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EMBROIDERED WEARABLE TEXTILE ANTENNA ON BENDING AND WET PERFORMANCES FOR UWB RECEPTION

M. S. Shakhirul, M. Jusoh, A. Sahadah, C. M. Nor, and Hasliza A. Rahim
Embedded, Network and Advanced Computing (ENAC), School of Computer and Communication Engineering, Universiti Malaysia Perlis (UniMAP), Kampus Pauh Putra, 02600, Arau, Perlis, Malaysia; Corresponding author: muzammiljusoh11@gmail.com

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ABSTRACT: *This research proposed an integration of the telecommunication system within garment and wearable product known as textile antenna. Such antenna performances on bending and wet conditions are discussed in the manuscript. This embroidered antenna provides a wide operating band satisfying an ultrawideband application of 3.1–10.6 GHz at 10 dB return loss. The proposed antenna is developed from a simple circular with T-slot structure and a partial ground plane. The fabricated textile antenna was made from both conductive and nonconductive wearable materials. The simulated and measured bend angles of 20°, 30°, 40°, 50°, 60°, 70°, and 80° is analyzed in terms of reflection coefficient via computer simulation technology software and programmable network analyzer, respectively. Moreover, the proposed embroidered antenna performance in wet conditions are investigated in four states of antenna inside water, antenna immediately wet, antenna approximately dry, and antenna completely dry. Simulated and measured results of reflection coefficient, surface current distribution, and gain are presented to validate the usefulness of the presented design.* © 2014 Wiley Periodicals, Inc. Microwave Opt Technol Lett 56:2158–2163, 2014; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.28527

Key words: *embroidered antenna; textile antenna; bending; wet performances*

1. INTRODUCTION

Recently, wearable textile antenna has gained huge attention among the researchers and industry players with respect to the fast growing and wide range of wireless body centric system such as in sports, security, healthcare, and military applications [1]. The concept of integrating the communication system into the garment has improved the quality of the human being life by providing the wearable tracking- and monitoring-based application. In such system, wearable antenna plays an important role in realizing and ensuring the reliability of the wireless communication link between body-worn electronic and the surrounding environment. These textile antennas have advantages of light weight, washable, high flexibility, soft, and comfortable to the wearer [2,3].

To the authors knowledge so far, the wearable textile antenna can be categorized into three; embroidery, patch, and printed and painted [4–6]. Research in [4] discussed a wearable textile antenna with multiple resonance frequency for FM reception using conductive embroidery of metal composite embroidery yarn on a polyester woven substrate. A square ring patch with a polygon-shaped slot with wide band performance is needed in bending conditions when a frequency shift is probable [5]. Such patch antenna focusing on Cordura substrate textile, which fulfilled the mechanical qualification requirements. An inkjet-printed textile antenna is studied in [6] where it proposed an interface coated layer, which bond to a standard polyester cotton fabric to overcome surface roughness. However, this manuscript is focusing on embroidery textile antenna for ultrawideband (UWB) application.

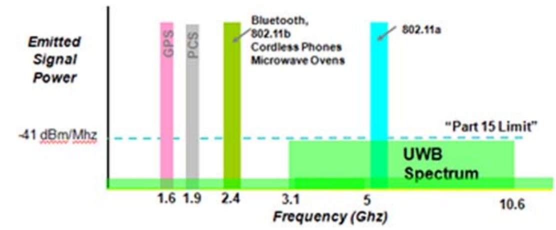


Figure 1 Operating frequency of UWB and narrowband system [7]. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

The commercial use of UWB between operating frequency of 3.1–10.6 GHz has been approved by the Federal Communications Commission (FCC) in 2002 [7]. However, the UWB system must possess a very low-power spectral density with the ability to coexist with the narrowband system as depicted in Figure 1. Therefore, with the lower transmission power to the receiver end has contributed to the higher life battery. Owing to the other benefits of UWB technology, such as multipath robustness and license exemption [8], the high impedance bandwidth (BW) of 7.5 GHz reduces the wearable antenna device.

In this letter, the wearable textile antenna operating at UWB band has a substrate dimension of 60 × 63 mm^2 with a partial ground plane. The proposed antenna consists of a circular-shaped radiator with a feed line structure. Analysis of the presence and absence of the T-slot is investigated in simulation and measurement mode toward the reflection coefficient result. Ultimately, the analysis shows that the radiator with T-slot has better impedance BW that meet UWB requirement with high efficiency of more than 88%. Moreover, further investigation on the bending angles at particular 20°, 30°, 40°, 50°, 60°, 70°, and 80° are carried out. The result shows that the 20°, 60°, and 70° angles give better impedance band as compared to the others. However, the main challenge arises during fabrication process. Besides, the proposed embroidery antenna performances on wet condition has been studied in four states of inside water, immediately wet, approximately dry, and completely dry. All design and simulation is carried out using computer simulation technology (CST) simulation software. While all fabrication and measurement are performed in the Amrellab of Universiti Malaysia Perlis (UniMAP).

The remainder of this article is organized as follows. In Section 2, the development of the wearable antenna design with and without T-slot is discussed. Besides, the fabricated material used also presented in this section. The analysis of the seven bending angles performance toward reflection coefficient is discussed. Moreover, the simulated and measured antenna performances in few wet conditions are converse in Section 3. Finally, conclusion is drawn in Section 4.

2. ANTENNA DESIGN AND CONFIGURATION

Instead of using rigid circuit boards, cotton fabric is used as substrate, conductive fabric “Nora dell” as a ground plane and

TABLE 1 Type of Substrate Materials

Tvpes	Permitivity, ε_r	Thickness (mm)	Characteristic
1. Cotton	0.5	1.6	Long wearing, easy-care clothing and cheap Soft and comfortable to wear Cotton provides a durable and strong condition.
2. Denim	1	1.5	Strong and durable fabric constructed. Very absorbent and resistant to tearing.
3. Felt	2	1.38	Nonwoven textile, produced by matting, condensing and pressing fibers together.
4. Hypalon coated Dacron fabric	3	1.524	High tensile strength, high resistance to stretching, durability, outstanding electrical property.
5. Woven fiberglass fabric	2.2	1.524	High tensile strength, high resistance to stretching, durability, outstanding electrical property.
6. Fleece fabric	1.25	2.56	Comfortable - has breath ability, allowing body perspiration to escape (wick) to the outside to be evaporated. Maintains insulative/warmth properties even when wet Completely washable Machine dryable on low heat; no ironing.
7. Flannel fabric	1.7	1	Loss tangent is 0.025 100% cotton material with smooth, firm and flurry surface made that fabric suitable for wearable application.
8. Jeans fabric	1.7	1	Loss tangent is 0.025

silver plated nylon thread as patch antenna. The properties of selected conductive fabrics may optimize the characteristics of the designed textile antenna in a specific application. Some of the electrotextiles properties are flexible when worn, comfortable, low electrical resistance to minimize losses, and lightweight. There are three Nora dell elements, which are nickel, copper, and nylon silver. Nora dell proposed a highly protective from galvanic corrosion and extremely flexible to the harsh environment of up to 90°C temperature [9]. Therefore, the "Nora dell" is selected.

2.1. Substrate Materials

There are many substrate materials such as cotton, denim, felt, hypalon cotted Dacron fabric, woven fiberglass, fleece fabric, flannel, and jeans fabric. Each of them has different permittivity, thickness, characteristics, and performances as tabulated in Table 1. However, this research focuses on using cotton fabric as a substrate material, which is made from 100% of cotton. Cotton fabric is an easy-care clothing. Instead of soft and comfortable to wear, it provides a durable and strong condition. Cost wise, cotton fabric is cheaper than denim, felt, and jeans. Different characteristics of the textile materials contribute to the different antenna performance. Therefore, it is important to determine its relative permittivity and thickness. The E8362B portable network analyzer (PNA) operates from 10 MHz to 20 GHz is used to measure the relative permittivity for the cotton fabric, which resulted to 1.5. The measured cotton textile thickness obtained from vernier caliper is 0.5 mm.

2.2. Conducting Materials

Textile antenna exist with the combination of substrate and conducting materials. There are few available and commercial used of conducting materials such as silver platted nylon, Nora dell, shieldit super, copper conducting sheet, shieldit conducting fabric, copper taffeta conducting fabric, and woven copper thread. Regarding fabrication techniques for textile antenna, a conductive thread need to be used in the embroidery techniques. Silver platted nylon thread is chosen as conducting materials that provide high quality conducting thread. According to the manufacturer specifications, this conducting material provides superior strength, ability to resist the normal conditions of use such as multiple deformations for wearable applications. In fact, the conducting thread can be washed with the ability to resist temperature up to 150°C [10]. In embroidery technique, thread is sewn at the substrate edge that eventually penetrate at the back of the substrate. Therefore, another layer of cotton is inserted between the conductive thread and Nora dell (conductive fabric as ground plane) to isolate both of them. Thus, three layers of textile materials are stacked together where upper layer—Layer 1 (radiating element) of silver platted nylon, Layer 2 (isolator)

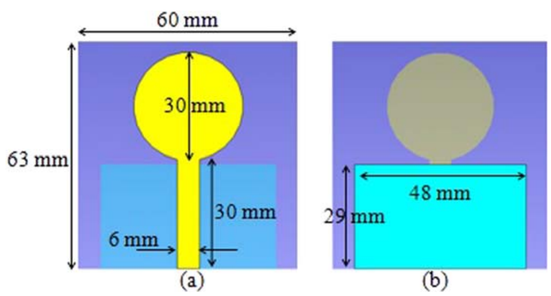


Figure 2 Antenna without T-slot. (a) Front view and (b) back view. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

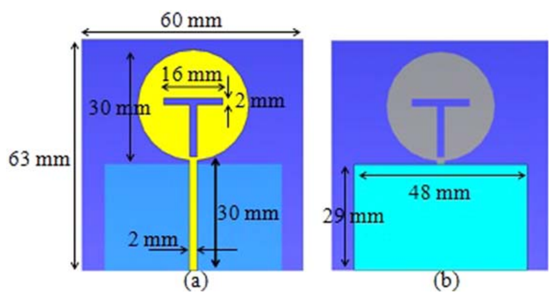


Figure 3 Simulated antenna with T-slot. (a) Front view and (b) back view. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

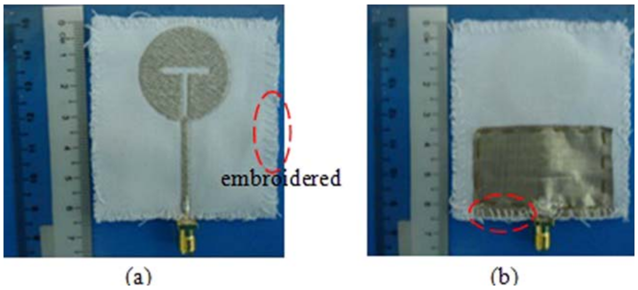


Figure 4 Fabricated antenna with T-slot. (a) Front view and (b) back view. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

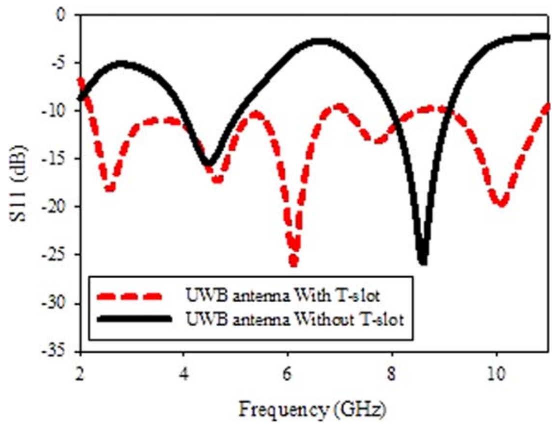


Figure 5 Simulated $S11$ of embroidered UWB antenna with and without T-slot. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

of cotton fabric, and Layer 3 (ground plane) of Nora dell with thickness of 0.13 mm.

2.3. Antenna Configuration

All simulation and design are carried out in the CST simulation software. In this article, a circular-shaped antenna with 15 mm radius is fabricated on 60×63 mm^2 substrate textile. The partial antenna ground plane of 48×29 mm^2 plays a major role of tuning matching circuit in realizing the antenna to function for UWB application with a resonance frequency (fr) of 6.85 GHz. The circular antenna radius (a) is calculated using Eq. (1) while the antenna feed dimension is performed using basic equations for the patch antenna [10].

$$a = \frac{87.94}{\mathrm{fr}(\sqrt{\varepsilon_r})} \quad (1)$$

There are two developed UWB antenna of with and without T-slot (Figures 2 and 3). Initially, the antenna without T-slot is proposed as shown in Figure 2. However, it is not capable to achieve matching reflection coefficient of less than -10 dB throughout the UWB band. Therefore, the T-slot structure has been integrated into the antenna design as shown in Figure 4. Such T-slot with 16×2 mm^2 is constructed on the middle of the circular shape with feed line of 30×2 mm^2. Further investigation has been performed by fabricating the antenna with T-slot. The geometry of the antenna structure is depicted in Figure 4. The red line circle shows the embroidered texture at the edge of the antenna dimension. The SMA has been directly soldered to the feed line of embroidered antenna, which connected to the top radiating and the ground plane.

3. RESULTS AND DISCUSSION

The goal of the design antenna is to achieve $S11$ of less than -10 dB where 90% of power transmitted and 10% of power reflected. To validate this concept, the experimental antenna measurement is focused on the reflection coefficient result that perform using PNA in the research cluster of School Computer and Communication Engineering UniMAP. Initially, comparison of two prototype antennas that developed with T-slot and without T-slot are studied. Moreover, further investigation has been made on the bending conditions inclusive of gain, efficiency, and surface current. Besides, the antenna performances on the wet surrounding is discussed as well.

3.1. Analysis of Embroidered UWB Antenna With and Without T-slot

Figure 5 shows the simulated reflection coefficient of embroidered UWB antenna with and without T-slot. Under tolerable $S11$ of less than <-10dB, the simulated antenna design using silver nylon conducting sheet without T-slot structure has achieved a dual BW at 4.5 and 8.5 GHz resonance frequency, which does not meet the design specifications of UWB application. Therefore, the T-slot has been implemented at particular optimum positioned of the wearable textile UWB antenna that eventually resulted to the good reflection coefficient ($|S11| <$ 10 dB) at the interest frequency range of 3.1–10.6 GHz. Moreover, it is observed in Table 2 that the textile antenna with T-slot has a lower gain of 3.7 dBi as compared to the wearable antenna without T-slot of 4.1 dBi throughout the UWB frequency range. Since more silver nylon conducting cut is removed, the value of gain has been degrade inline with the reduction of the effective aperture size of the antenna with T-slot as shown in Eq. (2).

$$G = \frac{4\pi \mathrm{Ae}}{\lambda^2} \quad (2)$$

G is the antenna gain, Ae is the effective aperture size of the antenna, and λ is the antenna wavelength. Antenna with T-slot is further investigated on the bending performances as carried out in Section 3.2.

TABLE 2 Comparison of Gain, Directivitiy, and Efficiency

Embroidered	Frequency (GHz)	3	4	5	6	7	8	9	10
UWB antenna	Gain (dB)	4.079	4.079	4.079	4.079	4.079	4.079	4.079	4.079
without T-slot	% Efficiency	98	98	98	97	97	98	97	96
Embroidered	Frequency (GHz)	3	4	5	6	7	8	9	10
UWB antenna	Gain (dB)	3.753	3.753	3.753	3.753	3.753	3.753	3.753	3.753
with T-slot	% Efficiency	98	98	97	97	98	98	98	98

TABLE 3 The Bending Conditions of the Embroidered UWB Antenna With T-slot

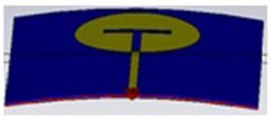
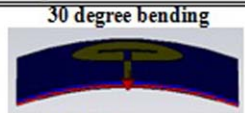
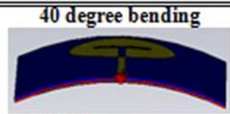
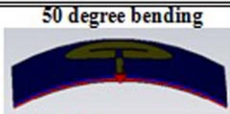
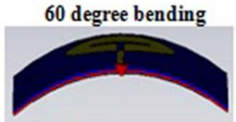
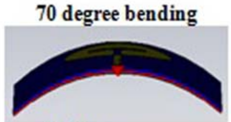
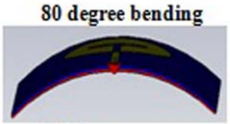
20 degree bending	30 degree bending	40 degree bending	50 degree bending
	 $r = 114.59$mm	 $r = 85.94$mm	 $r = 68.75$mm
$\theta = \frac{20 \times \pi}{180} = 0.349$ (Angle in radian)	60 degree bending	70 degree bending	80 degree bending
$r = \frac{S}{\theta} = \frac{60}{0.349} = 171.92$ mm (radius of cylinder)	 $r = 57.29$mm	 $r = 49.11$mm	 $r = 42.97$mm

Figure 6 Reflection coefficient measurement. (a) Flatten condition and (b) bending condition. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

3.2. Analysis of Embroidered UWB Antenna on Bend Conditions

All the analysis of embroidered UWB antenna with T-slot on bending angle has been done in simulation and verified in measurement. There are seven focused bending conditions of 20°, 30°, 40°, 50°, 60°, 70°, and 80° as tabulated in Table 3. Practically, the bending is designed using a hard paper, which based on the calculated cylinder radius. Where the proposed antenna is properly lean to the hard paper as shown in Figure 6(b). Moreover, Figure 6 shows the snapshot of reflection coefficient measurement for the presented antenna using a network analyzer and low loss cable.

Figure 7 demonstrates the measured $S11$ result of the proposed antenna. While the Agilent Technologies E83628 PNA can cater from 100 MHz to 20 GHz, the $S11$ graph is plotted between targeted frequency ranges 1–13 GHz. Eventhough all measured result indicate some variations, the $S11$ has successfully achieved desired ranges of frequencies with all bending results are below −10 dB. Throughout the bending degrees, the UWB antenna with T-slot has successfully achieved the targeted frequency at 20°, 60°, and 70° with approximately similar BW of 7 GHz. However, the 60° bend has the better $S11$ impedance matching if compared to the others. The simulated gain and efficiency of embroidered UWB antenna with T-slot on bending conditions are tabulated in Table 4. Regardless of the bend conditions, it shows that an average gain and efficiency of the proposed antenna are 4 dBi and 98%, respectively. Figure 8 depicts the simulated current distribution of the embroidered UWB antenna with T-slot of 60° bend at four different frequencies; 4, 6, 8, and 10 GHz.

3.3. Analysis of Embroidered UWB Antenna on Wet Conditions

Research on wet has considered four conditions of inside water, immediately wet, approximately dried, and totally dried as shown in Figure 9. These considerations are based on the relevant environment when the antenna is worn by the user. Inside water and immediately wet refer to the antenna during the rainy and spray environment. The approximately dried refer to the antenna when it is exposed to the human sweat. While, totally dried means the antenna has no contact to the water.

Figure 10 shows the measured reflection coefficient of embroidered UWB antenna on few wet conditions. The PNA

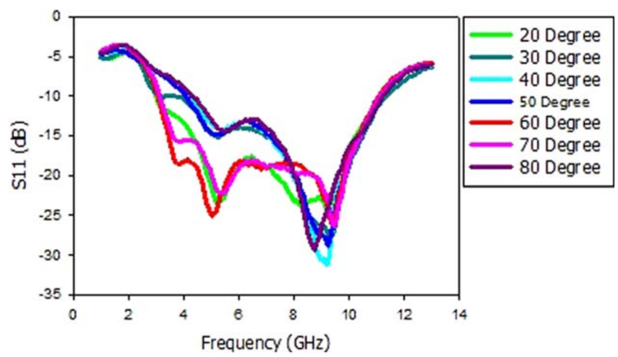


Figure 7 Measured embroidered UWB antenna with T-slot on bending conditions. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

TABLE 4 **Simulated Gain and Efficiency of Embroidered UWB Antenna With T-slot on Bending Conditions**

Angle	Frequency (GHz)	3	4	5	6	7	8	9	10
20°	Gain(dBi)	3.935	3.904	3.469	3.065	4.745	4.501	4 230	4.300
	% Efficiency	98	97	96	95	98	98	98	97
30°	Gain (dBi)	3.956	3.963	3.463	3.034	4.745	4.486	4.311	4.429
	% Efficiency	98	97	97	95	98	98	98	97
40°	Gain (dBi)	4.002	4.079	3.597	3.063	4.741	4.513	4.342	4.570
	% Efficiency	98	98	97	95	98	98	98	97
50°	Gain (dBi)	3.984	4.168	3.757	3.025	4.766	4.511	4.359	4.649
	% Efficiency	98	98	97	95	98	98	98	97
60°	Gain (dBi)	4.032	4.175	3.954	3.093	4.6S6	4.541	4.521	4.888
	% Efficiency	98	98	98	96	98	98	98	98
70°	Gain (dBi)	4.078	4.308	4.152	3.039	4.699	4.527	4.507	4.805
	% Efficiency	98	98	97	95	98	98	98	97
80°	Gain (dBi)	4.040	4.402	4.375	2.960	4.668	4.461	4.431	4.928
	% Efficiency	98	98	98	94	98	98	97	98

capture the $S11$ from 1 to 13 GHz frequency band. All graphs indicates that the proposed antenna in all wet conditions are capable to realize wideband under tolerable reflection coefficient of smaller than 10 dB, $S11 < -10$ dB. As indicates by green and black color, the inside water and immediately wet achieved 6 GHz BW with operating frequency of 6–12 GHz. Both graphs show similar pattern plot and performance. The immediately wet means the antenna has been exposed to water for almost 10

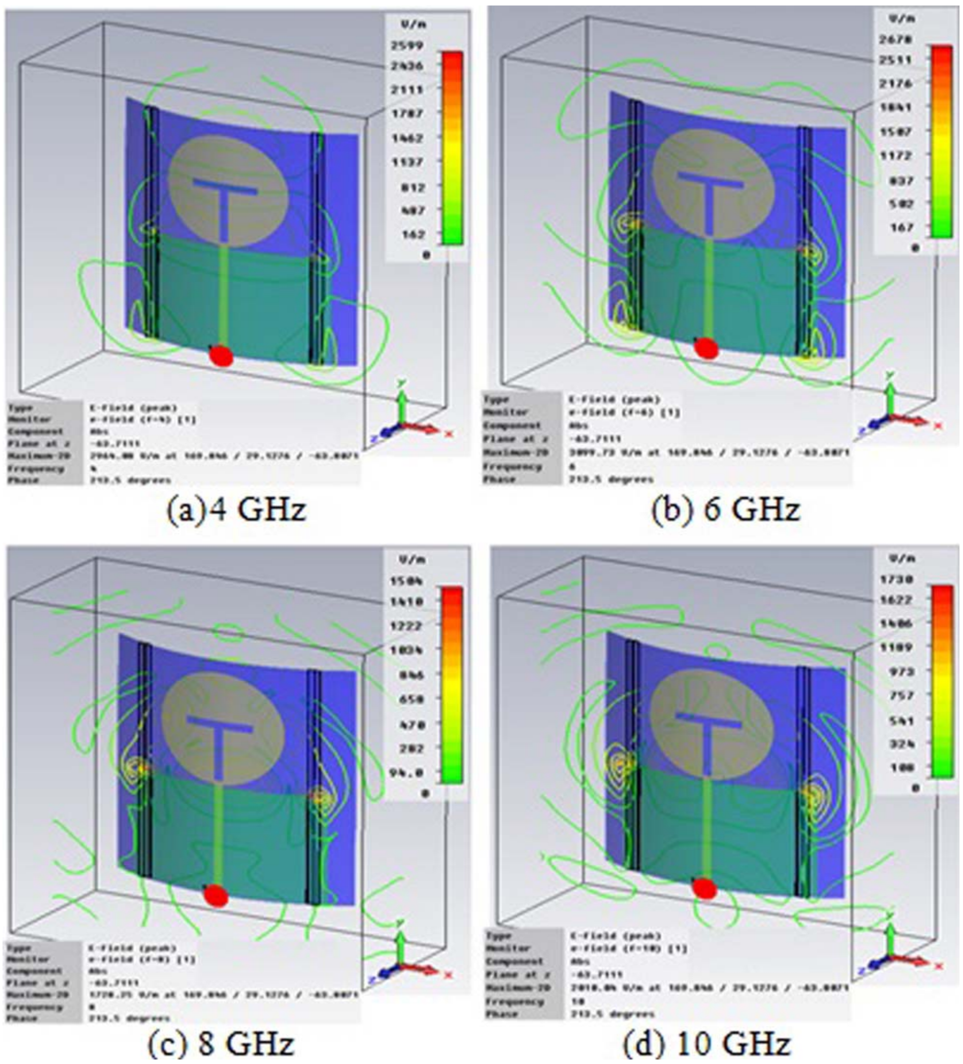


Figure 8 Simulated current distribution of the embroidered UWB antenna with T-slot at four different frequencies. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

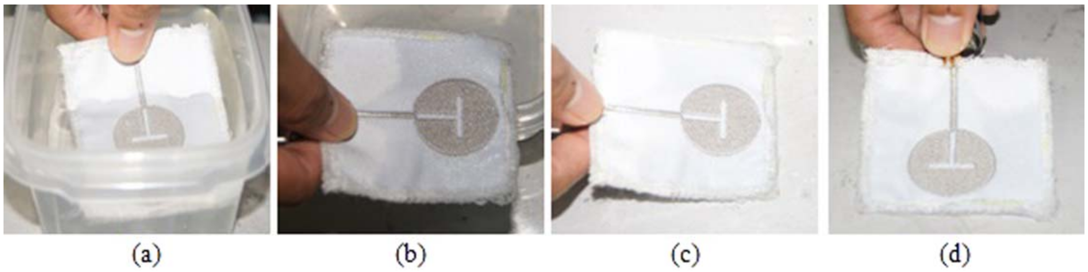


Figure 9 Antenna on few wet conditions. (a) Inside water, (b) immediately wet, (c) approximately dried, and (d) totally dried. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

s. Since, the antenna is cotton, a lot of water has been absorbed. The approximately dried has better BW result of 8 GHz. However, the totally dried antenna has successfully achieved more than 7.5 GHz BW as regulated by FCC with the an average $S11$ impedance matching of -20 dB throughout the UWB frequency.

4. CONCLUSION

The proposed textile and wearable textile antenna performances on wet and bending conditions are investigated in the manuscript. Initially, the antenna design is emphasis in conjunction to achieve the UWB frequency band of 3.1–10. 6 GHz under minimum $S11 < -10$ dB. Therefore, the simple antenna structure with T-slot has been developed from conductive and nonconductive wearable materials. The simulated and measured reflection coefficient performance is carried out using CST software and PNA, respectively. Based on the simulated and measured bend angles of 20°, 30°, 40°, 50°, 60°, 70°, and 80°, the antenna with 60° bend angle has the best impedance matching with cater for the UWB frequency. Moreover, the embroidered antenna performances in wet conditions of inside water, immediately wet, approximately dry and completely dry are investigated. The measured reflection coefficient of completely dry indicates the better performance with minimum $S11$ of -20 dB average with 8 GHz BW.

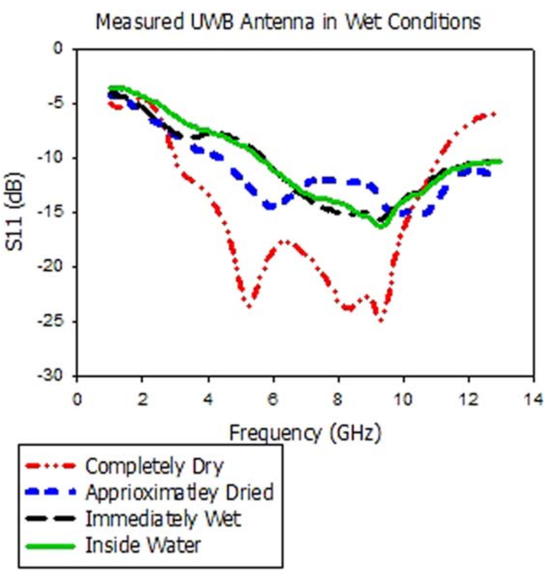


Figure 10 Measured $S11$ of embroidered UWB antenna on wet conditions. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

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