitting simulations to measured data are given in the last two columns of Table 1 along with the measured DC and extrapolated RF sheet resistance. Note that for samples four and five the provided RF sheet resistance is taken as the average calculated over the frequency range of interest. For the case of parallel polarization for sample one and sample two, the significant anisotropy—as seen in Fig. 3(a) and (b) is attributed to the sparse embroidery. As the DC measurement relies on circulating eddy currents which are not possible in sparsely embroidered samples, the DC resistance may be significantly higher than the actual DC and RF sheet resistance in the direction of the wires.

It is observed that sample three and sample four have nearly the same effective sheet resistance in the parallel direction. This suggests that an embroidery density of three passes is sufficient to obtain good reflection in the parallel direction.

Interestingly, sample five shows a higher effective sheet resistance than sample four in both DC and fitted values. This is attributed to the increased interleaving of the conductive threads resulting in an increased surface roughness as seen in Fig. 1(e)

and as noted in [14].

Considering polarization perpendicular to the embroidery direction, it is clearly observed that samples one and two show extremely poor reflection coefficients (as seen in Fig. 3(a) and (b)) and this is expected given the sparse embroidery density. Surprisingly, despite good performance for parallel polarization, sample three shows a relatively poor reflection coefficient; this can be understood by examining Fig. 1(c): where it is observed that despite having high embroidery density there are still gaps between the parallel wires resulting in higher impedance to an orthogonal current flow.

Further, interestingly there is a significant effective sheet resistance difference for samples four and five in the perpendicular direction relative to the parallel direction. This indicates that despite having a high embroidery density the samples still show significant anisotropy effects. This is most likely because current conduction perpendicular to the main thread direction relies on the interleaving of threads which is not homogeneous through the structure and is also uncontrollable as can be seen in Fig. 1(d) and (e).

Pass	R_{DC} (Ω/\square)	R_{RFS} (Ω/\square)	R_{\parallel} (Ω/\square)	R_{\perp} (Ω/\square)
1	623	623	115	2500
2	328	328	25	2500
3	15	15	10	2000
4	2.22	6.7	10	90
5	2.48	7.5	17	115

Table 1: Measured and fitted sheet resistance for the five embroidery samples.

5 Conclusions

Five embroidered structures of varying embroidery density were fabricated and their sheet resistance was characterized at both DC and RF. The measured DC sheet resistance was extrapolated to RF to see the correlation of the measured RF parameters to simulated RF parameters which were based on the assumption of isotropy and homogeneity. The reflection coefficient of all samples was determined by examining the scattering response under different polarizations. It was demonstrated that results based on assumption of isotropy might not be suitable indicators of the performance of the samples. Specifically material anisotropy needs to be considered when evaluating the RF sheet resistance. Additionally it was shown that an increasing embroidery density may after a certain point degrade performance possibly as a result of surface roughness. This indicates that for a particular type

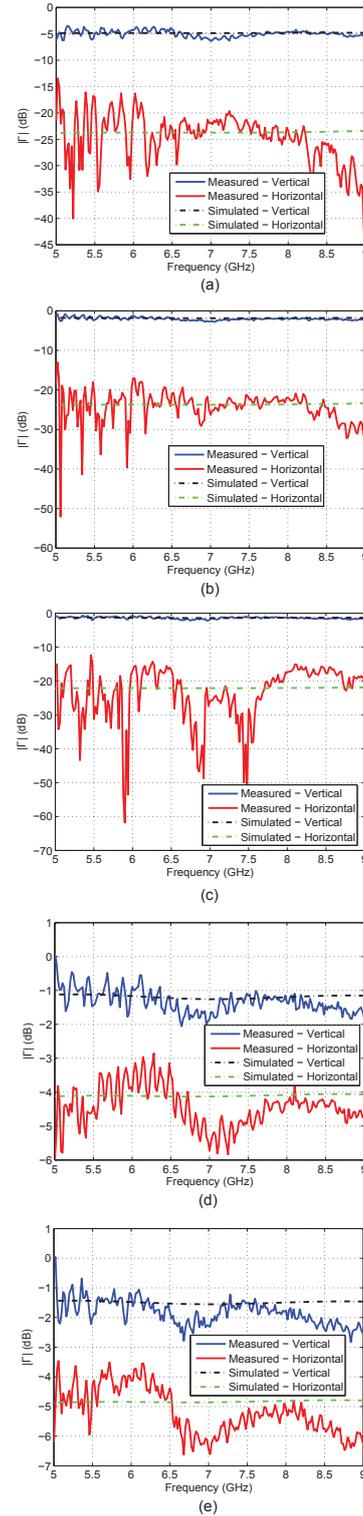


Figure 3: Reflection coefficient in two polarizations obtained from reflectometry for embroidered samples: (a) sample 1, (b) sample 2, (c) sample 3, (d) sample 4, (e) sample 5.

of conductive thread and stitch pattern, selecting a suitable density can improve performance in terms of RF sheet conductivity.

Acknowledgments

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