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Investigation and Comparison of 2.4 GHz Wearable Antennas on Three Textile Substrates and Its Performance Characteristics

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Abstract

In this paper, two different methods were used for investigating the RF characteristics of three types of textile materials. Goch, Jeans and Leather substrates were studied. A microstrip ring resonator method and DAK (Dielectric Assessment Kit) method were used. Bluetooth antennas were designed and fabricated using these substrates. The results were compared for the two methods. The bending effect of these antennas on its impedance characteristics due to human body movements was also studied. Finally, all antennas were simulated by CST simulator version 2016, fabricated using folded cupper and measured by Agilent 8719ES VNA. The measured results agree well with the simulated results.

Keywords

Wearable Antenna, Textile Material, Ring Resonator Method, DAK Equipment, Antenna Bending

1. Introduction

In recent years, flexible and textile antennas have taken a lot of attention due to their application in wearable systems. Nowadays, research efforts focus on the development of novel textiles to be used as antenna substrates. Wearable antennas need to be integrated within everyday clothing, be low profile, and be hidden as much as possible [1] [2]. A microstrip antenna with a textile material as a substrate is flexible, low profile, light weight and small size, therefore this type of antenna is more suitable for design and fabricates to be worn or carried on one's body [3] [4]. In the microstrip antenna, the material properties of the textile substrate such as: dielectric constant and loss tangent play important roles in the propagation of electromagnetic energy in dielectric media and have effect on the antenna performance [5]. A variety of techniques are available to measure these properties.

In this paper, two different methods for measuring the dielectric constant and loss tangent were used: the first using a microstrip ring resonator method and the second using DAK (Dielectric Assessment Kit). Therefore, the second has been used to confirm the results determined using the first. The measurement of dielectric constant and loss tangent of three different textile materials were performed: Goch, Jeans and Leather. First the microstrip ring resonator is a very popular technique for measuring the dielectric constant, and loss tangent because of its easy fabrication, planar structure, compact size and high quality factor, so there are few radiation losses of ring resonator and more accurate results [6] [7]. The ring resonator device consists of the ring and two feed lines on the upper surface of the substrate, and the ground plane occupies the lower surface of the substrate. Also a small gap Δ is included between the ring and each feed line, as shown in **Figure 1** [8].

By fabricating this ring model above using the three different textile materials: Goch, Jeans and Leather and obtaining the S_{21} for each other, the peak in the S_{21} was recorded around each resonance and the n^{th} resonance occurs at [9]:

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

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

Also, the insertion loss (S_{21} (dB)) is introduced as [10],

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

where: Q_L is the loaded quality factor, and Q_u is the unloaded quality factor.

(Hint: if Q_L and Q_U are similar, this means that this material is very lossy, so it must be $Q_U \gg Q_L$ to avoid excessive losses).

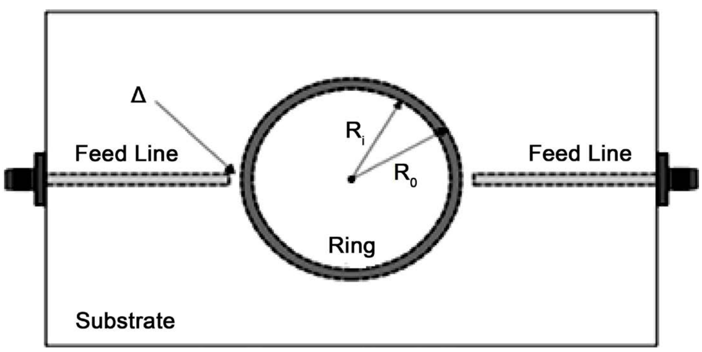

Figure 1. The relative positions of the ring and feed lines on the upper surface of the substrate.

Also, the loaded quality factor can be measured from S_{21} curve as [10],

$$Q_L = \frac{f_0}{\Delta f} \tag{3}$$

where: f_0: is the resonance frequency, and Δf is the difference between high freq. and low freq. around f_0 ($\Delta f = f_h - f_l$).

To calculate the loss tangent of any material firstly must be determined unloaded quality factor (Q_u) from Equation (2) and then applied it in Equation (4) [11],

$$\frac{1}{Q_u} = \frac{1}{Q_c} + \frac{1}{Q_d} \tag{4}$$

where: Q_d is the dielectric quality factor, and Q_c is conduction quality factor.

Also the conduction quality factor can be calculated by [11],

$$Q_c = h\sqrt{f_0 \mu_0 \Pi \sigma_c} \tag{5}$$

where: h is the thickness of substrate, f_0 is the resonance frequency, μ_0 is the permeability of free space, and σ_c is the conductivity of conduction walls.

From Equation (4), the dielectric quality factor (Q_d) can be determined by subtracting the conductor quality factor (Q_c) from the unloaded quality factor (Q_u), and then the loss tangent can be obtained as [11],

$$\tan\delta = \frac{1}{Q_d} \tag{6}$$

The second method is The Dielectric Assessment Kit (DAK) equipment which offers high-precision dielectric parameter measurements (permittivity, permeability, conductivity, loss tangent) over the very broad frequency range from 10 MHz to 67 GHz for applications in the electronic, chemical, food, and medical industries [12]. This method has been used to confirm the results determined using the ring resonator method.

In Sections 2 and 3, based on the results of dielectric constant and loss tangent of three different textile materials: Goch, Jeans and Leather, we designed and fabricated three wearable Bluetooth antennas to compare between three textile materials in Section 4. However, it's not possible to keep wearable antenna position in flat at all the time due to human body movement [13]. Therefore, the performance characteristics of these wearable Bluetooth antennas under bent conditions are also investigated in Section 5.

2. Ring Resonator Method

In order to design any microstrip antenna on textile substrate the dielectric constant and loss tangent of this substrate must be known. For this purpose, we used the microstrip ring resonator method to measure the dielectric constant and loss tangent of three different textile materials: Goch, Jeans and Leather. The thickness of the different substrate materials are measured by using digital vernier gauge and are mentioned in Table 1. Figure 2 illustrates the fabricated geometry of the microstrip ring resonator which applied on three square (50 × 50 mm) different textile materials as substrates and square ground plane with dimensions 50 × 50 mm. The dimensions of the ring and inset feed for three geometries are the same and mentioned in Table 2. The measured S_{21} for the ring resonator for three different substrates is shown in Figure 3. The results of ring resonator method for dielectric extraction (dielectric constant ε_r and loss tangent $\tan\delta$) are tabulated in Table 3.

Table 1. The thickness of the textile materials.

Substrate Thickness	Material		
	Goch	Jeans	Leather
Thickness (mm)	1.2	0.6	1.3

Table 2. The Dimensions of Ring Resonator Structure.

Ring Dimensions	Length			
	Mean Radius (R_m)	inset feed Width (W_f)	inset feed Length (L_f)	Gap (Δ)
Value (mm)	8.5	3	14	1

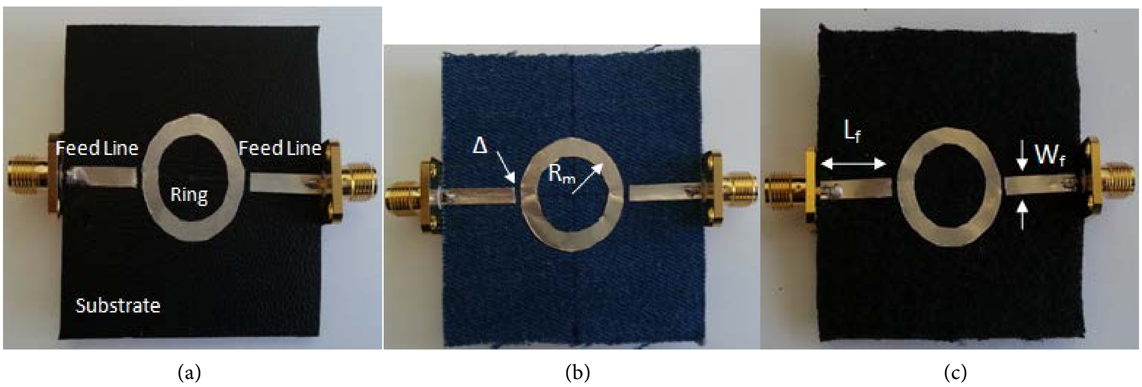

Figure 2. The Fabricated Ring Resonator Structure for: (a) Goch, (b) Jeans, and (c) Leather substrates.

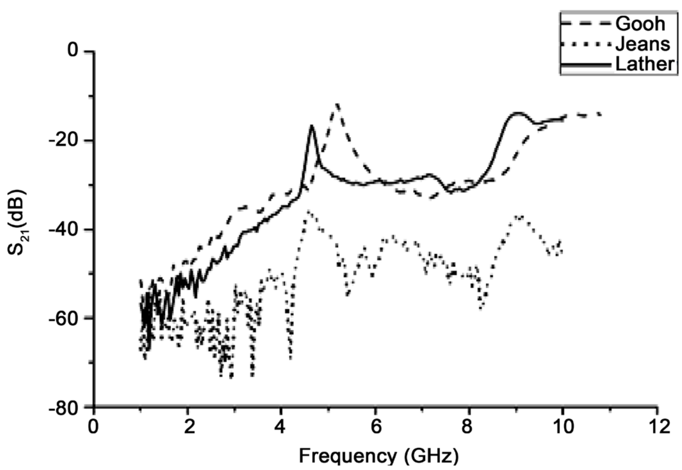

Figure 3. Measured S_{21} as a function of frequency for the ring resonator for three different substrates: Goch, Jeans and Leather.

Table 3. The Results of Ring Resonator Method for Characterization of Three Textile Substrates.

Ring Resonator Results	Dielectric Properties Characterization				
	Mode	Resonant Frequency (GHz)	Insertion loss (S_{21} (dB))	dielectric constant (ε_r)	loss tangent ($\tan\delta$)
Goch Substrate	n = 1	5.1	−11.8	1.266	0.029
	n = 2	10.21	−14.6	1.25	0.04
Jeans Substrate	n = 1	4.26	−35.5	1.73	0.077
	n = 2	8.89	−36.9	1.69	0.073
Leather Substrate	n = 1	4.2	−16.6	1.788	0.039
	n = 2	8.81	−13.9	1.72	0.044

Table 4. The Results of Dielectric Assessment Kit (DAK).

DAK Results	Dielectric Properties Characterization	
	dielectric constant (ε_r)	loss tangent ($\tan\delta$)
Goch Substrate	1.32	0.034
Jeans Substrate	1.78	0.085
Leather Substrate	1.79	0.042

3. Dielectric Assessment Kit Equipment (DAK)

Another method for measuring the dielectric constant and loss tangent of the same three textile materials: Goch, Jeans and Leather, is called the dielectric assessment kit (DAK) equipment. This method is used to confirm the results which obtaining from the ring resonator method. The measured results of the DAK equipment for dielectric extraction (dielectric constant ε and loss tangent $\tan\delta$) are tabulated in Table 4.

From comparing the obtained results using the two methods, it can be observed that both of them estimate the values for Goch, Jeans and Leather, but there are some slight differences between them, this is an inherent thing.

4. Bluetooth Antenna Design

A three Bluetooth microstrip patch antennas using three different types of textile materials as substrates are designed. These substrates are Goch, Jeans and Leather which already have been identified their dielectric characteristics (dielectric constant ε and loss tangent $\tan\delta$) in sections 2 and 3. Figure 4 illustrates the fabricated geometry of each antenna where the copper foil is cut in proper dimensions and then pasted on the textile substrate. These dimensions are mentioned in Table 5.

The simulated and measured S_{11} for this antenna are plotted in Figure 5. From these results, found that the measured results agree well with the simulated results for jeans but there are slight differences for Goch and Leather due to

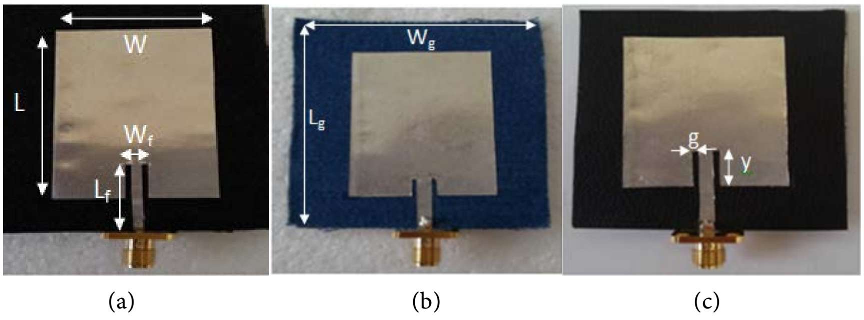

Figure 4. The Fabricated Geometry of Wearable Patch Antenna with: (a) Goch, (b) Jeans, and (c) Leather substrates.

Table 5. The Dimensions of Wearable Patch Antennas (units: mm).

Antenna Dimensions	Length							
	Width (W)	Length (L)	Ground Width (W_g)	Ground Length (L_g)	Inset feed Width (W_f)	Inset feed Length (L_f)	Stub Length (y)	Gap (g)
Goch	30	52	50	72	2	10	10	1
Jeans	30	45	50	65	3	10	5	1
Leather	30	43	50	63	3	10	10	1

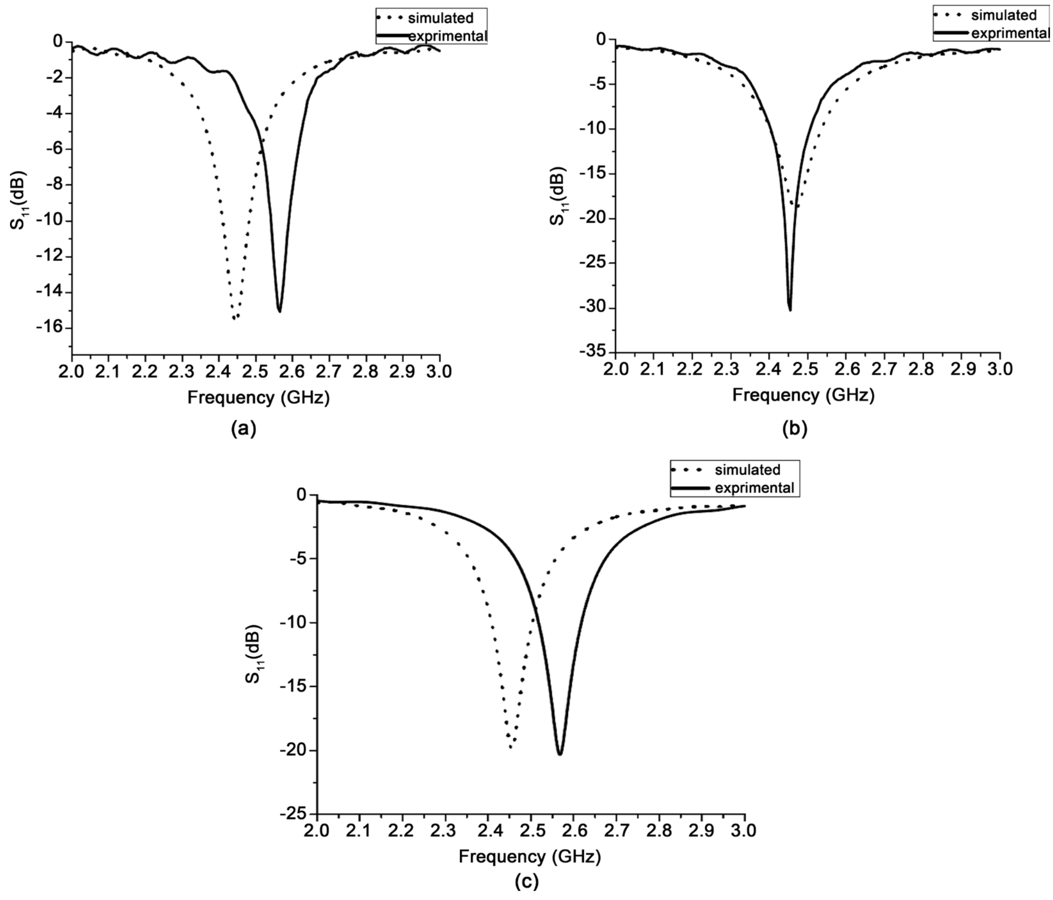

Figure 5. Simulated and Measured S_{11} of the proposed antenna with: (a) Goch, (b) Jeans, (c) Leather.

some problems during manufacturing. The simulation performances of these antennas are also mentioned in Table 6. Finally, in each patch wearable antenna the current distributions are simulated in Figure 6, in addition, the radiations patterns of the proposed antennas in E-plane ($\varphi = 0^{\circ}$) and H-plane ($\varphi = 90^{\circ}$) are also simulated and plotted in Figure 7.

From Figure 5, the experimental matching frequency band as in the S_{11} curves has shifted up relative to the simulated one but this shift is more in the Goch and Leather substrates than Jeans substrate. In Table 6, from comparing between Goch and jeans substrates, Jeans is twice more lossy than Goch, moreover the thickness of Jeans is just half of that of Goch. So, the efficiency of Jeans substrate is much lower than Goch antenna, also from comparing between Goch and leather substrates, the realized gain of Goch is much close to the patch with

Table 6. The simulation performance of the three Wearable Antennas for Bluetooth applications.

Antenna Performance	Simulated Results		
	S_{11} (dB)	Realized Gain (dB)	Efficiency %
Ant. with Goch	−15.6	4.54	80.3
Ant. with Jeans	−18.9	1.82	53
Ant. with Leather	−19.87	4.901	82.1

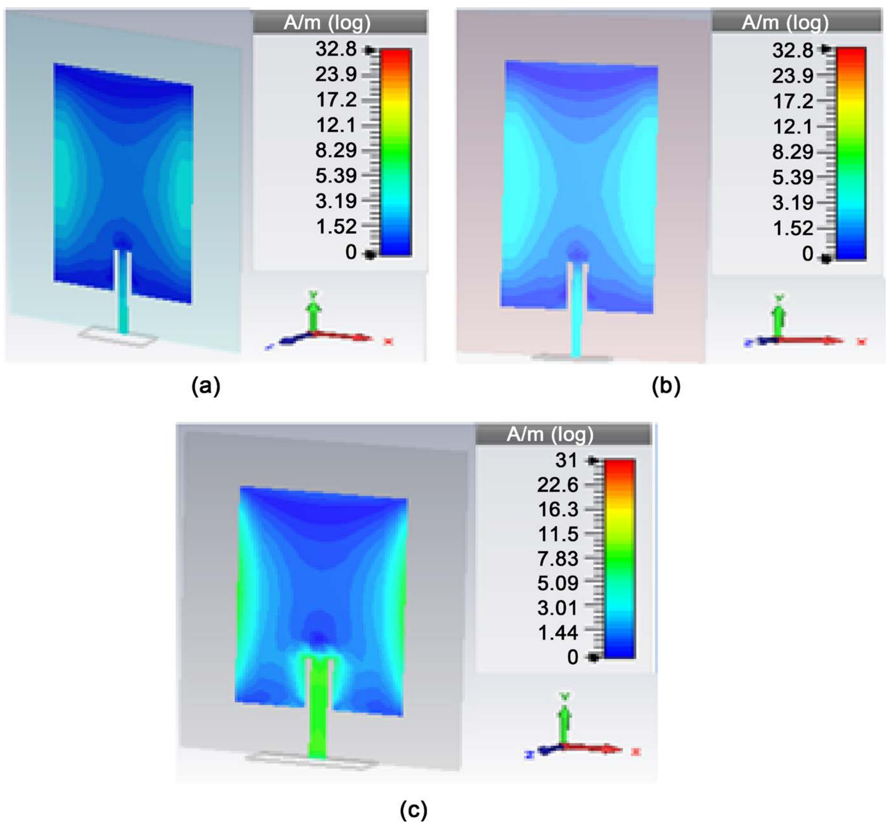

Figure 6. The Current Distribution for the proposed Wearable Antennas with: (a) Goch, (b) Jeans, and (c) Leather.

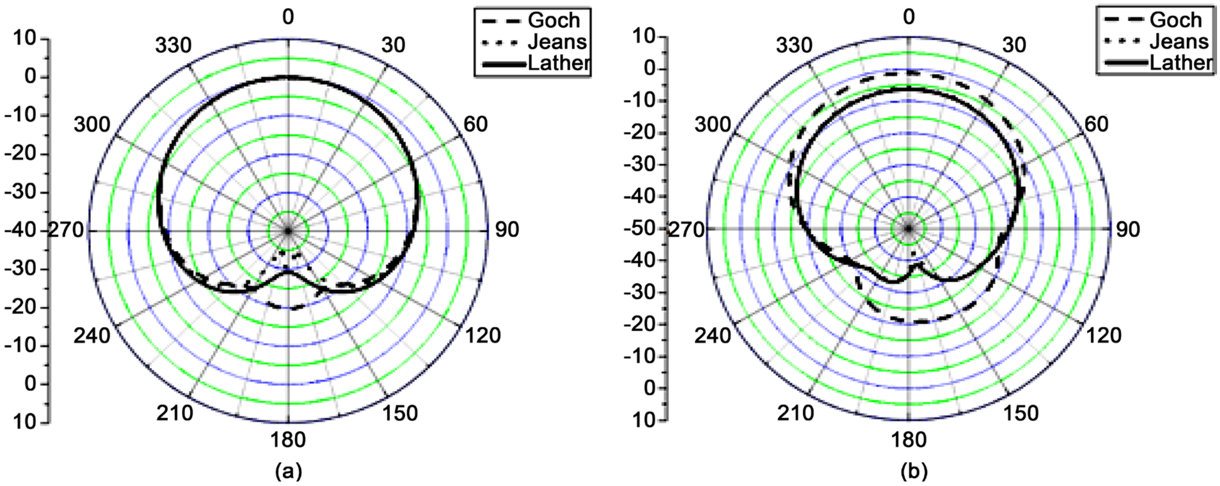

Figure 7. Radiation Pattern for the three Antennas at 2.45 GHz in: (a) E-plane ($\varphi = 0^\circ$) and (b) H-plane ($\varphi = 90^\circ$).

leather substrate, due to the two substrate material with similar loss tangent, dielectric constant and thickness.

5. Effects of Antenna Bending on Its Performance Characteristics

To investigate the effect of antenna bending on its impedance characteristics for three Bluetooth patch antennas with three different textile materials: Goch, Jeans and Leather, this study is carried out by bending each textile antenna around curved surfaces with diameters of 70 mm and 150 mm. These dimensions are typical for human body (e.g., arm, leg, and shoulder). The results for wearable patch antennas for flat position and for both bending diameters are shown in Figure 8.

Figure 8(c) indicates that the resonant frequency remains more constant for certain amount of bending than Figure 8(a) and Figure 8(b). So, the antenna pasted on Leather substrate performs better than the other antennas pasted on Goch or Jeans substrates.

6. Conclusion

Two methods for fabric characterization were presented in this paper: a microstrip ring resonator method and DAC (Dielectric Assessment Kit) method. They used for measuring the dielectric constant (ε_r) and loss tangent ($\tan\delta$) of three different textile materials: Goch, Jeans and Leather where the second has been used to confirm the results determined using the first. Based on these data, three Bluetooth rectangular patch wearable antennas were designed and fabricated on these materials. Comparing between the simulated and measured results and also keeping in mind the effect of bending on each textile antenna, we found that the Bluetooth patch wearable antenna with Leather textile material is easier to place within clothing where it has higher water resistance than the other. In addition, the Goch textile material is fluffy and hairy. When the patch is pasted on

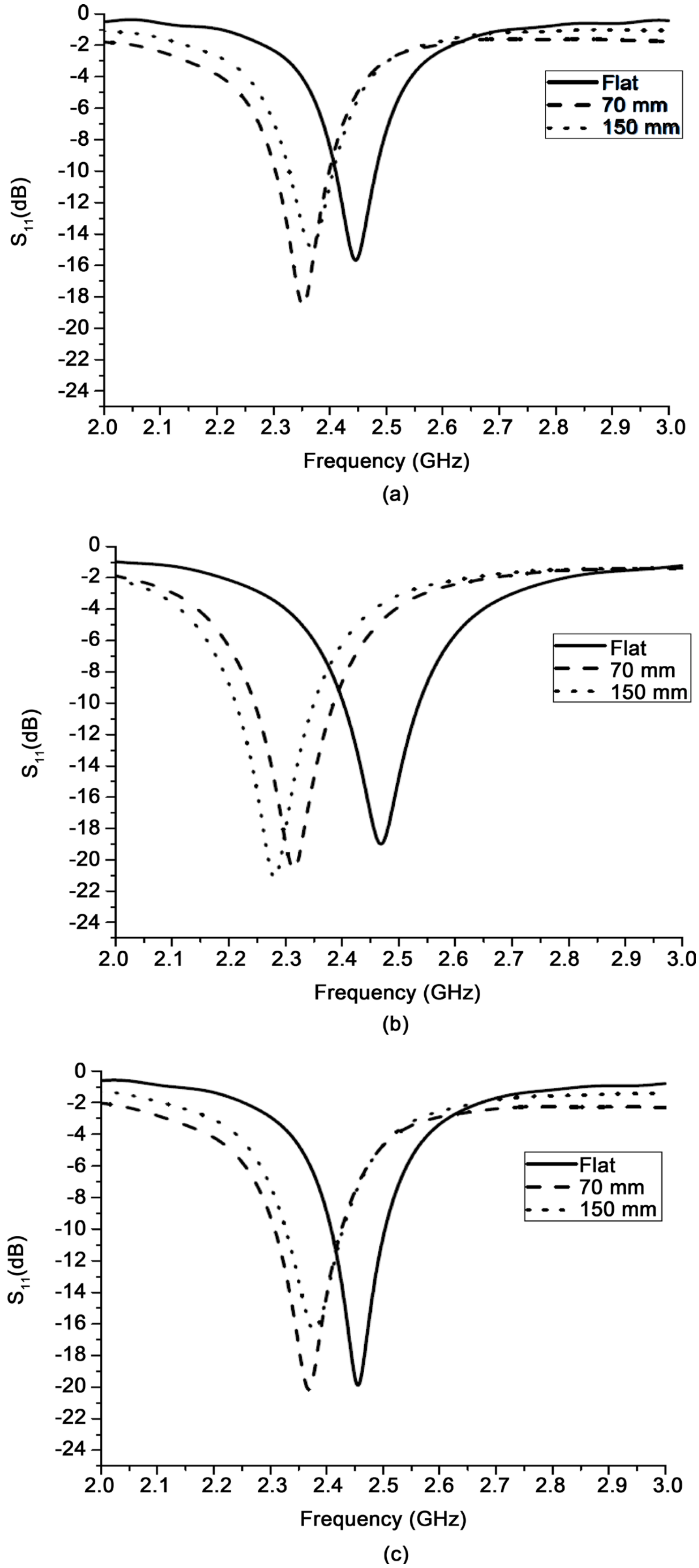

Figure 8. S_{11} for Antennas Bending while antennas flat and curved with diameter 70 mm and 150 mm: (a) Goch, (b) Jeans, and (c) Leather substrates.

it, there is air layer between patch and substrate to make it press and then return to the original thickness, so the results are not more accurate. Also the jeans textile material is very lossy material because the loaded and unloaded quality factors are very close to each other according to insertion loss results. Therefore, the leather textile material is the best choice as a substrate for wearable microstrip antennas.

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