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EMBROIDERED FULLY TEXTILE WEARABLE ANTENNA FOR MEDICAL MONITORING APPLICATIONS

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Abstract—Telecommunication systems integrated within garments and wearable products are such methods by which medical devices are making an impact on enhancing healthcare provisions around the clock. These garments when fully developed will be capable of alerting and demanding attention if and when required along with minimizing hospital resources and labour. Furthermore, they can play a major role in preventative ailments, health irregularities and unforeseen heart or brain disorders in apparently healthy individuals. This work presents the feasibility of investigating an Ultra-WideBand (UWB) antenna made from fully textile materials that were used for the substrate as well as the conducting parts of the designed antenna. Simulated and measured results show that the proposed antenna design meets the requirements of wide working bandwidth and provides 17 GHz bandwidth with compact size, washable and flexible materials. Results in terms of return loss, bandwidth, radiation pattern, current distribution as well as gain and efficiency are presented to validate the usefulness of the current manuscript design. The work presented here has profound implications for future studies of a standalone suite that may one day help to provide wearer (patient) with such reliable and comfortable medical monitoring techniques.

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1. INTRODUCTION

The new concept of a wearable textile system has made its entry into the textile world. This concept is aimed at enhancing the quality of life for human beings by providing them with a wearable continuous monitoring system. Monitoring in general is a necessary activity in risky environments such as mining, diving, mountain climbing as well as other sorts of military and security actions. However, medical monitoring specifically is found to be necessary in order to transfer and transmit data for inpatients in hospital environment, in home for homebound patients or even outpatients. Hence, all these broad applications of monitoring with data transmission functions can be achieved by using wearable antennas that do not force the wearer to abandon the comfort zone with such compact and durable materials. Recently, possibilities of connecting completely independent appliances with the textile have emerged. Full success however will be achieved only when antennas and all related components are entirely converted into 100% textile materials [1–3]. Therefore, by embedding antennas and interconnections in garments, a patient-friendly standalone suit can be obtained. Moreover, the use of embedded textile components guarantees washing of the suit and accordingly reuse of it [2–4].

On the other hand, the commercial use of frequency bands from 3.1 to 10.6 GHz was approved for ultra-wideband (UWB) systems by the Federal Communications Commission (FCC) in 2002 [5]. UWB transmission devices do not need to transmit a high-power signal to the receiver and can have a longer battery life or be smaller to reduce the wearable devices size. By merging the UWB technology with textile technology, an UWB antenna using 100% clothing materials and suitable for wearable application is fabricated and presented in this paper. Unlike previous textile antennas, the present antenna design is found to be capable of meeting the requirements of wearable electronic devices such as being robust, consuming a small amount of power, being comfortable to wear with flexible materials and very compact size antenna prototypes. In addition, the current manuscript materials used can guarantee washing of the wearable device and accordingly reuse of it. The measured results of the present antenna designs are compared with simulations, and good agreement is observed.

2. SYSTEM ON TEXTILE

Wearable textile systems are quite non-obtrusive devices that allow physicians to overcome the limitations of ambulatory technology and provide a response to the need for monitoring individuals over weeks or even months. They typically rely on wireless miniature sensors enclosed in patches and bandages or even in items that can be worn such as a ring or a shirt. With all these mentioned findings, markets are opened up to a wide range of potential requirements and investigations for these novel materials implementing antenna designs and applications. Since 1997, wearable telecommunication systems have become popular topics in research institutions. Numerous papers have been published about the design, fabrication and applications of wearable antennas and systems. Some of these developments are highlighted below. A dual band wearable antenna was discussed in details [5–7]. The development of rectangular patch antenna employing fabric substrate materials was studied [1, 8]. Similar studies have been done in order to investigate the suitability of using substrate fabric materials for antenna designs [9, 10]. Furthermore, another investigation using electro-textile materials for designing microstrip patch antenna was reported in [1, 11]. On the other hand, wideband and ultra-wideband antennas using rigid substrate materials were reported with detailed discussions in [12–15]. Planer monopole antennas for UWB communications with truncated ground plane were designed and investigated using inflexible substrates in [16–18]. Moreover, UWB antennas with slotted design features were reported in [19, 20] where rigid substrate was used for the design material. In addition, UWB sensors and their suitability for medical applications were also considered [21–23]. With all these mentioned findings, markets are open to a wide range of potential requirements and investigations for these novel materials implementing the UWB antenna designs and applications.

In general, antenna comes in all different shapes and sizes. However, UWB antennas seem most suitable for integration into clothing. These antennas consist of a metallic patch on top of a dielectric substrate that is mounted onto a conducting ground plane. Thus, these types of antennas, when integrated into clothing, will have a compact geometry, light weight, low cost and be soft and comfortable to the wearer. Moreover, UWB antennas are often used for mobile communication equipment since they can readily be incorporated with other electronic circuits. UWB antennas offer a lot of flexibility in design, such as shape, feed structure and feed point location. With regard to wearable textile systems, these compact UWB antennas are most suitable to find a place on a garment. Additionally, in low or medium data-rate applications, as wearable computing, UWB antenna offers low-power operation and extremely low radiated power, thus being very attractive for body-worn battery-operated devices. However, several wearable antennas aspects contribute to the overall design features of the antennas such as the avoidance of elastic fabrics, taking into account wetness aspects and considering bending conditions of the wearable system. Moreover, designers need to ensure that the wearable telecommunication devices operate properly in the vicinity of human body. Since UWB antennas provide a kind of omni-directional radiation pattern component, special attention must be paid to the Specific Absorption Rate (SAR) in order to avoid harm to human body.

In this paper, an UWB fully textile wearable antenna has been designed and analyzed. The substrate of the designed antennas was made from flannel fabric along with two different types of conducting materials that will be discussed in more details within this manuscript. Moreover, the originality of this paper lies with new textile implementations of UWB wearable antennas; no new essential antenna premise is tackled. However, previous textile antennas were usually composed of materials that were not possible to allow washing and reusing of the wearable suite. Our new antennas were made entirely from textile materials along with new feature provided by being easily and directly integrated into clothing, which guarantees washing of the wearable device and accordingly reuse of it. Moreover, the material used has the ability to resist the normal conditions of use such as multiple deformations along with its ability to resist temperature up to 150°C.

2.1. Substrate Materials

Using fabrics as substrate materials instead of rigid circuit boards enables the placement of small antennas and sensors [1]. In this work, our study focuses on using the flannel fabric as a substrate material which is made from 100% cotton material and suitable for wearable applications. To our best knowledge, this is the first attempt utilizing flannel fabric as substrate material for designing wearable textile antennas. Most of substrate fabric material researches that were reported before did not consider the stacking issues of fabric layers. In this paper, the flannel fabric used for the investigation has a kind of smooth and firm surface with an additional feature of being fluffy surface material. These features were beneficial when additional layers are required in order to increase the thickness of the fabric that results in widening the antenna bandwidth along with other benefits that will be discussed later in more details within this manuscript. The word textile is typically used for antenna class and fabric to describe particular material. However, in many cases these words are interchangeable. Moreover, in order to characterize the effect of textile materials accurately, it is important to know its relative permittivity. The measured relative permittivity for flannel fabric at several frequencies using the free space method was about 1.7.

2.2. Conducting Materials

Conducting materials are required in order to build the communication system. These communication devices or systems require appropriate materials and structures and must be compatible with wearable textile antenna requirements [1, 2]. In this paper, a systematic study is demonstrated using two types of conducting materials. The first type of conducting material used for preliminary design investigation is the copper self adhesive conducting sheet with a thickness of 0.03 mm. However, due to the impractical usage of the copper conducting sheet (not possible to be washed, not attractive to the wearer, cannot withstand the multiple deformation process, etc.), the other type of conducting material is proposed and investigated in this paper. This conducting material is a kind of high quality conducting thread. According to manufacturer specifications, this conducting thread is made from a silver Plated Nylon thread to ensure superior strength and conductivity along with the ability to resist the normal conditions of use such as multiple deformations. Additionally, the conducting thread can be washed with ability to resist temperature up to 150°C. Choosing such a type of conducting thread material will facilitate and provide the wearer/patient with comfortable and durable clothing materials. Furthermore, using conducting thread materials will aid the wearable system to resist regular textile maintenance processes as well as the normal conditions of use such as multiple deformation (extension, bending, compression) or even wet and laundry (water, elevated temperatures, detergents, enzymes). Conductive threads are created from single or multiple strands of conductive and non-conductive fibres. The strong non-conductive fibres can protect the thin fragile conductive fibres from external tension, which makes the conductive thread more mechanically robust and still maintain the electrical functionality.

3. MANUSCRIPT DESIGN CONTEMPLATION

In order to obtain the UWB antenna design presented in this manuscript, a few parameters needed to be calculated such as the radius of the radiating element. These parameters are calculated according to Equation (1) below. Where a is the radius of the circular patch antenna in millimetre; f_r is the resonance frequency in GHz; ε_r

is the relative permittivity of the textile substrate material.

$$a = \frac{87.94}{f_r\sqrt{\varepsilon_r}} \tag{1}$$

The simulation has been carried out using CST microwave office software simulation package. However, to study the effect of conducting materials accurately and due to software limitations, the wearable UWB textile antenna using three stacked layers of flannel substrate fabric along with the copper conducting sheet was initially designed and simulated. The simulation process has been followed by fabricating two antenna prototypes utilizing copper conducting sheet for the first antenna prototype while conducting thread has been employed for the other antenna prototype. Moreover, measured results of both antenna prototypes were compared with the simulated results of the UWB antenna prototype utilizing copper conducting sheet. Thus, the wearable UWB antenna using copper conducting sheet was designed and simulated based on the characterization information of flannel substrate fabric (ε_r of 1.7 and $\tan\delta$ of 0.025) mentioned in previous sections. Moreover, a partial ground plane is implemented in the simulation of this antenna design. Such types of truncated ground plane play an important role in the broadband and wideband characteristics of the designed antennas [16, 17]. Figure 1 below demonstrates the CST Model along with the geometry and dimensions in millimetre of the wearable textile UWB antenna design presented in this manuscript showing that the design of this antenna has been conducted in air space. A 50 ohm microstrip feed line was provided for the antenna feed; hence the position was determined according to [24, 25]. Three stacked layers of flannel substrate fabric along with the copper conducting sheet have been implemented for the UWB antenna design. The size of the substrate is 60 mm × 60 mm with a patch radius of 14 mm. In order to enhance the bandwidth as well as optimizing the design, one slit at the top of the circular patch and two slits at the bottom of the circular patch were implemented in the present design along with a square slot at the centre of the circular patch with a size of 6 mm × 6 mm. The ground plane size is 50 mm × 27 mm. All these dimensions are illustrated in Table 1 and supported by Figure 1. According to the simulation results, the copper self adhesive sheet UWB antenna design is found to be able to cover the range of frequencies from 3 GHz up to 20 GHz.

4. FABRICATION PROCESS

Consequently, fabrication process of the wearable fully textile UWB antenna was conducted for the UWB antenna prototypes using copper

Table 1. Dimensions of the designed wearable e-textile UWB antenna in millimetres.

	Substrate thickness [mm]	Substrate dimensions [mm]	Patch radius [mm]	Partial ground plane dimensions [mm]	Upper Square slot dimensions [mm]	Centre Square slot dimensions [mm]
Wearable textile antenna	3	60 × 60	14	50 × 27	15 × 15	6 × 6

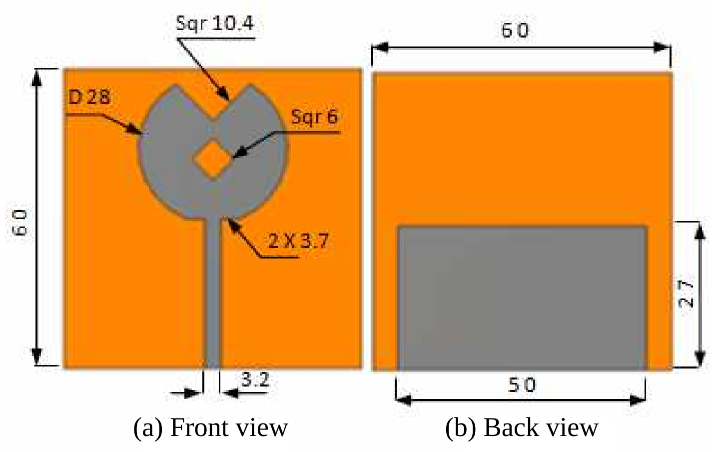


Figure 1. CST design model along with dimensions in millimetres of the proposed wearable fully textile UWB antenna design.

self adhesive sheet conducting material and the conducting thread for each antenna prototype. Each of the conducting material has been applied to the radiating element (front side) as well as the ground metal (back side). At the same time, three stacked layers of flannel fabric have been used as the substrate material in both antenna prototypes. In the case of the antenna prototype with self adhesive copper conducting sheet, the attachment of the conducting material to fabric substrate material turns out to be very critical. In fact, only a simple cutting tool (e.g., a scalpel) was used. Thus, the definition and sharpness of conducting copper sheet edges are found to be essential in order to make those edges/ parts precise and accurate. However, the self adhesive sheet turned out to be a good solution as it has been evenly placed and fastened over flannel substrate material.

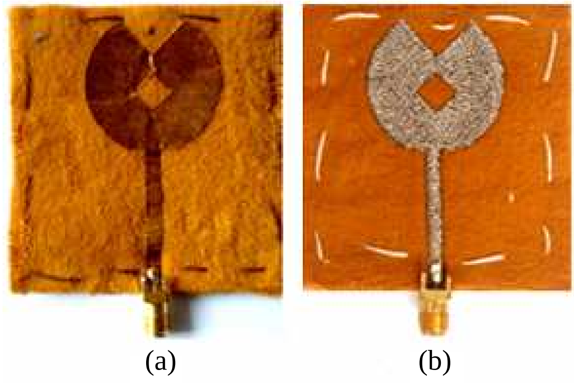


Figure 2. Snapshot of the fabricated prototypes of the wearable fully textile UWB antenna. (a) Copper conducting sheet antenna prototype. (b) Conducting thread antenna prototype.

A computer controlled embroidery machine was used to stitch the conducting thread on the firm surface of flannel substrate fabric in order to create the UWB wearable fully textile antenna prototype. However, as stated in the previous section, flannel fabric has a kind of smooth and firm surface with an additional feature of being fluffy surface material. These features were beneficial when more layers of fabric become essential. In fact, stitching the conducting thread on the surface of flannel fabric results in a conducting area at both sides of each layer (top and bottom surfaces). Thus, three layers of flannel fabric were stacked resulting in the upper layer (Layer #1) that consists of the radiating element (front side), followed by Layer #2 consisting of flannel isolating layer and finally Layer #3 that consists of the ground metal (back side). In addition, direct metal soldering is used to connect the top radiating patch and the ground plane to the SMA coaxial connector in both antenna prototypes as illustrated in Figure 2. The fabricated antenna satisfied the requirements of providing the wearer with compact size, flexible materials, ease of washing, and very attractive wearable device.

5. RESULTS AND DISCUSSIONS

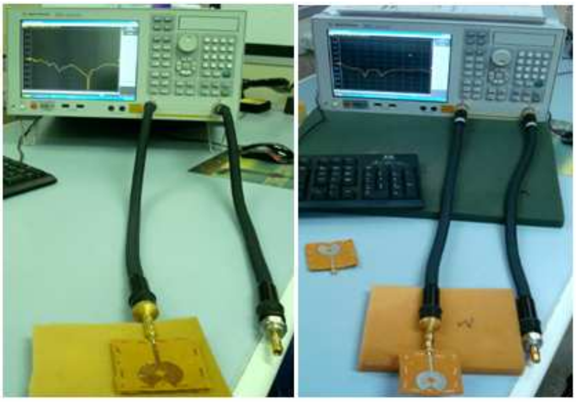
In order to provide better investigation and due to software limitation, the simulated results shown in this section present the antenna prototype with copper self adhesive sheet. Thus, this section will firstly present the simulated return loss ($|S_{11}|$) and bandwidth results of the

UWB antenna design utilizing copper self adhesive sheet, followed by measured results comparison of both antenna prototypes of the current manuscript. Similar comparisons will be provided for the simulated and measured radiation pattern results. In addition, only simulated results of gain, efficiency, and current distribution of UWB antenna design utilizing copper self adhesive sheet will be presented with more detailed discussion.

5.1. Simulated and Measured Return Loss Results

The wearable textile UWB antenna simulated design using copper conducting sheet showed good return loss ($|S_{11}|$) results over the frequency range of the interest from 3 GHz up to 20 GHz. These results further indicated that the measured value of the relative permittivity was valid enough to provide design information. According to that, a network analyzer was used to measure the ($|S_{11}|$) results as a function of frequency of the copper conducting sheet antenna prototype as well as the conducting thread antenna prototype. Figure 3 demonstrates a snapshot of ($|S_{11}|$) measurement environment for the antenna designs of the current manuscript.

Moreover, Figure 4 makes a clear verification between simulated and measured ($|S_{11}|$) results. The simulated upper frequency achieved



(a) Copper tape antenna prototype (b) Conducting thread antenna prototype

Figure 3. Snapshot of return loss measurement environment both fabricated wearable textile UWB antenna prototypes. (a) Fabric antenna using copper sheet. (b) Fabric antenna using conducting thread.

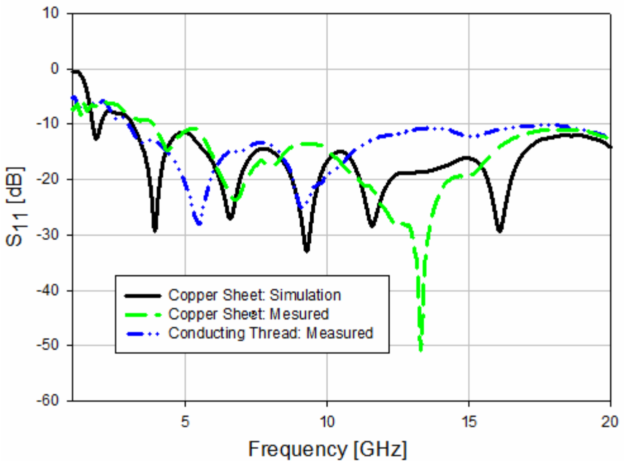


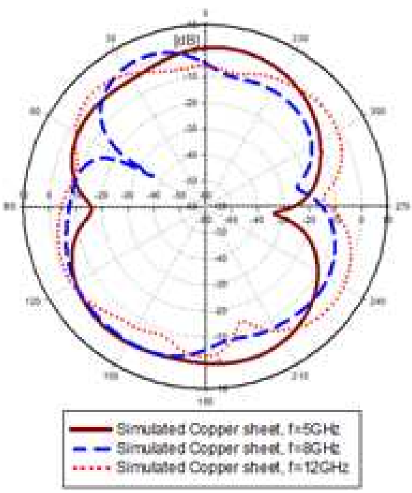
Figure 4. Comparison between simulated and measured ($|S_{11}|$) and bandwidth results of the designed and fabricated wearable fully textile UWB antenna.

by the copper conducting sheet design was above 20 GHz. However, for the sake of better comparison and due to limitations of the measurement device used, the plotted range of frequencies of simulated and measured results as shown in Figure 4 were between 3 GHz and 20 GHz. The black solid line demonstrates the simulated ($|S_{11}|$) and bandwidth results of the UWB antenna design utilizing copper conducting sheet, while the green line shows the measured ($|S_{11}|$) and bandwidth results of the UWB antenna prototype employing copper conducting sheet. The blue line demonstrates the measured ($|S_{11}|$) and bandwidth results of the UWB antenna prototype using conducting thread. Although there were some variations between simulated and measured plotted results, the ($|S_{11}|$) measured results of both antenna prototypes were able to cover the desired range of frequencies with all results below -10 dB. Figure 4 exhibits that the simulated and measured ($|S_{11}|$) results were comparable and that the proposed antenna designs provide 17 GHz bandwidth with compact size and flexible materials.

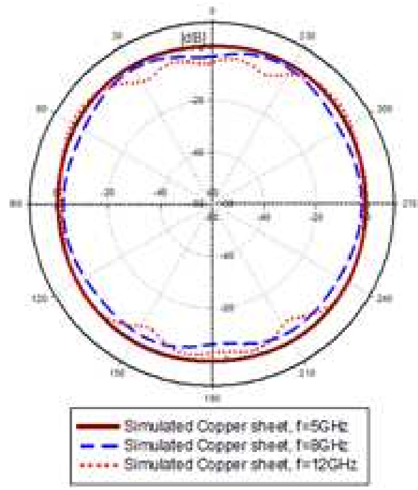
5.2. Simulated and Measured Radiation Pattern Results

Figure 5 clarifies the behaviour of 2D simulated and measured co-polar radiation pattern components in the horizontal and vertical planes with three different frequency samples at 5 GHz, 8 GHz, and 12 GHz achieved by each UWB antenna design of the current manuscript. On the other hand, radiation pattern measurement process has been conducted in air space. However, for the sake of better comparison along with the limitation of measurement equipments used, the measured radiation pattern results were plotted in the range between −90° and +90°. Moreover, the magnitude of the radiation pattern has been normalized to simplify the viewing of measured results.

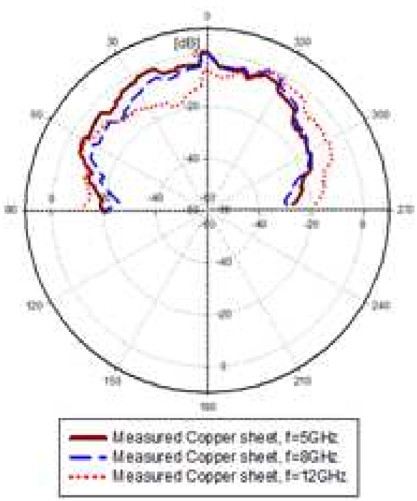
Figures 5(a) and (b) represent the simulated co-polar radiation



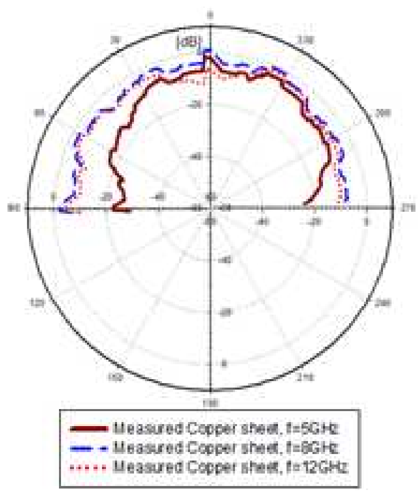
(a)



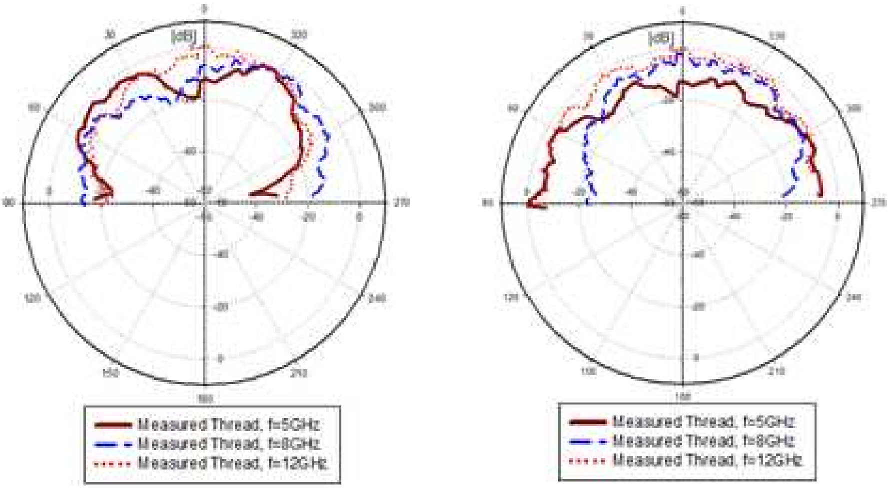
(b)



(c)



(d)

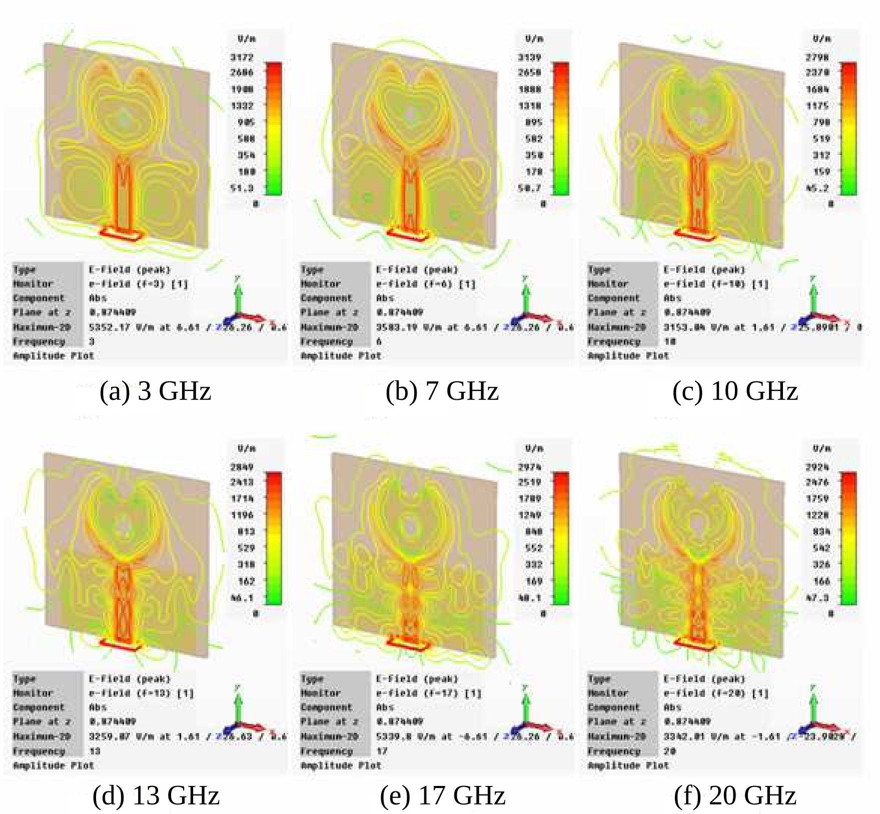


(e) (f)

Figure 5. Three different frequency samples of simulated and measured co-polar radiation pattern components in the horizontal and vertical planes for each UWB antenna design. (a) E-co polar horizontal plane of simulated copper sheet results. (b) E-co polar vertical plane of simulated copper sheet results. (c) E-co polar horizontal plane of measured copper sheet results. (d) E-co polar vertical plane of measured copper sheet results. (e) E-co polar horizontal plane of measured thread results. (f) E-co polar vertical plane of measured thread results.

pattern components of the copper conducting sheet UWB antenna design for the horizontal and vertical planes, respectively. The measured co-polar radiation pattern components of the fabricated antenna prototype using copper conducting sheet for the horizontal and vertical planes, respectively, are all demonstrated in Figures 5(c) and (d). Figures 5(e) and (f) illustrate the measured co-polar radiation pattern components of the conducting thread fabricated antenna prototype for the horizontal and vertical planes respectively.

From Figures 5(a) and (b), it can be noticed that the antenna resembles omni-directional radiation pattern components in the vertical plane whatever frequency under analysis, while two nulls are visible along the horizontal plane for each frequency under analysis. From Figures 5(c), (d), (e), and (f), one can observe that there was a slight difference between simulated and measured radiation pattern results for both fabricated antenna prototypes in the horizontal and vertical planes. This slight difference can be related to fabrication tolerance and misalignment during measurement setup. Generally, both results correlate well to each other since the patterns were similar. Realized from these results, although UWB antennas are known by its low-power operation and extremely low radiated power, special attention must be paid to the Specific Absorption Rate (SAR) in order to avoid harm to human body. According to these results, the proposed UWB antenna designs introduce a kind of omni-directional radiation pattern component, and future antenna designers need to ensure that the wearable telecommunication devices operate properly in the vicinity of human body.



(a) 3 GHz (b) 7 GHz (c) 10 GHz

(d) 13 GHz (e) 17 GHz (f) 20 GHz

Figure 6. Current distribution simulated results of the copper conducting sheet UWB antenna design with six different frequency samples ranging from 3 GHz up to 20 GHz.

5.3. Simulated Current Distribution Results

Current distribution results make the idea visible in order to understand how the current flows in the conducting areas of the simulated UWB textile antenna. Figure 6 demonstrates these results of the proposed antenna design using three stacked layers of flannel substrate fabric along with the copper conducting sheet material. Six different frequency samples that were at 3 GHz, 7 GHz, 10 GHz, 13 GHz, 17 GHz and 20 GHz have been provided for the discussion. From Figures 6(a) and (b), high strength of current in the range of frequencies from 3 GHz up to 7 GHz is found to be radiated along the conducting parts of the antenna especially along the transmission line as well as the bottom and top of the circular patch. On the other hand, the rest of frequencies from 8 GHz up to 20 GHz were found to have high strength of current along the transmission line as well as the bottom of the circular patch. These results are all demonstrated in Figures 6(c), (d), (e) and (f).

5.4. Simulated Gain and Efficiency Results

The variations of frequencies versus the gain of the proposed antenna design using three stacked layers of flannel substrate fabric along with the copper conducting sheet material are all demonstrated in Table 2. The maximum gain achieved was about 7.4 dB at 20 GHz. In contrast, the highest percentage of efficiency reached 97% at 12 GHz. On the other hand, the lowest efficiency was about 85% at 3 GHz. Consequently, results show that the present design has low power consumption due to the achievement of gain that was less than 5 dB in most range of frequencies between 3 GHz and 20 GHz. In addition, the efficiency of the antenna could be considered vast compared to commercial antennas.

Table 2. The variation of frequency versus gain and efficiency simulated results of the copper conducting sheet UWB antenna design.

Frequency [GHz]	3	4	5	6	7	8	9	10	11
Gain [dB]	2.6	2.1	2.8	3.6	4.7	4.9	4.9	4.7	4.0
Efficiency [%]	85	95	90	94	97	95	96	94	96
Frequency [GHz]	12	13	14	15	16	17	18	19	20
Gain [dB]	4.0	4.2	4.5	4.8	4.9	4.0	5.9	6.7	7.4
Efficiency [%]	97	96	95	92	90	87	88	88	92

6. CONCLUSION

This work demonstrates that fully textile antennas and specially e-textile materials themselves have strong potential to be used as antennas for transmission purposes in garments. Due to the usage of the conducting thread material, the fabricated antenna has satisfied the requirements of providing the wearer with compact size, flexible materials, ease of washing and is a very attractive wearable device. The proposed antenna designs provide 17 GHz bandwidth and show good measured return loss ($|S_{11}|$) characteristics, omni-directional patterns as well as adequate gain and efficiency. According to these results, future antenna designers need to ensure that the wearable telecommunication devices operate properly in the vicinity of human body. Moreover, washable packaging of the electronics and durable interconnections remain major challenges to be tackled for all wearable electronics and intelligent textile developments. Treating these systems in the way that we treat our daily garments is very demanding and such a huge challenge. Consequently, evaluation of long term behaviour, durability and system performance after repeated wetness and laundering should invariably be considered in research tasks. There is still a long way to go to obtain reliable commercial smart garments.

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