Novel Electrotextile Patch Antenna on Jeans Substrate for Wearable Applications

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Abstract—This paper aimed to take closer steps towards real wearability by investigating the possibilities of designing and fabricating highly efficient and fully flexible wearable microstrip patch antenna for operating frequency of $5.8\,\text{GHz}$ as a center frequency. Two types of conducting materials have been used for conducting parts: conventional metal plane and woven electro-textile material, while a non-conducting jeans fabric has been used as antenna substrate material. The dielectric constant $\varepsilon_r = 1.78$, and loss tangent $\tan\delta = 0.085$ of the jeans substrate measured by using two different methods. Also, the electromagnetic properties of the electro-textile are studied in details. The conductivity of e-textile cell is equal to $2.5 \times 10^6\,\text{S/m}$ and the surface impedance of e-textile cell equal to $0.0395 + J18.4\,\Omega$. Furthermore, the proposed wearable antenna may be attached to human body, so the specific absorption ratio (SAR) must be calculated. Finally, the proposed design is simulated by CST simulator version 2016, fabricated using folded copper and measured by Agilent8719ES VNA.

1. INTRODUCTION

Wearable, body-worn antennas get more and more attention for body-centric communications because they can be easily worn on body and integrated into clothes [1]. Since 1997, wearable systems have become common subjects in researches. Many papers have been published about the design, fabrication and applications of these antennas. Some of these developments are reported in [2–4]. In recent years, electro-textiles (e-textiles) have taken a lot of attention as hopeful materials for the development of wearable antennas to make them fully flexible, which allows the smart clothes to communicate freely through wireless networks [5]. E-textiles are used as antenna patches and ground plane, while dielectric-textiles are used as antenna substrates [6–9].

In the antenna design, as the dielectric properties of the textile substrate, dielectric constant and loss tangent play important roles in the propagation of electromagnetic energy in dielectric media and have effect on the antenna performance [10]. The electromagnetic properties of the electro-textiles also play vital roles in antenna design and performance [11].

This paper includes an e-textile patch antenna design which is made from Jeans fabric substrate material with two types of conducting materials that will be discussed in more details in the following sections. Two different methods for fabric characterization are presented. The first method is a microstrip ring resonator. The second is DAC equipment (Dielectric Assessment Kit) setup to confirm the results. Further, this paper studies the electromagnetic properties of e-textiles for wearable antennas and calculates the basic resistance and inductance in a grid. Also, the SAR calculations for the presented antennas are performed on-body environments to ensure they operate properly in the nearness of the human body.

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2. MEASUREMENT OF JEANS TEXTILE CHARACTERISTICS

The dielectric constant and loss tangent for jeans textile material are measured by using two different methods. The first is a microstrip ring resonator method. The ring resonator model consists of a ring and two feed lines pasted on the upper surface of the jeans substrate. The ground plane occupies the lower surface of the jeans substrate, and a small gap Δ is also included between the ring and each feed line [12, 13]. The fabricated ring resonator model is shown in Fig. 1(a). By measuring S_{21} for this model shown in Fig. 1(b), the dielectric constant and loss tangent for jeans textile material can be measured. The peak in S_{21} was recorded around each resonance. The nth resonance occurs at [13]:

$$f_n = \frac{nc}{2\pi r \sqrt{\varepsilon_r}} \tag{1}$$

where r is the mean radius, c the speed of light in a vacuum, and ε_r the required relative dielectric constant.
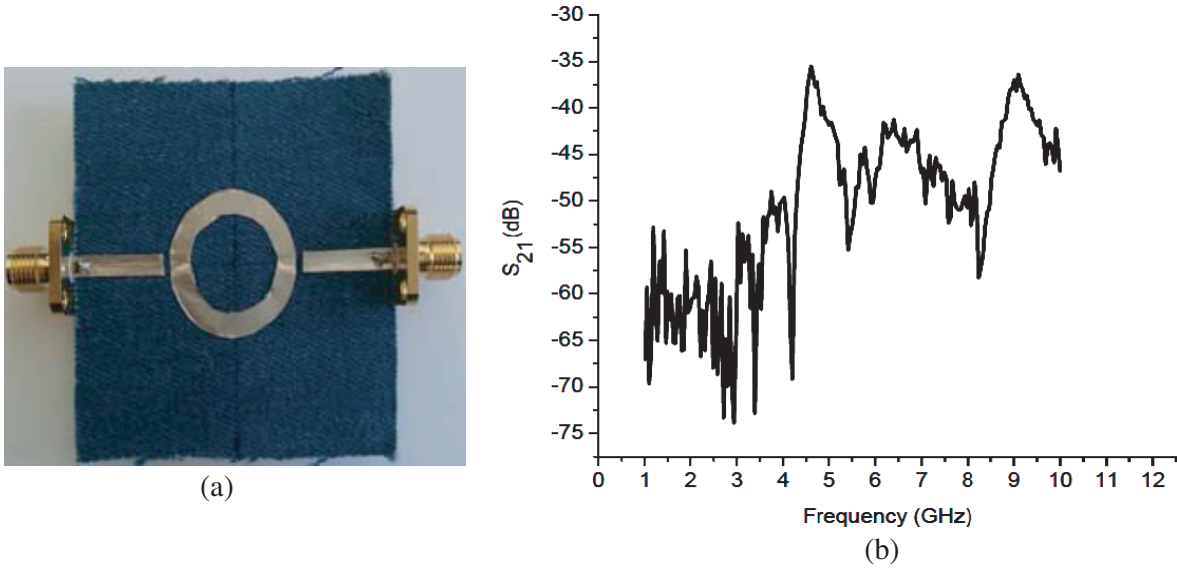

Figure 1. The fabricated ring resonator model pasted on jeans substrate: (a) fabricated geometry, and (b) measured S_{21} with the frequency.

The insertion loss (S_{21} (dB)) is introduced as [13],

$$\text{IL} = 20 \log_{10} \left(1 - \frac{Q_L}{Q_u} \right) \tag{2}$$

where Q_L and Q_u are the loaded and unloaded quality factors.

From the loaded and unloaded quality factors the loss tangent can be obtained and more details in [14]. The results of ring resonator method for characterization of jeans textile are mentioned in Table 1.

Table 1. The results of ring resonator method for characterization of jeans textile substrate.

Material	Mode	Resonance Frequency (GHz)	S_{21} (dB)	dielectric constant (ε_r)	loss tangent ($\tan \delta$)
Jeans	$n = 1$	4.26	-35.5	1.73	0.077
	$n = 2$	8.89	-36.9	1.69	0.073

The second method is DAC (Dielectric Assessment Kit) equipment [15]. Therefore, it has been used to confirm the results determined using the first one. Comparing the obtained results using the two methods, it can be observed that close values are found between the two methods for jeans textile material and more details in [14]. The measured dielectric constant, loss tangent and thickness of the jeans substrate are mentioned in Table 2.

Table 2. The charactrization results of the jeans textile substrate.

Substrate Material	Dielectric constant (ε_r)	loss tangent ($\tan \delta$)	Thickness (mm)
Jeans	1.78	0.085	0.6

Comparing the obtained results of the two methods, it can be observed that close values are found between the two methods for jeans textile material, but there are some slight differences between them, which is an inherent thing.

3. ELECTROMAGNETIC PROPERTIES OF E-TEXTILE CELL

Generally, there are two methods to make the dielectric textile electrically conductive. The first one is by applying conductive coating on the dielectric textile surface. The second is by interleaving normal fabrics with conductive metal threads via weaving or knitting [16]. However, woven fabrics perform better than coated fabrics, because of discontinuities of coated fabrics which increase the surface resistance [17]. We can also increase the conductivity of woven fabrics by increasing the conductive thread density in it.

Woven electro-textile fabric has more intersections in its pattern, which means that less distance between metal grids aligned along the current flow to keep conduction losses as low as possible as shown in Fig. 2 [18].
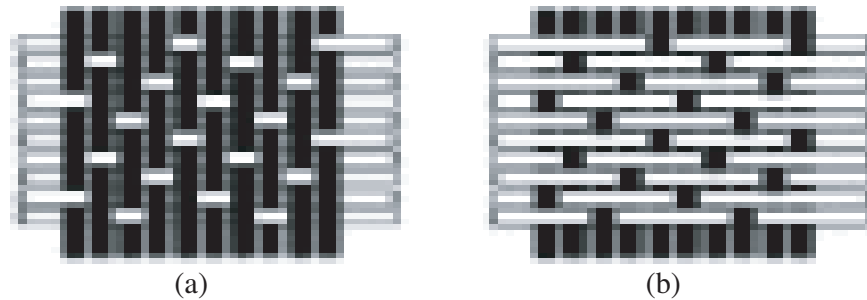

(a)   (b)

Figure 2. Woven pattern of fabric: (a) front, (b) back [18].

In this paper, the e-textile has a woven pattern with woven density N ppi, and the conductive fabrics are made from round copper wires, with diameter of 80 μm.

The distance between two conductive wires in any woven fabrics can be expressed as [18],

$$d = \frac{25.4 - 0.08N}{N - 1} \text{ (mm)} \tag{3}$$

If the distance between two conductive wires (d) is equal to 0.5 mm in this paper, the copper density in this fabric is 45 ppi.

Although connective threads are not normally considered components, they have very important properties of noise and high frequency performance of electronic circuits [19]. So, for the conductive threads whose length is a small fraction of the wavelength, the two most important characteristics are resistance and inductance [19]. In this paper, the proposed wearable antenna is used in the WiFi band, especially at 5.8 GHz. Furthermore, the wavelength can be calculated by:

$$\lambda = c/f_0 \tag{4}$$

where c is the speed of light, and f is the resonance frequency.

While $f_0 = 5.8$ GHz, the wavelength is equal to 51.7 mm. In addition, the electrical dimensions of the e-textile cells are electrical small approximately equal to $\lambda/10$, so we should construct lumped parameter electric circuit models. In many cases, the inductance is more important than resistance. Even at relatively low frequencies, a conductive thread usually has more inductive reactance than resistance [19].

3.1. Inductance of Round Conductive Threads

The total inductance is actually the sum of the internal inductance plus external inductance. The internal inductance is the effect of the magnetic field within the conductive wire itself, and it is usually negligible compared with the external inductance except for closely spaced conductive wires [19]. In addition, internal inductance is reduced even more when high-frequency currents are considered because as the result of skin effect, the current is concentrated near the surface of the conductor [19]. In this paper, the skin depth of the copper wires at resonance frequency can be calculated by [19],

$$\delta_s = \frac{1}{\sqrt{\pi f_0 \mu_0 \sigma}} \tag{5}$$

where f_0 is the resonance frequency, μ_0 the permeability of free space, π a constant approximately equal to 3.14159, and σ_c the conductivity of copper wire ($\sigma_c = 5.8 \times 10^7$ s/m).

While at $f_0 = 5.8$ GHz, the skin depth is equal to 8.68×10^{-7}, which is a little distance. Therefore, the external inductance is normally the only inductance of significance where the radius of the copper wire $r_c > 2\delta_s$. In this paper, we assume that the two wires are separated ($d/r_c > 5$) (d is the distance between the two wires). According to this condition, the per unit-length of the external inductance of two parallel wires can be expressed as [20],

$$l = \frac{\mu_0}{\pi} \ln \frac{d}{r_c} \tag{6}$$

where r_c is the copper wire radius, μ the permeability of the free space ($\mu = 4\pi \times 10^{-7}$ H/m), and d the distance between two wires.

From Eq. (6), we can get that the per-unit-length inductance is 1.01×10^{-6} H/m, and then the inductance in a grid length is $L = 0.505$ nH.

3.2. Resistance of Round Conductive Threads

Resistance is the second important characteristic of a round conductive copper wire. At high frequency, due to the skin effect, the resistance of conductive wires is a surface resistance where all the currents are surface currents [19]. In this paper, the ratio between the radius of the copper wire and skin depth is $r_c/\delta_s \sim 46$. So, the per-unit-length of the surface resistance of copper wire can be expressed as [20];

$$r = \frac{1}{2r_c}\sqrt{\frac{\mu_0 f_0}{\pi \sigma_c}} \quad r_c \gg \delta_s \tag{7}$$

where r_c is the copper wire radius, μ the permeability of the free space ($\mu = 4\pi \times 10^{-7}$ H/m), f the operating frequency, σ_c the copper conductivity ($\sigma_c = 5.8 \times 10^7$ S/m), and d the distance between two wire.

From Eq. (7), we can get that the per-unit-length resistance of copper wire is $79.06\,\Omega$/m, and then the resistance in a grid length is $R = 0.0395\,\Omega$.

3.3. The Conductivity and Surface Impedance of E-Textile Cell

Now, we can calculate the conductivity of e-textile cell where the conductivity (σ) is the reciprocal of the resistivity (ρ). The resistivity of an e-textile cell can be calculated by [21],

$$\rho = r \times A = r \times \frac{\pi d_c^2}{4} \tag{8}$$

where r is the per-unit-length resistance of copper wire; A is the cross section area over which the current flows; d_c is the diameter of the copper wire.

From Eq. (9), we can get that the resistivity is equal to $3.9 \times 10^{-7} \, \Omega \cdot m$ and then the conductivity of e-textile cell equal to $\sigma = 1\rho = 2.5 \times 10^6 \, \text{S/m}$). Although electro-textile material has less conductivity than pure copper material ($\sigma < \sigma_c$), this material achieves real wearability for the body-worn microstrip antenna Furthermore, the surface impedance of e-textile cell can be calculated by [21],

$$Z = R + JX_L = R + J2\pi f_0 L \tag{9}$$

where R is the resistance in a grid length, π a constant approximately equal to 3.14159, f the operating frequency, and L the inductance in a grid length.

From Eq. (9), we can get the surface impedance as $Z = 0.0395 + J18.4 \, \Omega$. Furthermore, the copper wire has very low resistance value, so the antenna with e-textile material is efficient and more flexible.

4. ANTENNA DESIGN

Three proposed microstrip patch wearable antennas operated at 5.8 GHz as a resonance frequency are designed and fabricated. Geometries of the three antennas are shown in Fig. 3. All geometry parameters of the presented antennas are the same and mentioned in Table 3.
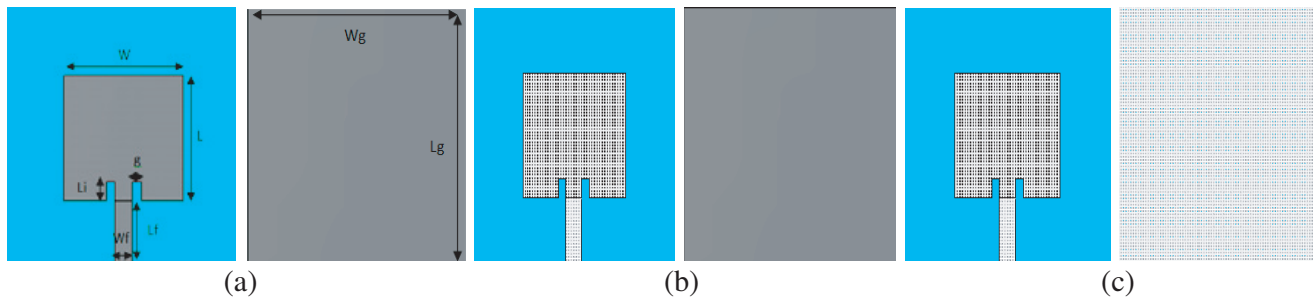

(a) (b) (c)

Figure 3. The geometries of wearable antennas using different conductive part: (a) pure copper antenna; (b) semi-e-textile antenna, and (c) fully e-textile antenna.

Table 3. The dimensions of wearable patch antenna (unit: mm).

Width (W)	Length (L)	Width of Ground (W_g)	Length of Ground (L_g)	Width of inset feed (W_f)	Length of inset feed (L_f)	Length of Stub (L_i)	Gap (g)
20	19.2	40	40	3	10	3	1.5

The antennas are pasted on jeans textile material as a substrate. The conductive part is different. The first one uses a pure copper tape for patch and ground plane. The second uses woven electro-textile material for patch and a pure copper tape for ground plane. The third uses woven electro-textile material for patch and ground plane to make a completely textile wearable antenna. Fabricated geometries of the three antennas are measured by Agilent8719ES VNA as shown in Fig. 4.

5. SIMULATED AND EXPERIMENTAL RESULTS

In this paper, the e-textile material is simulated in the simulation program by two methods: the first one by using a copper sheet with a lower conductivity $\sigma = 2.5 \times 10^6 \, \text{S/m}$ ($\sigma < \sigma_c$) and the second method by using cotton/copper threads woven to each other. The simulated and measured S_{11} for the pure copper antenna are plotted in Fig. 5. The simulated and measured S_{11} for the semi-e-textile antenna and fully e-textile antenna by using two different simulated methods are plotted in Fig. 6 and

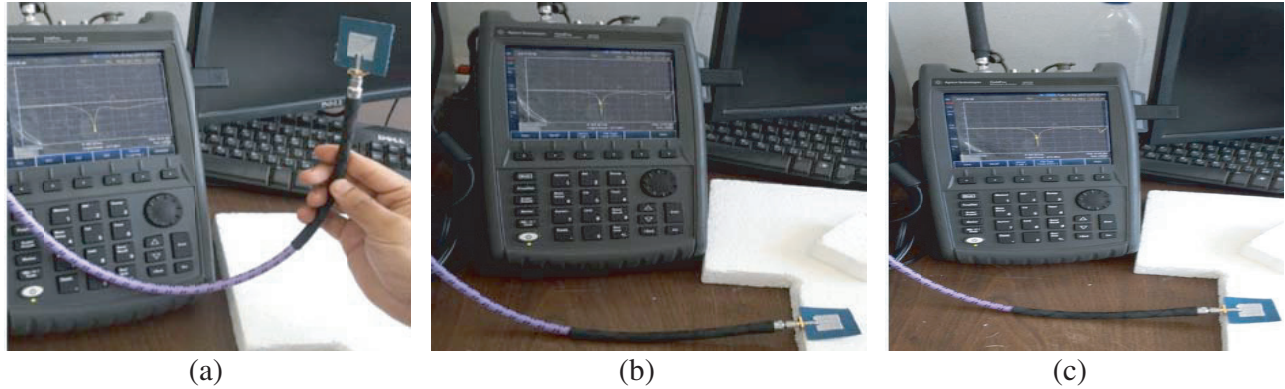(a)   (b)   (c)

Figure 4. The fabricated antenna with connector and cable with Agilent8719ES VNA: (a) pure copper antenna; (b) semi-e-textile antenna, and (c) fully e-textile antenna.
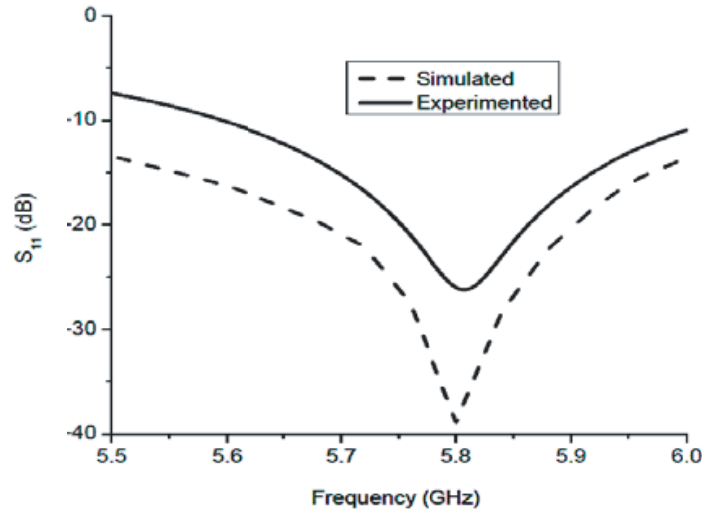

Figure 5. The measured and simulated S_{11} of the proposed pure copper antenna.

Fig. 7. From these results, it is found that the simulated results of the second simulation method agree well with the measured results compared to the first method and are more accurate. However, the first method of e-textile simulation provides better antenna performance than the second method.

From Fig. 6 and Fig. 7, in the first simulation method, both e-textile antenna resonances have gone down slightly to 5.85 GHz compared to the pure copper antenna resonance because the current flows along copper sheet with lower conductivity, and with decreasing the conductivity, the resonance frequency is also decreased. However, in the second simulation, the e-textile antenna resonances have gone up slightly to 5.85 GHz compared to the pure copper antenna resonance because of shorter current paths on the patch and the ground plane where the current flows in the copper threads only, and with decreasing the current flow path, the resonance frequency is increased. Further, by comparing the three curves it is found that the most suitable method to simulate the e-textile material is the second method which is more close to the fabrication.

The realized gains versus frequency for the proposed three antennas are plotted in Fig. 8, and the current distributions for the proposed antenna in three different cases are simulated by two methods and plotted in Fig. 9 and Fig. 10. In addition, in each patch wearable antenna the radiations patterns in E-plane ($\varphi = 0°$) and H-plane ($\varphi = 90°$) are also simulated by two methods and plotted in Fig. 11 and Fig. 12. Further, the simulation performances of the proposed patch antenna in the three cases is mentioned in Table 4.
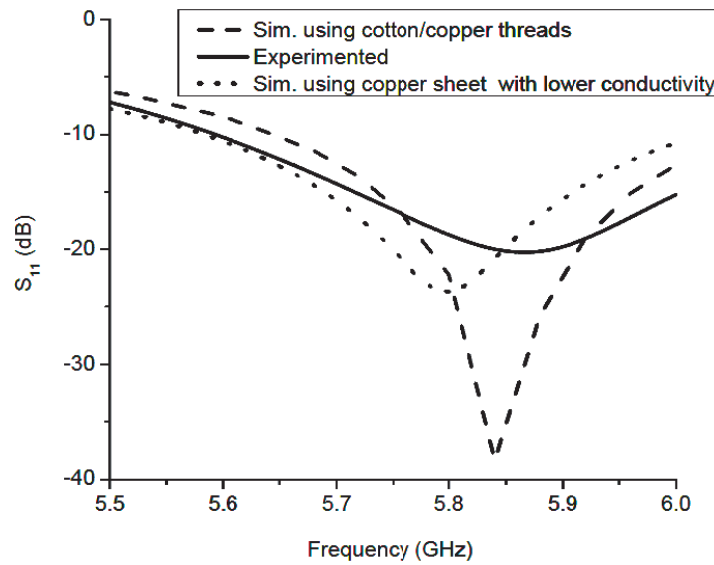
Figure 6. The measured and simulated S_{11} of the proposed semi-electro-textile antenna.
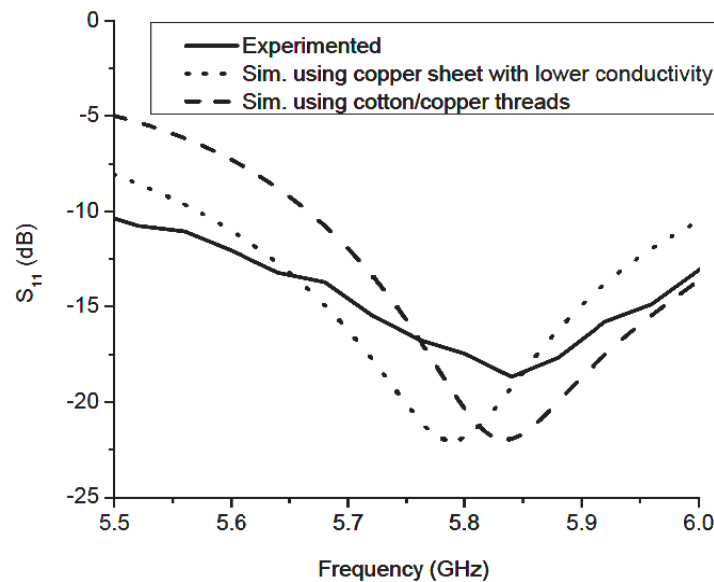

Figure 7. The measured and simulated S_{11} of the proposed fully-electro-textile antenna.

From Fig. 8 and Table 4, the pure copper tape antenna and semi-e-textile antenna have close values in the gain and efficiency and are better than the fully e-textile antenna. However, the copper tape is not reliable; it may be flaked off and breaks. Also, the e-textile antenna has some drawbacks. For example, there is an obvious offset in the frequency band as well as decreased radiation efficiency. So, the fully e-textile antenna is an efficient and fully flexible wearable microstrip patch antenna with acceptable performance.

Finally, SAR simulation results according to the international safety standards [22] FCC (SAR < 1.6 mW/kg over 1 g) and ICNIPR (SAR < 2 mW/kg over 10 g) for the proposed antenna in different cases are shown in Fig. 13, and these results are mentioned in Table 5. These results are carried out on CST MICROWAVE STUDIO 2016 simulator. It is a full wave numerical simulator which uses the finite integration technique (FIT) [23].
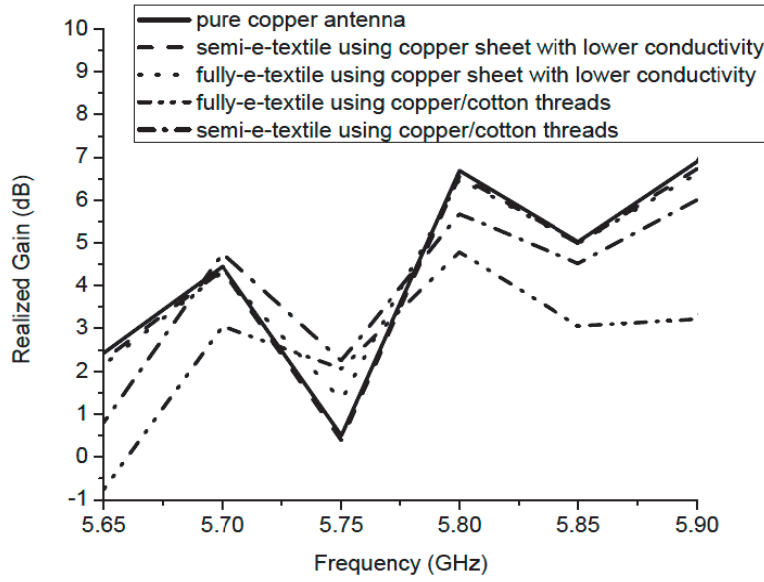
Figure 8. The realized gains for the proposed antenna in different cases and by two simulation method.

(a)   (b)   (c)
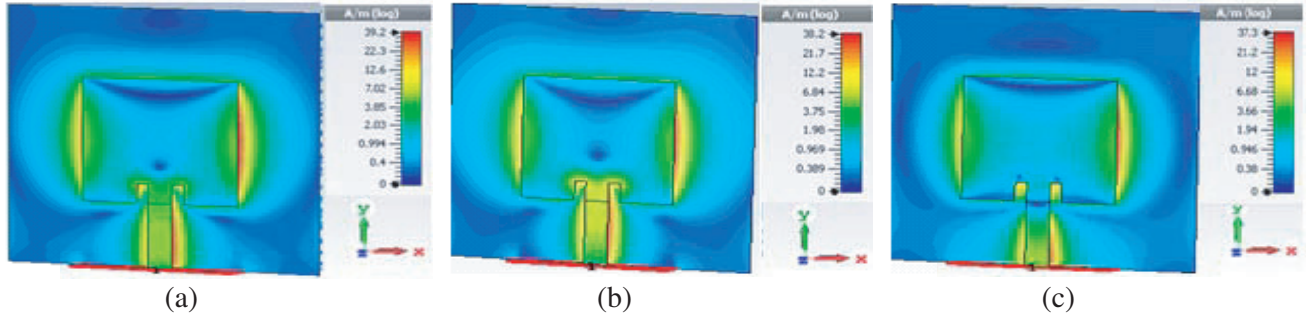
Figure 9. The current distribution of different proposed antenna using copper sheet with $\sigma < \sigma_c$: (a) pure copper antenna; (b) semi-e-textile antenna, and (c) fully e-textile antenna.

Table 4. The simulation performance of the proposed patch antenna in the three cases.

Antenna Type	Using copper sheet with $\sigma < \sigma_c$				Using cotton/copper threads			
	Resonant Freq. (GHz)	Return Loss S_{11} (dB)	Gain (dB)	Efficiency (%)	Resonant Freq. (GHz)	Return Loss S_{11} (dB)	Gain (dB)	Efficiency (%)
Pure copper	5.8085	−38.53	6.68	65	5.8085	−38.53	6.68	65
Semi-e-textile	5.7971	−31.277	6.57	62	5.86	−37.843	4.52	59.8
Fully e-textile	5.7092	−28.824	6.49	59	5.892	−21.52	3.05	54.1

From Table 5, it is found that all SAR values are very low and satisfy the international safety standards. However, by using e-textile material instead of copper tape in the antenna design, the SAR value is increased a little due to increasing the back radiation, but still an acceptable value.
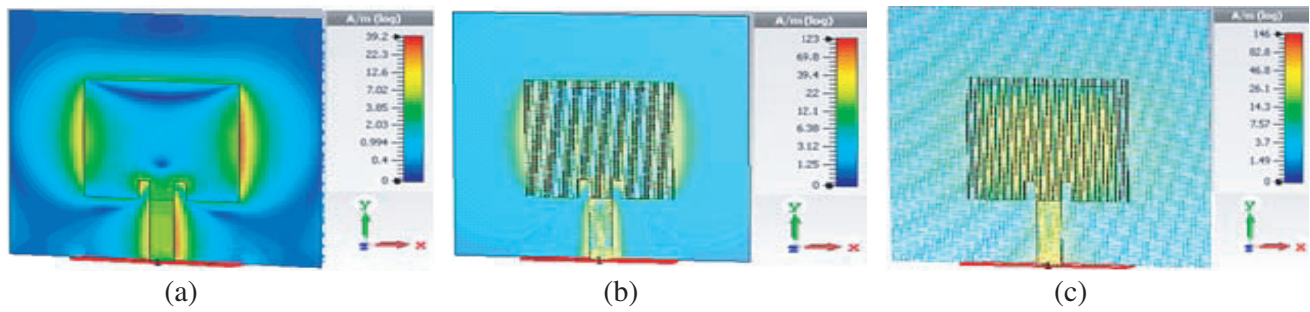
Figure 10. The current distribution of different proposed antenna using cotton/copper threads: (a) pure copper antenna; (b) semi-e-textile antenna, and (c) fully e-textile antenna.
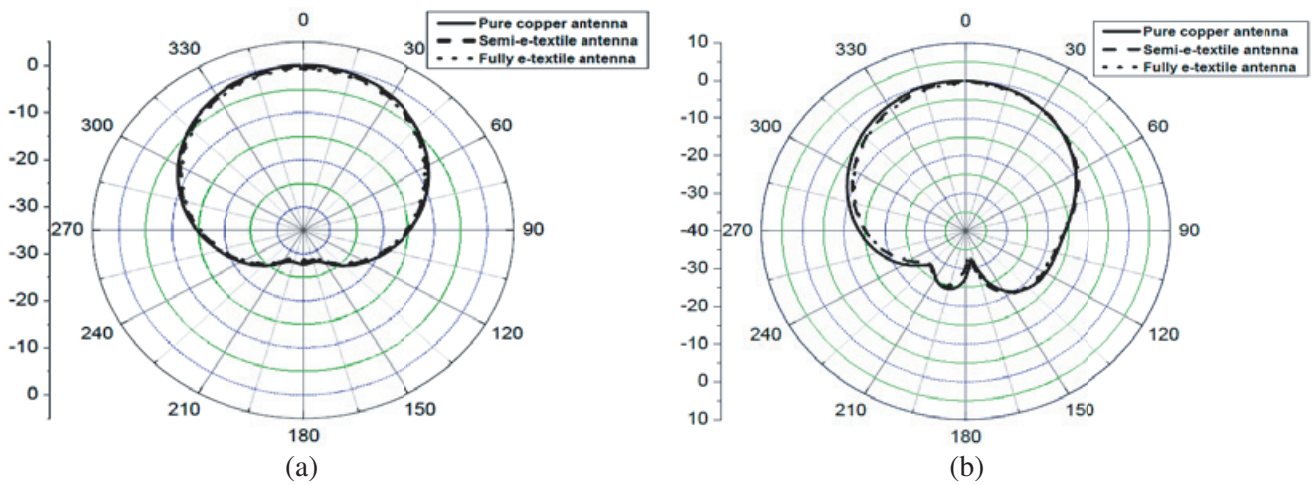

Figure 11. Radiation pattern for the three antennas at 5.8 GHz in: (a) E-plane ($\varphi = 0°$) and (b) H-plane ($\varphi = 90°$) using copper sheet with $\sigma < \sigma_c$.

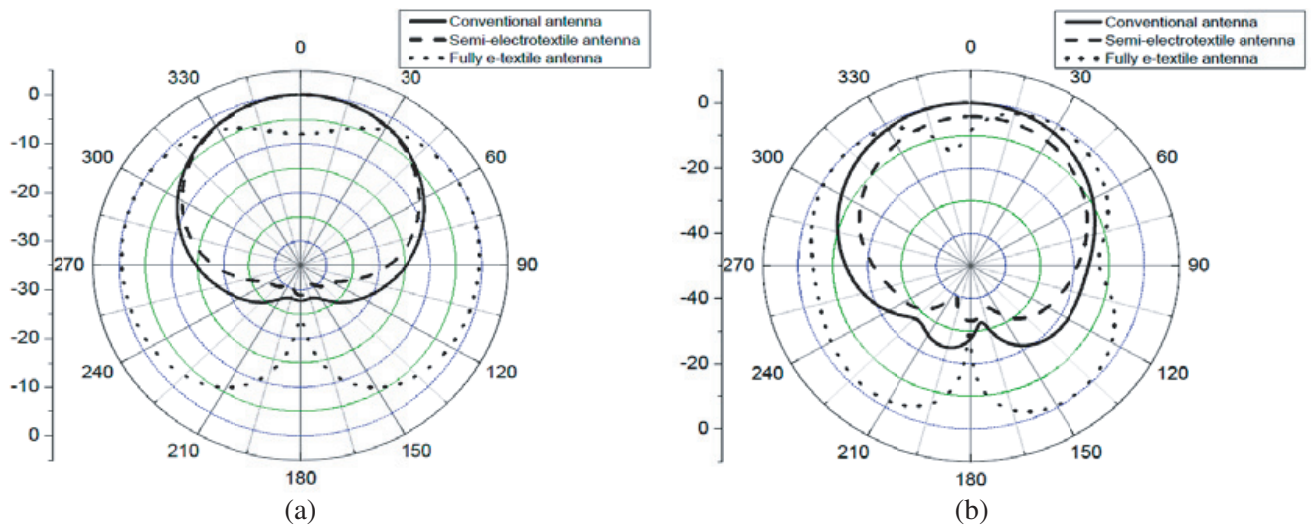**Figure 12.** Radiation pattern for the three antennas at 5.8 GHz in: (a) E-plane ($\varphi = 0°$) and (b) H-plane ($\varphi = 90°$) cotton/copper threads.
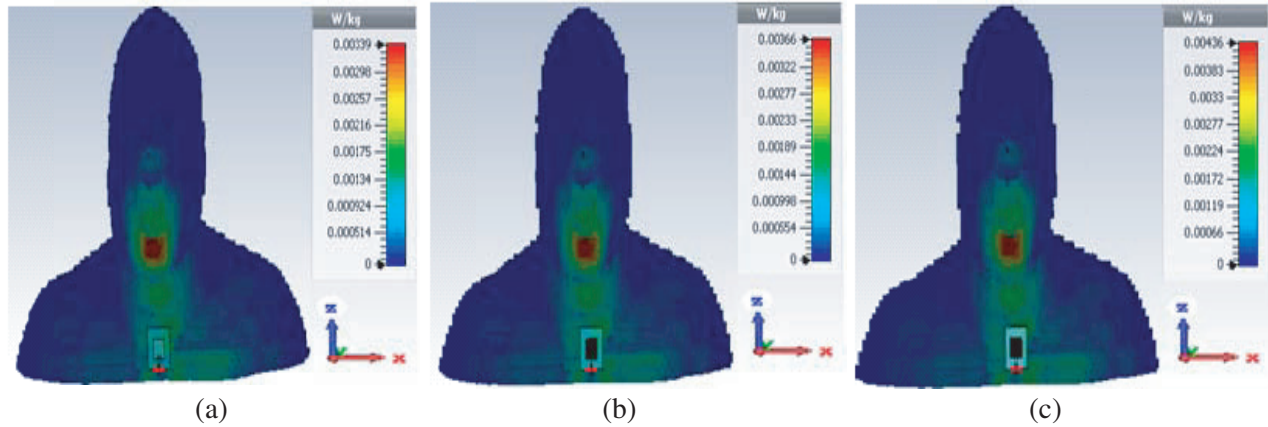
(a)   (b)   (c)

Figure 13. SAR distribution on human voxel model (10 g) in distance 10 mm from antenna at 5.8 GHz: (a) pure copper antenna; (b) semi-e-textile antenna, and (c) fully e-textile antenna.

Table 5. The peak SAR values for the proposed antenna in three different cases in distance 10 mm from antenna at 5.8 GHz by FCC (1 g) & ICNIPR (10 g) standards.

Antenna Type	SAR value (w/kg)	
	10 g	1 g
Pure copper	0.00339	0.00866
Semi-e-textile	0.00366	0.00933
Fully e-textile	0.00436	0.0111

6. CONCLUSION

This paper presents the design and fabrication of an efficient and fully flexible e-textile wearable microstrip patch antenna pasted on jeans textile material to operate at 5.8 GHz as a center frequency, aimed to achieve real wearability in the wearable antenna design. The dielectric properties $\varepsilon_r = 1.78$ of the jeans substrate are measured by using two different methods: a microstrip ring resonator method and DAC (Dielectric Assessment Kit) equipment. The electromagnetic properties of e-textiles for wearable antennas like conductivity and surface impedance are studied. The basic resistance and inductance in a grid are calculated. Two methods are used for simulating the e-textile material in the simulation program. Although the first method obtains better performance results than the second, the second method is more close to the fabricated antenna. Further, the SAR value is considered an important parameter. In our design, the SAR value is very low and increased slightly by using e-textile material. All antennas are measured by Agilent 8719ES VNA. The measured results agree well with those obtained by the simulator from CST.

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