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Miniaturized Wearable Fractal Patch Antenna for Body Area Network Applications

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Abstract—**This article presents the design of a miniaturized wearable patch antenna to be utilized for the body area network (BAN) applications. To reduce the size of the antenna a crown fractal geometry antenna design technique has been adopted, and which resulted in a size reduction of 26.85%. Further, the polyester cloth has been used as the substrate of the antenna to make the proposed antenna a flexible one, and suitable for wearable biomedical devices. The designed antenna functions for the 2.45 GHz ISM band and has the gain and bandwidth of 4.54 dB and 131 MHz respectively, covering the entire ISM band. The antenna characteristics like return loss (S_{11}), directivity and radiation pattern have been simulated and analyzed. Specific absorption rate (SAR) and front to back ratio (FBR) of the proposed antenna at the human body tissue model (HBTM) in the planer and different bending conditions of the antenna have also simulated and analyzed, and the proposed antenna fulfils the desired design standards.**

Keywords—**biomedical, body area network, conformal, fractal, wearable antenna**

I. Introduction

THE Body area network (BAN) devices are gaining prominence and entering the widespread biomedical systems and have become an essential part of the biomedical applications [1]. The body-based communication is provided by wearable BAN devices. The wearable devices may be beneficial for patients, youngsters, athletes, firefighters, solders, and paramedics to see their body metrics including, body-temperature, pulse-rate, heartbeat, breathing-rate, blood-pressure, and lung-capacity [2]. The components used for these wearable BAN applications must be conformal, lightweight, miniaturized, and low-cost ensuring their effectiveness [3]. Numerous researches are going on to develop efficient wearable biomedical devices to achieve the most out of these required properties. The overall size of these wearable devices largely depends on the size of the antenna; therefore, small sized antennas are preferred in designing these devices [1].

Most of the BAN devices work in the ISM band, which has a central frequency of 2.45 GHz and 85 MHz bandwidth with frequency ranges from 2.4 GHz to 2.485 GHz. So, the wearable patch antenna designed to be used for the BAN application in the ISM band should cover the entire band. The wearable antenna should also be flexible and conformal so that it could be wearable comfortably to the human body at arm, chest, or other parts of the body. The substrate used for the wearable antenna plays a significant role in the flexibility of the antenna. Various flexible materials such as polyester cloth, jeans fabric, denim, polythene foam, cotton cloth, felt, fleece, Linear Low-Density Polythene (LLDPE), Poly-Di-Methyl-Siloxane (PDMS) etc. have been used by various researchers for making the substrate of the wearable antenna [7-15]. The body-worn textile material substrate-based antennas are more flexible and comfortable compared to the rigidly structured antenna. In this research work, the authors have a new miniaturized fractal antenna design for wearable BAN applications working in the ISM band. In this antenna design, the polyester cloth has been used as the substrate of the antenna, making the antenna suitable for wearable biomedical devices.

The proposed antenna covers the whole 2.45 GHz ISM band and show superior performance for the entire band. The human body must be secured from the unavoidable electromagnetic radiation from the wearable antenna [4]. So, in this research work of wearable antenna design, the SAR and FBR of the antenna have been simulated and analyzed by locating the proposed antenna at various distances to the HBTM. Further, if the antenna conforms to the areas of the human body parts such as arm or leg, the antenna will get physically deformed and because of this deformation the strength of the undesired electromagnetic radiation falling on the human body parts may increase [4]. So, in this research work, the SAR and FBR of the antenna have also been simulated and analyzed, by placing the bent geometry of the antenna, close to the HBTM, to find the effect of bending of the antenna in horizontal and vertical deformation at the different radii of deformation. Moreover, the value of SAR has been compared with the standards available and the proposed antenna fulfils the requirement of those standards. The research work analysis presented in this paper has been structured in the sections as follows. In the 2nd section, the antenna design method has been presented. In the 3rd section, the results and discussion have been presented. The 4th section present the simulation and performance analysis of the proposed antenna on HBTM in planer condition of the antenna at different distances; and in the different bending condition of the antenna; near the HBTM. The 5th section concludes the paper.

II. Antenna Design Method

The wearable patch antenna proposed in this research work has been designed by using fractal antenna design technology. The fractal antennas have self-similar structures, and such structures have been designed by employing iterative process.

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The fractal antennas have the capabilities to shift the resonant frequencies towards the lower end of the frequency scale, this result in size reduction of the antenna at the desired resonant frequency [5]. In this research work of fractal wearable antenna design, the authors have used this ability of the fractal structures to reduce the size of the antenna used for BAN applications.

A. Specific Materials used for the Substrate of the Wearable Patch Antenna

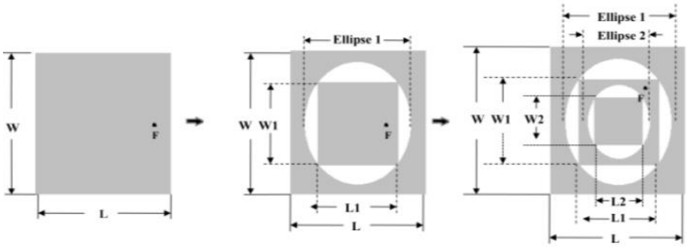
Various materials have been used for designating substrates of the wearable patch antenna by different researchers. Table I presents the list of the materials commonly used for designing wearable antennas. The wearable antenna should be conformal to the human body, and if the antenna is flexible then it could be conformal, so to make the antenna flexible, the flexible material should be used as a substrate of the wearable antenna. The characteristics of the antenna can be improved by using the substrate of the antenna with high thickness and low dielectric constant [6]. To make the proposed antenna flexible and conformal to the human body, the polyester cloth, which is a flexible material, has been used as the substrate of the proposed wearable patch antenna.

TABLE I
LIST OF SPECIFIC MATERIALS USED AS THE SUBSTRATE OF THE WEARABLE ANTENNAS

Substrate Material	Dielectric Constant	Loss Tangent	Ref. No.
Polyester Cloth	1.39	0.01	[7]
Jeans Fabric	1.67	0.025	[8]
Denim	1.6	0.01	[9]
Polythene Foam	1.07	0.0009	[10]
Cotton Cloth	1.51	0.02	[11]
Felt	1.44	0.044	[12]
Fleece	1.3	0.025	[13]
LLDPE	2.2	0.0003	[14]
PDMS	2.68	0.04	[15]

B. Wearable Fractal Antenna Design

The aim of this study is to design a miniaturized wearable fractal patch antenna used for BAN devices, working in the 2.45 GHz ISM band. In the proposed research work of antenna design, the crown fractal antenna design technique has used. The proposed wearable antenna geometry is based on the antenna proposed in [5]. As the fractal antenna structures are developed using iterative procedure, and so, the proposed wearable fractal patch antenna has been developed by using three stages of fractal geometry development. The first stage has the initial antenna structure; the second stage has the first fractal iteration structure; and the third stage has the second iteration structure i.e. the final fractal antenna structure. The initial antenna structure has a standard rectangular patch antenna structure as presented in Fig. 1a. The first fractal iteration structure as presented in Fig. 1b has been developed by creating a slot of elliptical shape from the center of the initial rectangular patch. Then, in the elliptical-slot area, a rectangle of 60% of the dimension of the initial rectangular patch has been inserted. The dimensions of the elliptical slot removed have been chosen so that all the corners of the inserted rectangle are in contact with the border of the elliptical slot. The same method is reused to acquire the second iteration structure as given in Fig. 1c. The dimension of the base rectangular patch antenna has been calculated by using standard equations [6] at the design frequency of 2.45 GHz and Table II presents the dimensions of all the three antenna structures. Annealed copper is utilized as the antenna patch and ground plane material. The polyester cloth fabric, having 1.39 and 0.01 as values of dielectric constant and loss tangent respectively, has been utilized as the substrate material of the antenna [7]. The antenna has been provided coaxial feed and the radius of the inner conductor of the coaxial connector has been taken as 0.55 mm. The radius and length of the coaxial connector have taken as 1.6 mm and 5 mm, respectively.



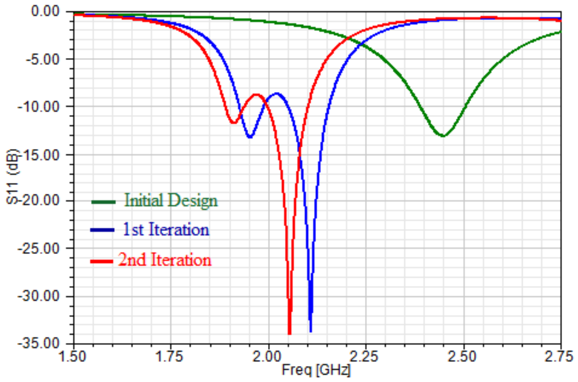
(a) (b) (c)

Fig. 1. Antenna design structures, (a) initial antenna structure, (b) 1st iteration antenna structure and (c) 2nd iteration antenna structure [5]

TABLE II
DIMENSIONS OF THE ITERATIONS STRUCTURE OF ANTENNA

Dimensions	Description	Values (mm)
L	Length of main rectangle patch	48.9
W	Width of main rectangle patch	56.0
L1	Length of 1st iteration rectangle patch	29.34
W1	Width of 1st iteration rectangle patch	33.6
P1	Primary axis radius of Ellipse 1	20.1
S1	Secondary axis radius of Ellipse 1	24.12
L2	Length of 2nd iteration rectangle patch	17.6
W2	Width of 2nd iteration rectangle patch	20.16
P2	Primary axis radius of Ellipse 2	12
S2	Secondary axis radius of Ellipse 2	14.4
Lg	Ground plane length	68.1
Wg	Ground plane width	75.1
Ls	Substrate length	68.1
Ws	Substrate width	75.1
h	Substrate thickness	3.2

The HFSS simulator software has been used to simulate all the proposed geometries. The feed points of initial antenna structure, first iteration structure and second iteration structure have found as (23, 0), (12, 13.5) and (12, 13.5) respectively, where the best-simulated results have obtained. The simulated return loss 'S_{11}' parameters of all the three antenna structures are, shown in Fig. 2. The S_{11} parameter of the initial antenna structure indicates that the antenna has resonated at 2.45 GHz showing strong correlations in designed and simulated values. The S_{11} parameter of the first iteration antenna structure indicates that the antenna has resonant frequency of 2.11 GHz showing a shift in resonant frequency towards lower end of frequency scale for same outer dimensions. The S_{11} parameter of the second iteration antenna structure indicates that the antenna worked at 2.065 GHz showing further reduction in working frequency which is an intrinsic feature of fractal patch antenna [5]. The S_{11} parameter of all the three antenna structures clearly shows the drift in frequency toward the lower end. This drift in resonant frequencies is because the first and second iteration structures have multiple slots that resulted in increasing the current path and this lowers the resonant frequency [5].



(d)

Fig. 2. Combined S_{11} parameters of initial, first and second iteration antenna structures

The second iteration antenna structure resonated at 2.065 GHz but the objective of this research work was to design wearable antenna for 2.45 GHz ISM band. So, to get the desired resonant frequency of 2.45 GHz for 2nd iteration geometry, the outer dimensions of the proposed antenna must be reduced. Therefore, the dimensions of antenna structure have been decreased in steps and the resulting geometries have been simulated until we obtained the desired resonating frequency of 2.45 GHz and covering the entire ISM band. In the proposed research work of antenna design, after the optimization we have got desired results at outer antenna dimensions of 'L' = 41.6 mm and 'W' = 48.15 mm where the second iteration antenna structure resonates at 2.459 GHz. having a bandwidth of 131 MHz extending from 2.386 GHz to 2.517 GHz and fulfilling the desired objective of this research work by covering the entire ISM band. Fig. 3 presented the second iteration of the proposed antenna structure with all the dimensions of the antenna structure.

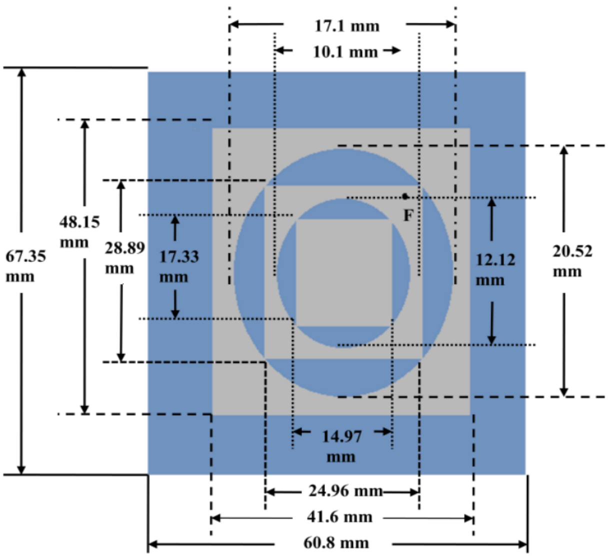


Fig. 3. Structure of the proposed wearable fractal patch antenna

The co-axial feed points of the second iteration antenna structure have been found as (10, 11) where the best-simulated results have obtained.

III. RESULTS AND DISCUSSION

The optimized second iteration antenna structure which is the proposed wearable patch antenna used for BAN applications in 2.45 GHz ISM with dimensions, as shown in Fig. 3 has been simulated and the simulated results of the antenna have been presented in Table III. The S_{11} parameters of the proposed antenna, as shown in Fig. 4, indicates that the antenna is resonating at 2.459 GHz with a return loss of –31.7 dB. The antenna has a bandwidth of 131 MHz ranging from 2.386 GHz to 2.517 GHz and has achieved the desired goal of this research to cover the entire ISM 2.45 GHz band. The proposed antenna provided a gain of 4.54 dB and this gain value has been sufficient for wearable antenna applications.

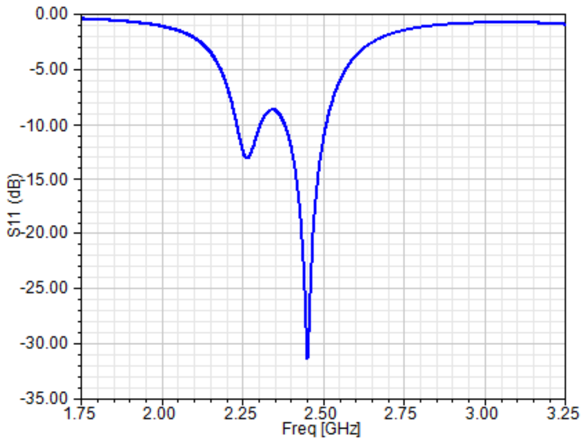


Fig.4. S_{11} parameter of the proposed antenna

TABLE III
SIMULATED PARAMETERS OF THE PROPOSED ANTENNA

Antenna Parameters	Values
Resonant Frequency (GHz)	2.459
S_{11} (dB)	- 31.7
Bandwidth (MHz)	131
Gain (dB)	4.54
Directive Gain (dB)	5.21
VSWR	1.0531
Antenna Efficiency (%)	87.14
Impedance Bandwidth (%)	5.32

Also, the voltage standing wave ratio (VSWR) value for the proposed antenna has been found as 1.0531, which has been sufficiently low for the desired wearable applications. Fig. 5 showed the radiation pattern of the proposed antenna and the antenna demonstrated good omni-directional response. The proposed wearable fractal patch antenna was designed with a patch size of 41.6 × 48.15 mm^2 resulting in the area of 2003 mm^2, whereas the simple rectangular patch antenna designed at 2.45 GHz, as shown in Table II, had the patch size of 48.9 × 56 mm^2 resulting in an area of 2728 mm^2. The proposed wearable antenna therefore has an area of 73.15% of the standard rectangular patch antenna designed at 2.45 GHz, resulting in a reduction of 26.85% in size. The overall size of the proposed antenna was therefore significantly reduced, and this fulfills the second objective of this research work to design a miniaturized wearable patch antenna for BAN applications.

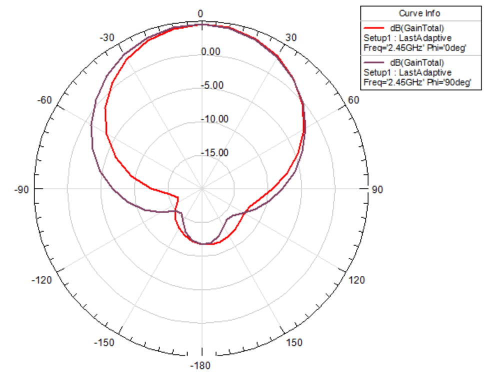


Fig. 5. Simulated radiation pattern of proposed antenna

IV. Performance of the Proposed Antenna on HBTM

The antenna has been designed to be used for wearable biomedical devices; and the human body must be safe from the unavoidable electromagnetic radiation emerging from the proposed wearable antenna [5]. Therefore, in this research work of wearable antenna design, the SAR and FBR of the antenna have been simulated and analyzed by locating the proposed antenna at various distances to the HBTM, which mimic the human body. The HBTM selected for testing has size of 100 × 100 × 40 mm^3 and formed by the rectangular shape consecutive layers of skin, fat, muscle, and bone, as shown in Fig. 6, and model details have been given in Table IV [17]. The SAR and FBR simulation have been carried out on the HBTM in the planer condition of the antenna, and in the bending condition of the antenna as discussed in the subsequent sections. Firstly, the planer condition of the proposed antenna has placed near the HBTM, and the SAR and FBR simulation has been carried out, by varying antenna to HBTM gaps. Secondly, the proposed antenna has been bent as per the wearing position of the antenna on the human body part, and the SAR and FBR simulation has been carried out by placing the bent condition of the antenna, near the HBTM. The SAR and FBR simulation have been carried out by using CST MWS simulation software.

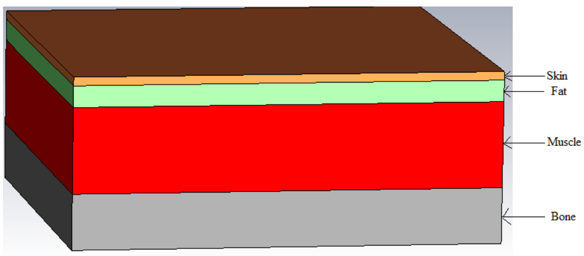


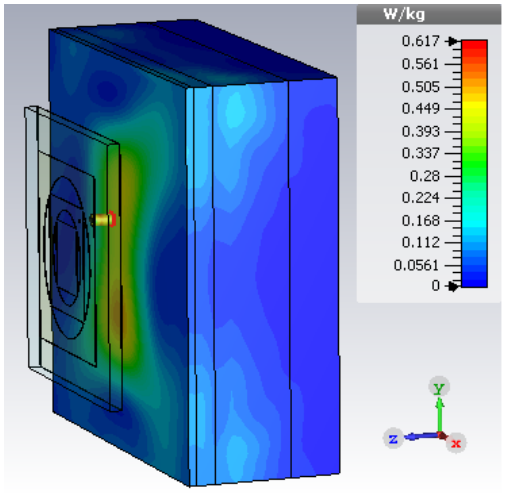
Fig.6. Human body tissue model

TABLE IV
MATERIAL PROPERTIES OF THE HBTM [17]

Parameter	1st layer (Skin)	2nd layer (Fat)	3rd layer (Muscle)	4th layer (Bone)
Dielectric Constant	37.95	5.27	52.67	18.49
Conductivity (S/m)	1.49	0.11	1.77	0.82
Density (kg/m^3)	1001	900	1006	1008
Thickness (mm)	2	5	20	13

A. *Simulation of Planer Condition of Antenna on HBTM*

In the simulation of the planer condition of the proposed antenna, the antenna has been positioned near the HBTM and HBTM gap has been varied from 10 mm to 20 mm. The antenna has been positioned with a gap of firstly 10 mm, secondly, 15 mm and then thirdly 20 mm between the model and the antenna ground. Fig. 7 shows the simulated SAR and FBR results of the proposed antenna placed close to the HBTM with different gaps and Table V presents the simulated results obtained. The value of SAR at 10 mm, 15 mm and 20 mm from HBTM have been found as 0.36052 W/kg, 0.80915 W/kg, and 1.4975 W/kg respectively, at average value of 1 g of human body tissue. As per the Federal Communications Commission (FCC) standard the value of SAR for the antenna should not exceed to 1.6 W/kg averaged to 1 g of human body tissue [16]. So these simulated values of SAR of the proposed wearable antenna have fulfilled the FCC standard. So, the proposed antenna has been found suitable for wearable biomedical applications. The FBR value at 10 mm, 15 mm and 20 mm from human tissue model have been found as 20.3 dB, 19.4 dB and 20.6 dB respectively and these values of FBR have been sufficiently high as per the requirements of the wearable biomedical applications.



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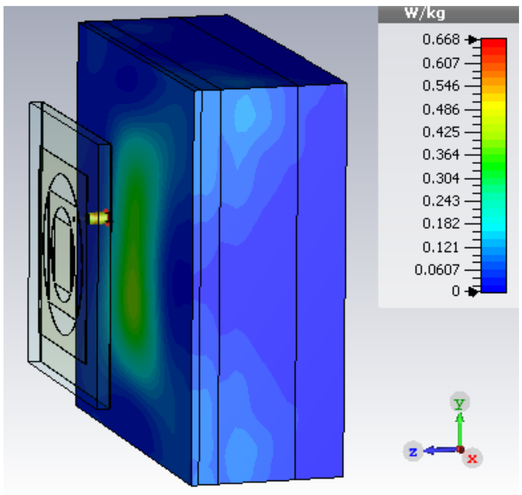

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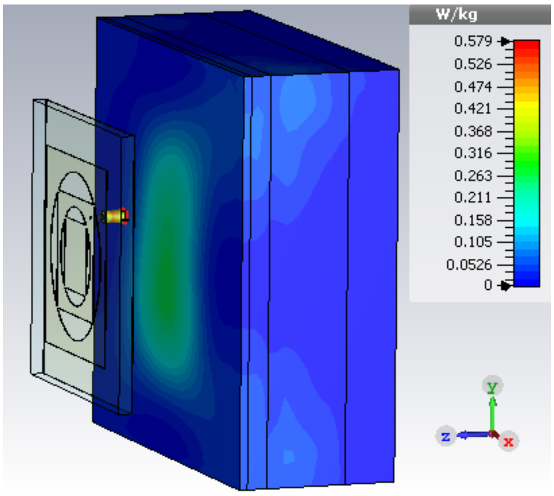


(c)

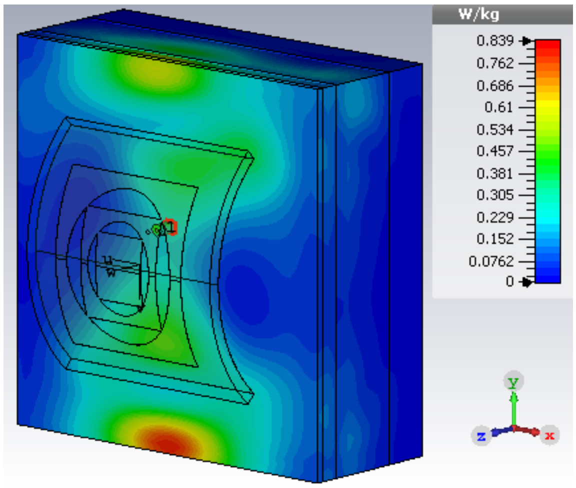
Fig. 7. (a) SAR at a gap of 10 mm, (b) SAR at a gap of 15 mm, and (c) SAR at a gap of 20 mm.

TABLE V
SAR AND FBR VALUE OF ANTENNA NEAR HBTM WITH DIFFERENT GAPS

Antenna Parameters	Distances of Antenna from HBTM		
	10 mm	15 mm	20 mm
SAR (W/kg)	0.617	0.668	0.579
FBR (dB)	20.3	20.4	20.6

B. *Simulation of Bent Conditions of Antenna on HBTM*

The proposed wearable antenna has to be aligned with the surface of the wearing position of the human body parts which requires the bending of the antenna. The bending of the antenna may result in the variation of the radiation falling on the body parts as compared with the radiations falling from the planer condition of the antenna. So to analyze this radiation, the antenna is required to be bent as per the wearing position of the antenna on human body parts such as arm or chest, and simulating the SAR and FBR of the antenna by placing the bent antenna geometry, near the HBTM. For this the antenna has been bent over with the radius of 40 mm and 60 mm horizontally and vertically by using CST MWS simulator software. The bent antenna structures have been positioned 15 mm from the HBTM and SAR and FBR simulation has been carried out. Figure 8 a-d present the simulated SAR value of the proposed wearable antenna placed at 15 mm from the HBTM at different bending radii in horizontal and vertically. Table VI presents the SAR and FBR values of the antenna in planer and varying bent conditions of the antenna. All the simulated SAR values are acceptable since, it did not exceed the limit of FCC standards [16]. Also, the simulation shows high value of FBR in all conditions, which implies reduced backward radiation. The performance of the proposed antenna is satisfactory in terms of SAR and FBR in the flat and both bent conditions. As the bending of antenna did not severely affect the SAR values and therefore the proposed antenna can be efficiently used for wearable applications.



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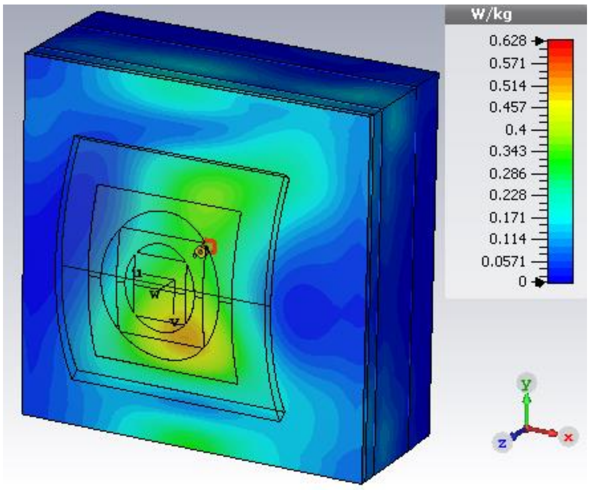

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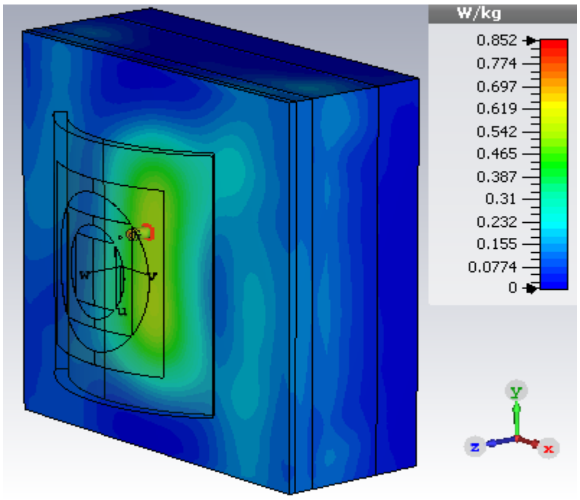

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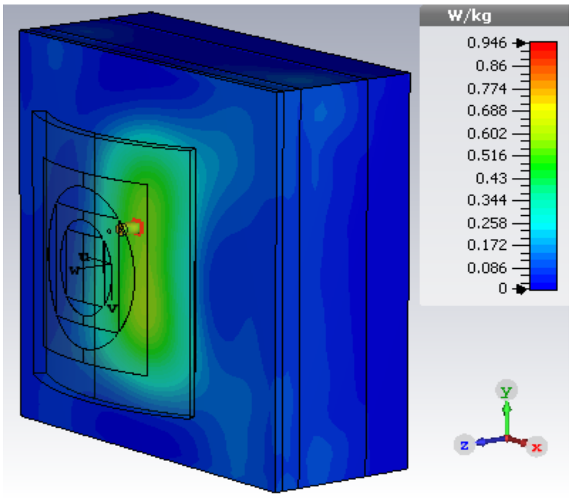

(d)

Fig. 8. Bent structure of proposed antenna positioned 15 mm from the human body model, (a) horizontally bent with 40 mm radius, (b) horizontally bent with 60 mm radius, (c) vertically bent with 40 mm radius, and (d) vertically bent with 60 mm radius.

TABLE VI
SAR AND FBR VALUES OF ANTENNA IN THE PLANE AND DIFFERENT BENDING CONDITIONS

Antenna Structures	Distances of Antenna from HBTM	
	SAR (W/kg)	FBR (dB)
Plain	0.668	20.4
Horizontally bent with 40 mm radius	0.839	16.60
Horizontally bent with 60 mm radius	0.628	18.70
Vertically bent with 40 mm radius	0.852	15.00
Vertically bent with 60 mm radius	0.946	15.60

V. CONCLUSION

In this research work the design of a miniaturized wearable fractal patch antenna has been proposed for BAN applications in 2.45 GHz ISM band. The proposed antenna operates at 2.459 GHz, having bandwidth of 131 MHz ranging 2.386-2.517 GHz by covering the entire ISM 2.45 GHz band. The proposed wearable fractal antenna has only 73.15% of the area as required for the standard rectangular patch antenna working at 2.45 GHz. Hence, the size minimization of 26.85% has been achieved by using fractal antenna design technology in this study. The SAR and FBR have been simulated at varying distances of the proposed antenna to the HBTM. The antenna in the planer condition shows SAR and FBR value of 0.579 W/kg (1 g of tissue) and 20.6 dB respectively when placed 20 mm from the human tissue model. In the different bent condition the antenna shows SAR ranging from 0.668 - 0.946 W/kg (1 g of tissue) and FBR ranging from 15.60 – 18.70 dB, when placed 15 mm near the human tissue model, which is acceptable as per FCC standards [16]. The proposed antenna has low SAR values and high FBR value in all the simulated conditions. Moreover, the proposed antenna is a flexible antenna as the polyester cloth is used as the substrate of the antenna. So, the proposed antenna is a suitable candidate for wearable BAN applications.

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