Towards Embroidered Textile Antenna Systematic Design and Accurate Modeling: Investigation of Stitch Density

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***Abstract*—In this paper, we present a study on the effects of stitch density towards the accurate modeling of embroidered textile patch antennas. A detailed full-wave model is used to accurately characterize the embroidery patch antenna with different stitch densities. The model accounts for the double-layer and nonuniform nature of the embroidery pattern. A generalized circuit model linked with particle swarm optimization (PSO) is then utilized to extract the effective circuit parameters and interpret the variations of antenna performance by embroidery stitch densities. The accurate modeling is further validated by systematically designing a low stitch density E-shape patch antenna with satisfactory performance.**

I. Introduction

The embroidered textile as a promising pathway towards the sensing [1] and wearable communications [2] applications have drawn an increasing attention. The seamless integration of electronics with ordinary clothes features versatile application contexts. It is favorable especially in medical and military applications. One of the major difficulties in embroidered antenna design is the accurate modeling that leads to systematic design and optimization. The major reason is that the embroidered electro-textile antennas have complex small structures that are not well studied and as a result it prolongs the design cycle and leads to non-optimal designs. In this paper, we present a study on the effects of stitch density towards the accurate modeling of of embroidered textile antennas.

II. Variation of Full-Wave Modeling on Stitch Density

In order to accurately characterize the embroidery-based antenna, a detailed full-wave model is introduced in [3]. The double-sided nature of embroidery pattern is modeled by two parallel conductive layers separated by a distance of d. The threads are aligned in a preferred direction and are not in perfect contact with each other along their full lengths. Therefore, the embroidered conductive surface is modeled by interspersing good conductive areas that emulate the threads with lower conductivity areas to provide a model for the higher resistance paths between adjacent threads. Finally, the thread residues introduced by the fabrication process significantly alter the desired structure near the edges. In order to model this effect in a simple manner, semi-rings are assigned along the two radiating edges, with radius of r for each of the ring elements.

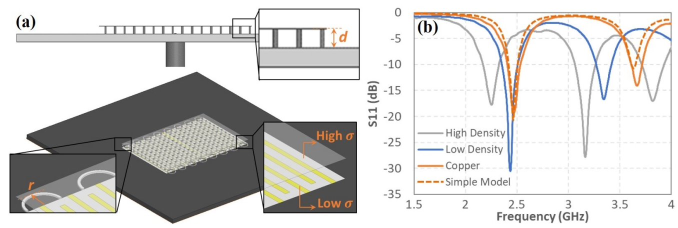

Fig. 1. (a) A detailed full-wave model that accounts for the double-sided embroidery nature of the electro-textile patch antenna. (b) The simulated S_{11} with the complete and simple models for the embroidery patch antennas with different stitch densities are compared.

TABLE I
THE DETAILED FULL-WAVE MODEL PARAMETERS FOR HIGH AND LOW STITCH DENSITIES.

Density	Double Layer Thickness d	Thread Residue Torus r	Meander Low Conductivity σ
1250 line/m	0.5 mm	1.2 mm	50 S/m
3750 line/m	3.0 mm	3.2 mm	200 S/m

The stitch density of the embroidery pattern is a critical parameter in designing and fabricating electro-textile patch antennas. The effect of stitch density should be properly reflected by the detail full-wave model parameters, e.g. the double-layer thickness d, the ring radius r, and the interspersing high-low conductivities σ_h and σ_l. Two cases of stitch densities (1250 line/m and 3750 line/m) are studied to compare the variations in full-wave modeling parameters. The prototypes with different stitch densities are fabricated, and S_{11} for each case is measured and compared with the detailed full-wave models to find the proper parameters, as listed in Table. I.

The radiation pattern of the embroidery patch antennas with low and high stitch densities are measured in the UCLA spherical near-field chamber. The results shown in Fig. 2 demonstrate good agreement between simulations and measurements for both co-pol and cross-pol radiations for antennas embroidered with low and high stitch densities.

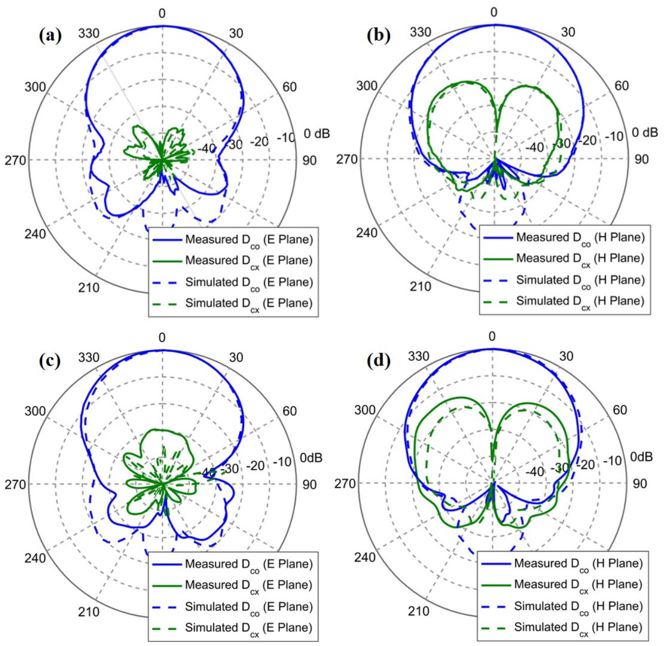

Fig. 2. The measured radiation pattern for embroidery patch antennas with low stitch density in (a) and (b), and high stitch density in (c) and (d).

TABLE II
THE CIRCUIT MODEL PARAMETERS FOR PATCH ANTENNAS USING COPPER AND EMBROIDERY PATTERNS WITH DIFFERENT STITCH DENSITIES.

Circuit Parameters	Density Study Cases			Circuit Parameters	Density Study Cases		
	High	Low	Copper		High	Low	Copper
C_0(pF)	21.12	23.04	43.50	L_5(nH)	0.566	0.697	0.007
$R_1(\Omega)$	171.46	289.65	437.26	$R_2(\Omega)$	114.14	188.11	451. 81
C_1(pF)	3.674	2.353	2.304	C_2(pF)	3.104	3.051	2.066
L_1(nH)	1.840	2.611	2.667	L_2(nH)	1.073	1.085	1.474

III. Circuit Model Interpretation

In this section, a generalized lumped element circuit model is utilized to study the effect of stitch density for embroidery patch antenna. With the multi-resonance circuit model linked with particle swarm optimization (PSO), the accurate Z parameter and S parameter over a wide frequency spectrum can be reconstructed with only a limited number of simulated frequency points required. A similar approach has been used to study the rectangular patch antenna bending effects as reported in [4]. The general expression for the input impedance of the equivalent circuit written as:

$$Z_{eq} = j2\pi f L_5 + \frac{1}{j2\pi f C_0} + \sum_{i=1}^{M} \left(\frac{1}{R_i} + \frac{1}{j2\pi f L_i} + j2\pi f C_i\right)^{-1} \quad (1)$$

where M denotes the number of resonances in the frequency band of interest, R_i, C_i, L_i are the equivalent lumped resistance, capacitance and inductance for the ith number of resonant mode. 3 cases have been studied for copper, high density (3750 line/m) and low density (1250 line/m) embroidery patterns. A normalized error function has been defined as the fitness function. By minimizing the fitness function, PSO finds the best parameters for the equivalent circuit model which generates the impedance curve closest to the measured results for each case.

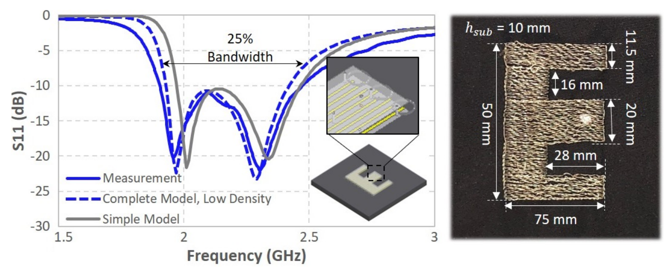

Fig. 3. An E-shaped embroidery patch antenna with low stitch density is built and measured to validate the stitch density study.

Table II lists the optimized circuit parameters for patch antennas using copper and embroidery patterns with different stitch densities. It is observed that comparing to copper, the embroidery patch antenna gives an increasing C_1 and decreasing L_1. The LC product increases, which results in a decreased resonant frequency. Comparing to the high-density, the low-density case has smaller variation to the case using copper as conductive material.

IV. Verification by E-Shaped Patch Antenna

As the final step of the study, an E-shaped patch antenna with low stitch density is built and tested to validate the modeling strategies and stitch density study. As shown in Fig. 3, the detailed full-wave modeling strategy with parameters listed in Table. I are used to generate the simulated S_{11} results and compared to measurements. The simulations with detailed modeling shows better agreement to measurement than the result for simple model.

V. Conclusion and Future Works

We present a study on the effects of stitch density towards the accurate simulation of embroidery-based patch antennas. A detailed full-wave model and a circuit model are used to study the variations of antenna performances for high and low stitch densities. The modeling strategies and stitch density study are further validated by an E-shaped patch antenna with measurements.

Acknowledgement

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