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Study of Double Ring Resonator Embroidered Wearable Antennas for Microwave Applications

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***Abstract*— In this work, the design, implementation and test of double ring resonator (DRR) wearable antennas is carried out. Specifically, symmetrical and non-symmetrical DRRs are coupled to a transmission line by means embroidered metallic thread on a felt substrate. Both designs present good e-textile antenna parameters performance in terms of return loss, directivity, realized gain and efficiency. Moreover, the specific absorption rate (SAR) to preserve the human body safety from radiation has been analyzed by means of numerical simulations including a realistic human voxel model, according to the international regulation. Experimental results confirm that the embroidered DRR antennas present a useful technique to transmit/receive microwave signals on wearable applications.**

***Index Terms*— e-textile, ring resonator, specific absorption rate, wearable antenna.**

I. Introduction

Textile electronics (e-textiles) is an emerging technology that enable humans' garments to interact with the technological anthropic surroundings [1]. Since e-textiles substrates are usually light weight, inexpensive, durable, zero maintenance and flexible (ability to bend, crumple), they are considered as suitable materials for implementing wearable antennas in wireless systems. Embroidery is the most advanced integration technique of electronic textile substrates, because embroidery machines allow repeatability, mass production of garments and customized designs in terms of thread distribution with a resolution in the order of <1 mm [2,3]. In addition, the design of highly efficient wearable antennas with low specific absorption rate (SAR) is required in order to minimize the electromagnetic energy absorbed by biological tissue when exposed to radiated electromagnetic energy and comply with international SAR regulations [4].

In this work the behavior of two wearable embroidered antenna based on symmetric and non-symmetric double ring resonators (DRRs) coupled to a microstrip are compared. The antennas are implemented on a felt substrate that can be attached or integrated to a garment. The considered structures do not limit the possible antenna placements across the outfit. Moreover, the SAR impact has been computed according to the IEEE standards [5,6].

II. Materials and Methods

A. Antenna Design

The proposed design layouts and embroidered prototypes are depicted in Fig. 1(a) and (b), respectively, including the main geometrical dimensions. The antenna topologies consist of a one (non-symmetrical) and a pair (symmetrical) double ring resonators (DRRs) coupled to a microstrip host transmission line. The inner circles with diameter l_1 are coupled to surrounding circle with diameter l_2 and gap g_2 between them. Both rings present a width, w. The gap between the outer ring and the host transmission line (width w_t and length l_3) is given by g_1. Both antennas are designed on a felt substrate (h=1 mm thickness) experimentally tested with a split post dielectric resonator (SPDR) to determine the dielectric constant and loss tangent by means of the resonance method. The values correspond to ε_r=1.2, and loss tangent δ=0.0013. The felt substrate is chosen because of its intrinsic low loss tangent and low cost in comparison with other fabrics [2]. The ground plane has been chosen as a homogeneous uniform commercial *WE-CF* adhesive copper sheet layer (thickness t = 35µm), for simplicity. The DRRs structure behavior can be described by means of LC resonant parallel tanks. These DRRs are excited by the port feed through a capacitive coupling between the host line and ring resonators and capacitive coupling between rings resonator to each other. The DRRs shape of resonators has been chosen to maximize the capacitance of the LC resonant tank. The port feeding dimensions are set to achieve a 50 Ω characteristic impedance. The proposed antennas have been simulated by means of the commercial full 3D electromagnetic software *CST Microwave Studio 2018*. The final dimensions of both prototypes are reported in Table I. The DRRs overall dimension have been determined for two different operation frequencies: the non-symmetrical case for f_{NS}=2.18 GHz (l_2≈λ/1.7) whereas the symmetrical case works at f_S=3.97 GHz (l_2≈λ/2.4). For a design reference, Fig. 2 illustrates the resonance frequency impact in terms of w for the non-symmetrical case.

B. Antenna Fabrication

An embroidery machine *Singer Futura XL550* is used for the antenna prototypes fabrication. The selected conductor yarn corresponds to a commercial *Shieldex 117/17 dtex 2-ply*

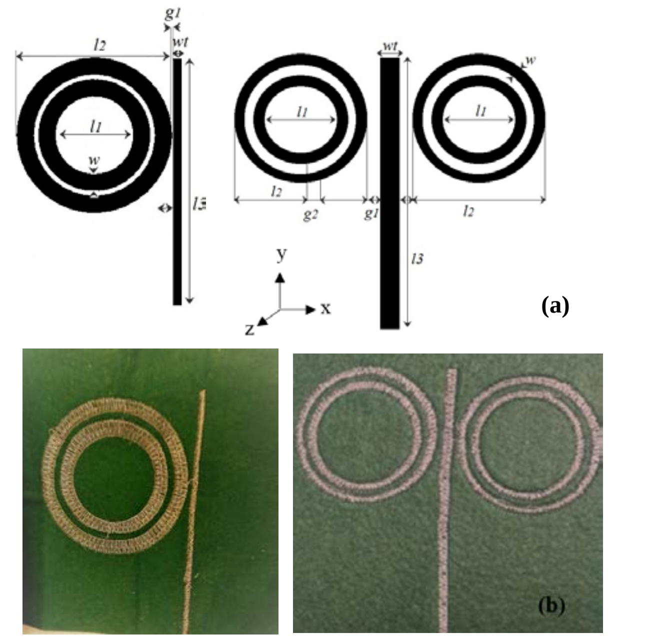

Fig.1. (a) Geometrical sketch of the proposed e-textile single and double textile DRR antenna. b) Embroidered prototypes on felt fabric.

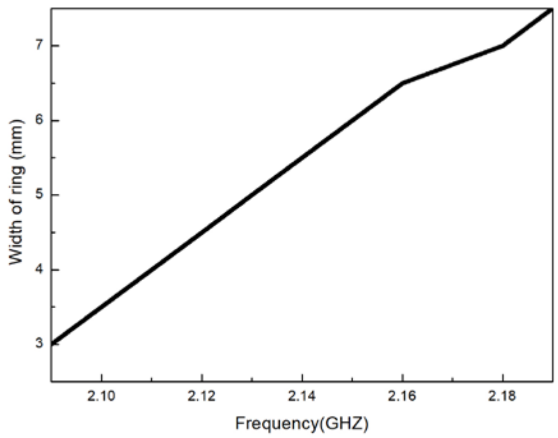

Fig.2. (a) Geometrical sketch of the proposed e-textile single and double textile DRR antenna. b) Embroidered prototypes on felt fabric.

that is composed by 99% pure silver plated nylon yarn 140/17 dtex with a linear resistance <30Ω/cm. The embroidered prototypes are shown in Fig. 1(b).

Due to the mechanical restrictions of the embroidery machine, the pattern was stitched with two types of threads. The sulky yarn is used as top thread and the conductive threads were used as bobbin threads. Also the default higher thread tension had to be lowered in order to maintain geometrical accuracy. The proposed designs were embroidered with a satin pattern with 40% stitch density. The stitch spacing corresponds to the distance between two needle penetrations on the same side of a column. The density determines the gap between stitches. For narrow columns, stitches are tight, thus requiring fewer stitches to cover the fabric. In areas with very narrow columns, less dense stitches are required because too many needle penetrations can damage the textile sample.

TABLE I
DESIGNED TEXTILE ANTENNA DIMENSIONS

Textile antenna	l_1 (mm)	l_2 (mm)	g_1 (mm)	g_2 (mm)	w_t (mm)	w (mm)
Embroidered Single DRR	38	74	1.2	3	4	7
Embroidered Double DRR	18	28.2	1	2	4	4.1

C. *Experimental Setup*

The antennas under test have been measured inside a RF diagnostic chamber *R&S DST200*. This anechoic chamber presents a highly effective shielding > 110 dB for interference-free testing in unshielded environments up to 18 GHz. In addition, a manual 3D positioner has been used to measure the radiation pattern gain by considering an angle step of 15 degrees. A microwave analyzer *N9916A FieldFox* operating as vector network analyzer has been used to determine the corresponding S11 parameters for return loss performance and S21 for radiation pattern realized gain measurement by means of a *R&S DST-B210* cross-polarized test antenna.

III. RESULTS AND DISCUSSION

In this section, the proposed antenna parameters as well as the SAR impact are presented and discussed.

A. *DRR Embroidered Antenna Performance*

Fig. 3 shows the measured and simulated values of the wearable antenna reflection coefficient (S11) and indicates a good agreement between them. The results show a good 50 Ω antenna matching. The non-symmetrical DRR case shows a │S11│<-12 dB at resonance frequency, whereas the symmetrical DRR presents │S11│<-19 dB. The -10 dB fractional bandwidth (FBW) is 1.83 % (2.16 GHz – 2.20 GHz) for the single DRR and 4.08% (3.84 GHz - 4 GHz) for the double DRR. The bandwidth is enhanced by means of the symmetrical double ring design due to the mutual coupling. Indeed, the double ring structure presents two main benefits: the double ring improves band-width, extending the effective radiation of an individual ring. The radiation efficiency is also improved, since the double ring design allows that the current flows on both of the metallic structures, rather than either of them. This fact can be observed comparing the surface current distribution of both topologies at resonance frequency (Fig. 4). Antennas with similar current distribution would radiate much more efficient than those made of a single metallic strip. This is due to the fact that the antenna's Ohmic loss is minimized by such a current distribution, the case is very similar to the resistance reduction by a multi-core cable.

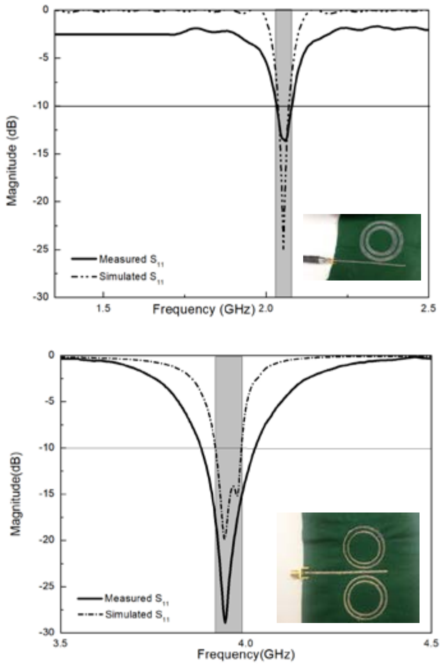

Fig. 3. Simulated and experimental return loss of the the proposed wearable antennas. (a) Single and (b) double DRR textile antenna.

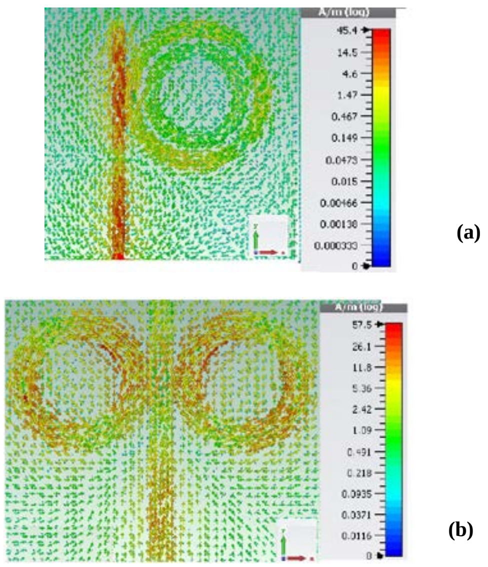

Fig. 4. Surface current distribution of the proposed wearable antennas at resonance frequency. (a) Single textile DRR antenna @ 2.18 GHz and (b) double textile DRR antenna @ 3.97 GHz.

Figs. 5 and 6 show the directivity as well as the radiation realized gain 3D patterns. The symmetric DRR pair allows increasing significantly the directivity and efficiency (η=93%) in comparison with the single structure (η=56%). The proposed antenna parameters performance are summarized in Table II. Fig. 7 shows the comparison

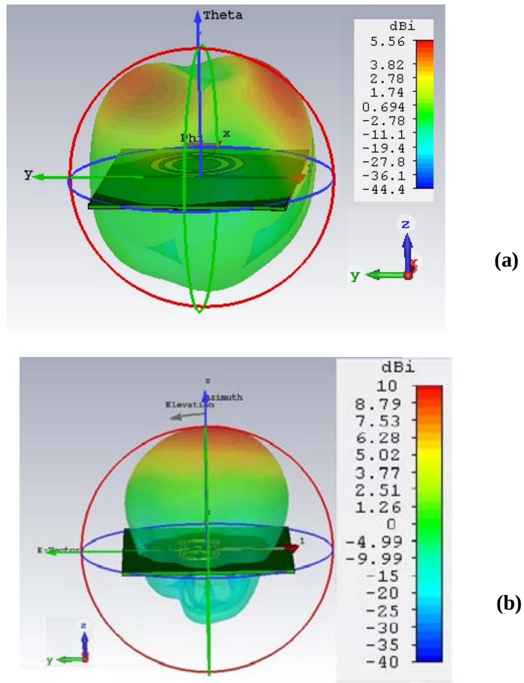

Fig. 5. Simulated 3D radiation directivity pattern of the proposed wearable antennas at resonance frequency. (a) Single DRR wearable antenna @ 2.18 GHz and (b) double DRR wearable antenna @ 3.97 GHz.

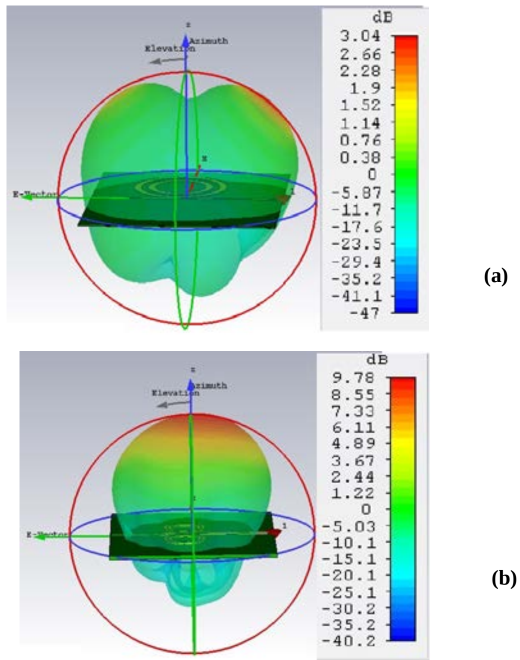

Fig. 6. Simulated 3D radiation gain pattern of the proposed wearable antennas at resonance frequency. (a) Single DRR wearable antenna @ 2.18 GHz and (b) double DRR wearable antenna @ 3.97 GHz.

between the simulated and measured normalized radiation gain patterns for the double DRR textile antenna.

TABLE II
TEXTILE ANTENNA PARAMETER SUMMARY AT RESONANCE FREQUENCY

Textile antenna	Fcenter / S11 (GHz / dB)	Directivity (dBi)	Gain (dB)	Efficiency (%)
Embroidered Single DRR	2.18 / -12	5.56	3.04	56
Embroidered Double DRR	3.97 / -19	10	9.78	95

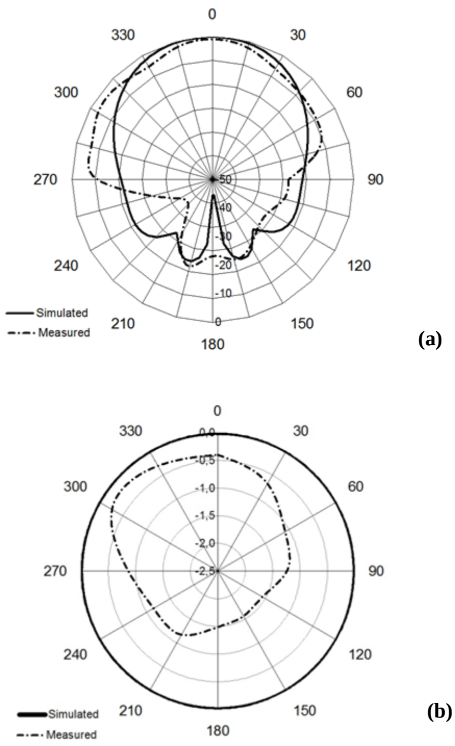

Fig. 7. Simulated and measured normalized radiation gain patterns for the double DRR textile antenna @ 3.97 GHz., (a) XZ-plane (φ=90º). (b) YZ-plane (θ=0º).

B. SAR Analysis

SAR is a measure of the radiated power absorbed per unit mass in a human body tissue. It is normally spatially averaged over a certain amount of exposed biological tissue. SAR is calculated using the root mean square (rms) of the electric field strength inside the human body, the conductivity, and the mass density of the tissue. The SAR limit recommended by European/Japan/China authorities is 2.0W/kg averaged over 10 g of actual tissue whereas in the United States/Canada/Korea the threshold corresponds to 1.6 W/kg for averaged over a volume of 1 gram of tissue, for the body or head. In order to obtain accurate results in terms of antenna performance and SAR, a realistic heterogeneous voxel model has been taken into account. Specifically, the Gustav male model (38 years old, 176 cm size and 69 Kg mass) available by the CST software, based on 57 biological tissues has been simulated [7]. A reference EM power value of 50mW (17 dBm) antenna input power has been considered since this value corresponds to the typical maximum transmitted power for wearable devices and applications. The IEEE/IEC 62704-1 standard has been used in the SAR computation at the antennas resonance frequency. The 3D obtained results are depicted in Fig. 6 (a), (b), respectively. All SAR values are extremely low and comply with the international safety regulations (Table III). The highest average SAR value corresponds to SAR 1g tissue for the double DRR case but it is a 70.8% lower than the limit recommendation. The rest of SAR values are more than 90% lower than the maximum allowed values. This fact is due to the directivity pattern of the antennas as well as the ground plane which preserves the back radiation towards to the body for both antenna prototypes.

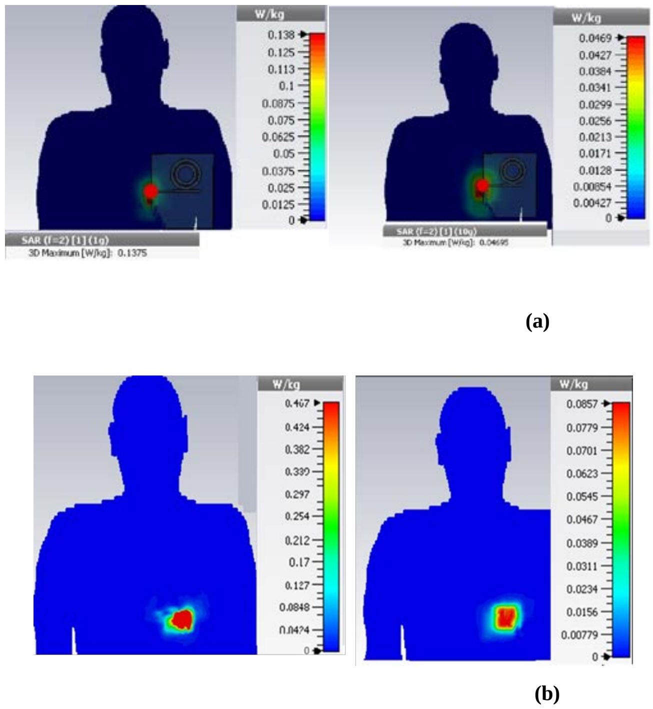

Fig. 8. 3D distribution for SAR 1 g tissue and SAR 10 g of the proposed wearable antennas at resonance frequency on Gustav's chest. (a) Single DRR wearable antenna @ 2.18 GHz and (b) double DRR wearable antenna @ 3.97 GHz.

TABLE III
SAR VALUES FOR THE VOXEL MODEL AT RESONANCE FREQUENCY @ P_{IN}=17 DBM AND MARGIN WITH REGARD TO THE MAXIMUM ALLOWED VALUE

Textile antenna	Peak SAR 1g tissue (W/Kg)	Peak SAR 10g tissue (W/Kg)
Single DRR @2.18 GHz	0.138 (<91.4% max)	0.047 (<97.7% max)
Double DRR @3.97 GHz	0.467 (<70.8% max)	0.086 (<95.7% max)

IV. CONCLUSION

Two symmetrical and non-symmetrical DRR e-textile antennas have been studied. Simulation and experimental results reveal that symmetrical DRR wearable antennas present a significant realized gain and efficiency due to the mutual coupling structure. Moreover, the obtained SAR results guarantee the human body safety from radiation, according to numerical simulations including a realistic human voxel model. Experimental results confirm that the embroidered DRR antennas present a useful technique to transmit/receive microwave signals on wearable applications.

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