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RESEARCH ARTICLE

Design and Performance Measurement of Worn-on-Body Instrumental Ultra-Miniaturized UWB Wearable Patch for e-Health Monitoring

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ABSTRACT A conformal, ultra-miniaturized, circuit integrated ultra-wideband (UWB) coplanar-waveguide (CPW) antenna system for worn-on-body applications is developed in this article. The performance study of the proposed antenna is performed over a four-layer human body tissue model. A shortened ground plane and a pair of L-shaped stubs are included to the umbrella-shaped patch configuration to enhance the impedance bandwidth between 3.15-10.55 GHz, which encompass a variety of applications like WiMAX band (3.3-3.8 GHz), WLAN band (5.150-5.350 GHz), unlicensed ISM band (5.725-5.875 GHz), and X-band (7.250-7.745, and 7.900-8.395 GHz). The realization of wideband behavior for the reported antenna is studied using the characteristic mode theory (CMT). A maximum peak gain of 4.2 dBi is achieved with maximum radiations in broadside with higher front-to-back ratio in both E-plane and H-plane. Furthermore, the robustness of the proposed antenna is evaluated by studying its performances under different conditions, such as using a coaxial feeding system, bending and assessing SAR levels. The antenna is fabricated and assembled with various circuit components to validate its performance with the simulated counterpart. The experiment is carried out by placing the antenna structure over different parts of the human body. Finally, a comparative analysis is carried out and it is found that the proposed antenna exhibits 98.2% compactness than the existing antenna designs available in the literature.

INDEX TERMS Characteristic mode theory, coplanar-waveguide antenna, conformal, ultra-miniaturized ultra-wideband, umbrella design, wearable.

I. INTRODUCTION

Over the past decades, the development of UWB technology has evolved to a great interest among researchers due to its advantages, such as low spectral density, low power consumption, low cost, and high data rates [1]. Since the release of unlicensed band 3.1-10.6 GHz by FCC in 2002, the research in UWB has seen manifold advantages targeting different operational modules and connectivity strategies [2]. As a fundamental part of the UWB communication system, antennas have drawn considerable attention and have aroused much popularity. Nevertheless, most of the antennas

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are unsuitable for UWB communications due to design complexity, and substantial size. Antenna designs reported in [3], [4], [5], and [6] are based on circular and elliptical-shaped patches integrated with various resonant structures to accomplish wide frequency bands of operation. A novel CPW feed patch antenna configuration featuring a circular and elliptical-shaped stub is presented in [7]. The antenna operates within the frequency band of 3.1-10.6 GHz. Yan et al. [8] proposed a circularly polarized wideband umbrella-shaped patch antenna by modifying an elliptical-shaped radiator. Likewise, utilizing different slotted geometry over the patch and ground layer of umbrella-shaped antenna designs in [9] and [10], a wide operational bandwidth of 3.1-13.4 GHz, and 7.5-12.5 GHz is retained, respectively. Although the reported designs in [7], [8], [9], and [10] have achieved an acceptable impedance bandwidth but suffer from several constraints like non-medical applications, design complexity, large circuital area, and non-flexible geometry. Indeed, UWB technology also seems to be a good candidate for on-body networks and has much popularity in wireless biotechnologies [11]. Therefore, in the context of WBAN applications, antennas have drawn significant attention over the past few years. The idea behind the development of wearable antennas has acquired several applications in health care monitoring, smart home, telemedicine, sports, military, etc. In recent years, research on wrist-worn wireless communication devices has been tremendously increased for applications in smartwatches and smart wristbands, [12], [13]. Two different configurations of wearable antenna systems is proposed for smartwatch applications in health care monitoring [14], [15]. Chen et al. [16] have developed an inverted L-shaped antenna configuration with a high-impedance surface. A dual-port circular MIMO antenna designed for smartwatch applications is presented based on characteristic mode theory. The antenna is tailored to operate within the 2.4-2.49 GHz range, covering both Wi-Fi and Bluetooth bands [17]. A four-port MIMO antenna configuration is integrated into the watchstrap for smartwatch applications, operating in the frequency range of 5.2-5.8 GHz [18].

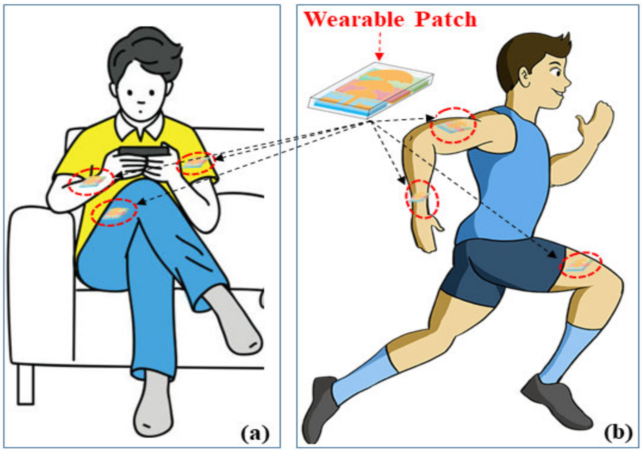


FIGURE 1. Wearable patch-based health monitoring system under different environmental conditions (a) Indoor, (b) Outdoor.

Noteworthy, as the wearable antennas are intended for body- worn applications, it is highly desirable to have flexible characteristics in order to suitably fit on human body parts that result in avoiding collision with other rigid substances which will protect the antenna structure from damage. A substantial amount of work has been done in developing flexible antenna structures for various wearable applications [19], [20]. UWB antenna with a flexible substrate operating within 4-6 GHz is designed for the detection of breast cancer [21] Similarly, for applications in the textile domain, a low-profile microstrip antenna modeled on denim jeans is introduced for wide-frequency UWB communications [22]. A four-port footwear wearable antenna structure is developed by Jayant et al. [23]. The suggested antenna possesses a flexible structure and operates between 2-14 GHz. Although in the reported antenna structures a significant performance has been obtained in terms of operational bandwidth, gain, and flexibility, but the antenna structures presented in [21] and [22], are larger in size, which makes them unsuitable for small movable parts of the body like wrist, fingers, and toes. In addition, the curvature effect and specific absorption rate (SAR) analysis has not been studied which is a major concern in case of wearable and flexible antenna structures. Likewise the antenna proposed in [23] exceeds the limit of compactness due to its implementation in footwear which has high risk of getting damaged. Therefore, to address the above constraints, a coplanar flexible ultra-miniaturized circuit integrated UWB antenna system intended to be operational over different parts of human body (wrist, biceps, and thigh) is presented for health care monitoring applications. The targeted operational scenario for the proposed wearable antenna in indoor and outdoor environments is illustrated in Fig. 1. This shows that the wearable patch (circuit integrated antenna) will collect relevant physiological data in different environments using biosensors and will process the data through analog signal conditioning and digital processor; finally the processed information will be transmitted wirelessly to the external base station [24]. The performance of the proposed antenna is evaluated through simulations over a four-layer human body tissue model. It offers distinct advantages over existing literature, including (i) remarkable compactness (98.2% compact in comparison to antenna structure in ref. [21]), (ii) utilization of characteristic mode theory to enhance impedance bandwidth, and (iii) a broad operational bandwidth ranging from 3.15 to 10.55 GHz. Furthermore, the robustness of the proposed antenna is thoroughly evaluated under diverse scenarios. This includes an examination of the antenna's performance in bending scenarios, an assessment of its performance behavior in proximity to the coaxial feeding system, and measurements of SAR. This comprehensive analysis provides insights into the antenna's durability and suitability for practical applications in different conditions. The novel features of the proposed antenna are compared with the existing literature and presented in Table 1. The paper is divided into the following six sections. The introduction is presented in Section I.

TABLE 1. Comparison of the proposed wearable patch with state-of-the-art.

Ref.	Substrate	Monopole Design	Antenna Size (mm^3)	System Analysis	Operating Freq. (GHz)	Freq. Band	CMT Study	Conf-ormal	SAR (W/kg)	Peak Gain (dBi)	Applications
[14]	FR4 Epoxy	L-Shaped	44×15×1.6 (= 1056)	No	5.11-5.8	ISM	No	Yes	0.57	4.52	Smartwatch
[15]	FR4 Epoxy	Circular	30×30×1.6 (= 1440)	No	MNB	NA	No	No	2, 4	6.6	Smartwatch
[16]	FR4 Epoxy	Inverted L-Shaped	38×38×2 (= 2888)	No	2.38-2.5	ISM	No	No	0.29	6.3	Smartwatch
[17]	FR4 Epoxy	CAR	NA	No	2.4-2.49	ISM	No	No	NA	3.5	Smartwatch
[18]	Polyamide	Rectangular Strip	40×38×8 (= 12160)	No	5.2-5.84	ISM	No	Yes	NA	3.3–5.6	Smartwatch
[21]	Phenylthiophene	Rectangular	20×14×1.6 (= 448)	No	4-6	ISM	No	No	NA	1	Wearable Bra
[22]	Denim Jeans	Edge truncated	36×29×2 (= 2088)	No	3-11	UWB	No	No	NA	7.2	BAN
[23]	Polyethylene	Dome Shaped	92×92×1.5 (= 12696)	No	2-14	UWB	No	Yes	0.001	7.2	Footwear
This Work	**Polyimide (Flexible)**	**Umbrella Shaped**	**16×10×0.05 (= 8)**	**Yes**	**3.15-10.55 2.71-10.56 3.29-10.53**	**UWB**	**Yes**	**Yes**	**1.99 1.96 2.04**	**4.2 (overall)**	**Wrist Biceps Thighs**

CAR: Circular Annular Ring. MNB: Multi Narrow Bands; NA: Not Available; BAN: Body Area Network, SAR: Specific Absorption Rate (W/kg), Peak Gain (dBi)

The geometrical design of the reported prototype structure and its evolution process is discussed and analyzed using CMT in Section II. Section III outlines the simulated performance and sensitivity analysis.

The measurement scenario and the experimental validation is covered in Section IV. The SAR analysis for the reported wearable patch is presented in Section V, and the conclusion is drawn in Section VI.

II. WEARABLE PATCH

A. INTEGRATED ANTENNA SYSTEM DESIGNS

Fig. 2(a) illustrates the proposed antenna geometry which exhibits an overall dimension of 16×10 × 0.05 mm^3. The other dimensions in mm are as follows: $L_s = 16$, $W_s = 10$, $R = 4.8$, $R_1 = 1$, $W_f = 1$, $L_f = 10$, $L_1 = 8$, $L_2 = 3.8$, $C = 1.6$, $C_1 = 0.1$, $L_g = 2$, $Wg = 3$. The designed antenna comprises a triple-stacked umbrella patches acting as a radiator and a shortened ground layer. Both patch and ground layers are coplanar on the conformal and biocompatible substrate polyimide having relative permittivity, $\varepsilon_r = 4.3$ and thickness = 0.05 mm. Fig. 2(b) shows the isometric view of the proposed antenna fed with coaxial feed system. Fig. 3(a) shows the exploded view of the proposed wearable patch (antenna integrated with different circuitry components). The electronic components are integrated over another polyimide layer; and placed at the backside of the antenna substrate. The dimensions of various components are: biosensor pack (4.5 × 4.5×0.1 mm^3) power supply unit (10×4 × 0.05 mm^3), data unit (10×4 × 0.05 mm^3), memory unit (5.5 × 4.5×0.1 mm^3), and battery (6.5 × 4.5×1.2 mm^3).

Noteworthy, the integrated antenna system is designed in such a way that the antenna layer is placed over the circuitry layer with zero gap in-between; and both the layers are packed together and enclosed with a polyimide (biocompatible) layer. During simulation, the battery is represented as a perfect electric conductor (PEC), whereas all other circuit components are represented as dielectric [25]. Moreover, as the proposed antenna is applicable for body-worn purpose, it is important to consider the effects of human tissues. To that regard, all the simulations are carried out by placing the integrated antenna structure over a four-layer human body tissue model which comprises skin ($\varepsilon_r = 37.45$, $\sigma = 1.74$), fat ($\varepsilon_r = 5.22$, $\sigma = 0.130$), muscle ($\varepsilon_r = 52.0$, $\sigma = 2.14$), and bone ($\varepsilon_r = 11.06$, $\sigma = 0.506$), in a cubic configuration having overall size 120 × 120× 50 mm^3.

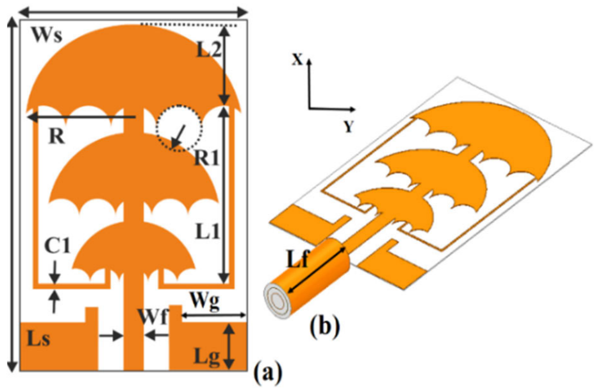


FIGURE 2. Proposed antenna geometry (a) Top view, (b) Isometric view with coaxial feed system.

The radiation boundaries (500 × 500×500 mm^3) are kept at a distance ≫ $\lambda_0/2$ (at 3 GHz) from the antenna edges as depicted in Fig. 3(b). The electrical properties of different tissue layers are considered corresponding to the lowest frequency (3 GHz) of the ultra-wideband [26].

B. ANTENNA DESIGN EVOLUTION

The evolution process for the reported antenna is displayed in Fig. 4. The reflection coefficient ($|S_{11}|$) plot comparison for Ant-1, Ant-2, and Ant-3 are displayed in Fig. 5(a) whereas, comparison for Ant-4, Ant-5, and Ant-6 is shown in Fig. 5(b). Initially, an umbrella-shaped patch antenna (Ant-1) is designed by modifying a semi-circular shaped radiator with multiple circular slots at the edges. The ground layer is coplanar with the patch radiator. Ant-1 resonates at 4.3 GHz with -10 dB impedance bandwidth from 3.25-5.5 GHz, covering WiMAX, and WLAN bands. Since, designing an UWB antenna system to operate within a spectrum of 3.1-10.6 GHz is the target goal; therefore, to enhance the bandwidth two additional umbrella-shaped radiators of decreasing overall size are vertically stacked beneath the first radiator as shown in Figs. 4(b) and 4(c), which are termed as Ant-2

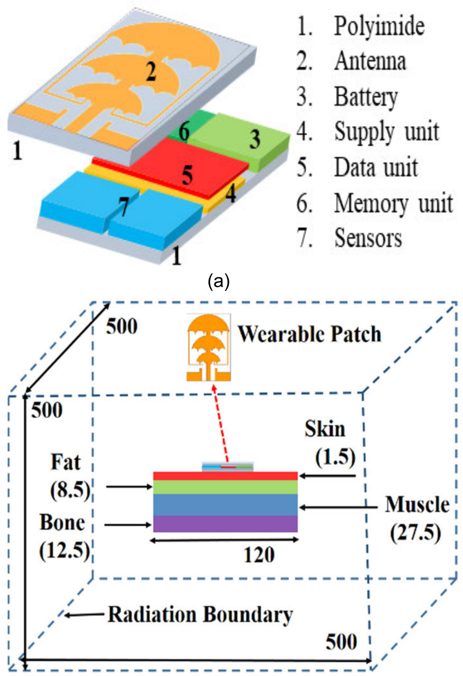


FIGURE 3. (a) Exploded view of the proposed antenna integrated with different circuitry components, (b) Human body tissue model.

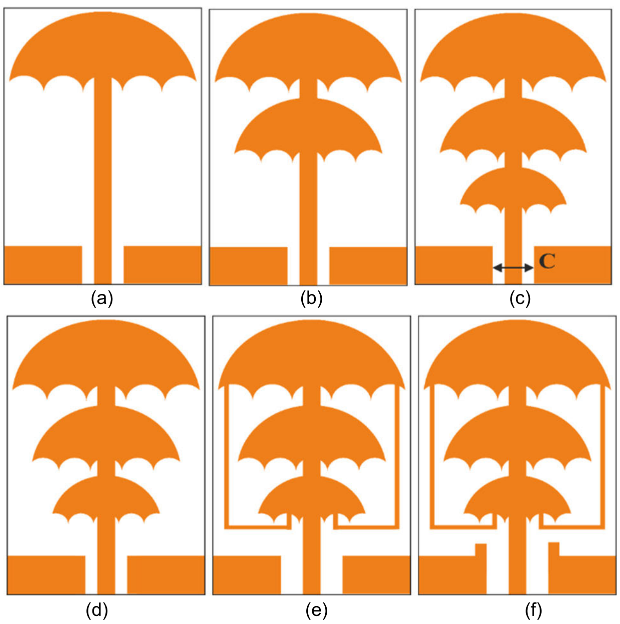


FIGURE 4. Antenna design evolution steps (a) Ant-1, (b) Ant-2, (c) Ant-3 (d) Ant-4, (e) Ant-5, and (f) Ant-6 (proposed).

and Ant-3, respectively. Consequently, the antenna operates within frequency band of 3.25-6.05 GHz, and 3.5-6.35 GHz respectively. Noted, compared to other antenna structure shapes such as, rectangular, circular, elliptical, etc., the umbrella-shaped structure offers higher impedance bandwidth due to larger (curved edges) antenna radiator's effective length [9]. Further, by increasing the separation between the ground plane in Ant-4; the modified ground improved the $|S_{11}|$ at lower frequency (~3 GHz) but the $|S_{11}|$ at higher frequency (~6 GHz) remains intact. Subsequently, to attain the target frequency spectrum, two L-shaped stubs are introduced connecting the umbrella-shaped patch at the top and bottom in Ant-5. The L-shaped stubs increase the patch's electrical length, which aids in enhancing the broad impedance bandwidth from 3.3-9.4 GHz in Ant-5. Finally, by truncating the ground plane in Ant-6 by length (Wg), the desired operating frequency spectrum of 7.4 GHz (3.15-10.55 GHz) is achieved. The design stages of Ant-1 to Ant-6 are summarized in Table 2. Noted, the design simulations for Ant-1 to Ant-6 are carried out in the presence of circuit elements.

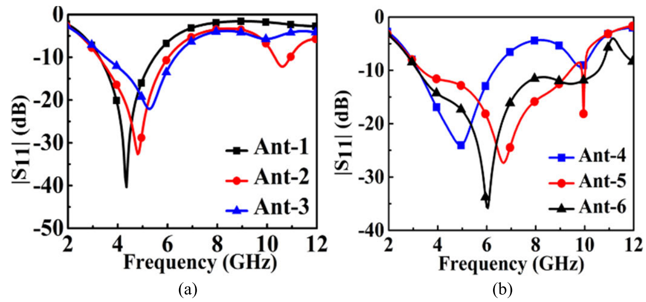


FIGURE 5. Comparison of simulated $|S_{11}|$ (a) Ant-1 to Ant-3, (b) Ant-4 to Ant-6.

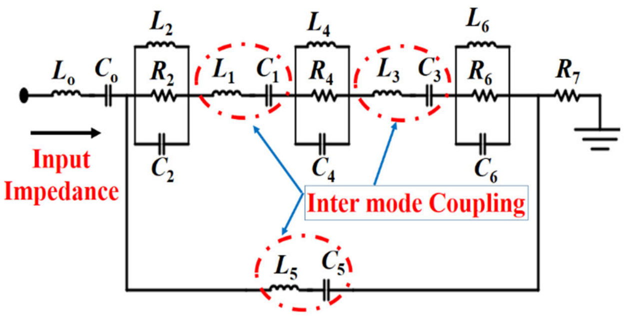
TABLE 2. Antenna design stages.

Design Steps	Geometrical Description with	Operating Band (GHz)	Peak Gain (dBi)
Ant-1	Single Umbrella with IS	3.25-5.5	0.43 @5.4 GHz
Ant-2	Dual Umbrella with IS	3.25-6.05	0.75 @5.8 GHz
Ant-3	Triple Umbrella with IS	3.5-6.35	1.12 @6.1 GHz
Ant-4	Ground plane separation	3.2-6.35	1.29 @6.3 GHz
Ant-5	Addition of L-shaped stubs	3.3-9.4	3.36 @9.3 GHz
Ant-6	Truncated ground plane	3.15-10.55	4.2 @10.4 GHz

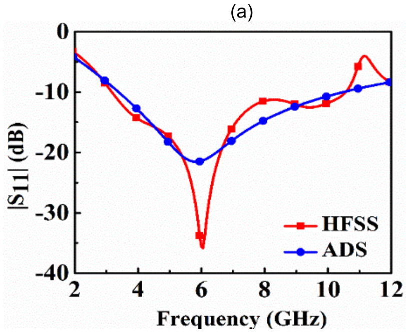
IS: Integrated System

C. EQUIVALENT CIRCUIT MODEL

In the context of ultra wideband (UWB) antenna design, matching bandwidth is attainable through the incorporation of multiple nearby resonances. Each of these resonances can be effectively modeled using parallel RLC tank circuit arranged in a series configuration [3], [27]. Hence, for a clearer comprehension of the resonance characteristics, an equivalent circuit model for the proposed antenna structure is established by interconnecting three parallel RLC resonance circuits based on three resonance modes in the frequency band of 3.15-10.55 GHz. Further, to address the impedance transformation resulting from feed inductance and static capacitance of the antenna, additional lumped components L_o and C_o are incorporated in the circuit. Moreover, to comprehensively analyze the equivalent circuit system, it is imperative to incorporate the coupling between the radiating modes. This intermode coupling is accurately modeled by introducing LC series lumped elements as defined in [28], [29], and [30]. The representation in Fig. 6(a) illustrates the equivalent resonance circuit model associated with the novel umbrella-shaped ultra wideband (UWB) antenna. The circuit model has been simulated employing a commercial



(a)



(b)

FIGURE 6. **(a) Equivalent circuit model for the proposed antenna, (b) Comparative $|S_{11}|$ plot for the proposed umbrella shaped UWB antenna.**

advanced design system (ADS) software. The values of all the components are as follows: $L_o = 0.21$ nH, $C_o = 3.18$ pF, $L_1 = 0.42$ nH, $C_1 = 9$ pF, $L_2 = 0.25$ nH, $C_2 = 0.24$ pF, $R_2 = 3.78\ \Omega$, $L_3 = 0.15$ nH, $C_3 = 1.31$ pF, $L_4 = 0.2$ nH, $C_4 = 0.23$ pF, $R_4 = 4.6\ \Omega$, $L_6 = 0.85$ nH, $C_6 = 0.23$ pF, $R_6 = 2.4\ \Omega$, $L_5 = 0.68$ nH, $C_5 = 0.22$ pF, $R_7 = 50\ \Omega$. Fig. 6(b) presents a comparative analysis of the $|S_{11}|$ parameters obtained from simulations conducted using HFSS and ADS. The results from both the simulators validates excellent agreement within the specified frequency band of 3.15-10.55 GHz.

D. PERFORMANCE ANALYSIS USING CHARACTERISTIC MODE THEORY

The effectiveness of the suggested antenna using characteristics mode theory (CMT) is discussed in this section. The theory of CMs was initially introduced to provide a more deterministic antenna design approach than the arbitrary or trial-error design approach. For a better understanding of mode characteristics, some equations are described below, which emphasize that the electric current $(\vec{J})$ on the surface of the conducting element is characterized by Eq. (1) as a sum of eigen current $(\vec{J}_n)$ with weighted coefficients [31].

$$\vec{J} = \sum_n \alpha_n . \vec{J}_n \tag{1}$$

where, α_n is the modal weighting coefficient which can be obtained using Eq. (2):

$$\alpha_n = \frac{V_n^i}{1 + J\lambda_n} \tag{2}$$

where, V_n^i is the modal excitation coefficient and can be expressed by Eq. (3), where, $\vec{E}_i$ is the impressed source.

$$V_n^i = \left(\vec{J}_n . \vec{E}_i\right) \tag{3}$$

When a mode is excited at its resonating frequency, it radiates maximum power, i.e. $\lambda_n = 0$. Therefore, Eq. (2) can be rewritten as $\alpha_n = V_n^i$, meaning that when $\lambda_n = 0$, the modal weighting coefficient is equal to the modal excitation coefficient, and the modal significance (MS) is defined by Eq. (4):

$$MS_n = \left| \frac{1}{1 + J\lambda_n} \right| \tag{4}$$

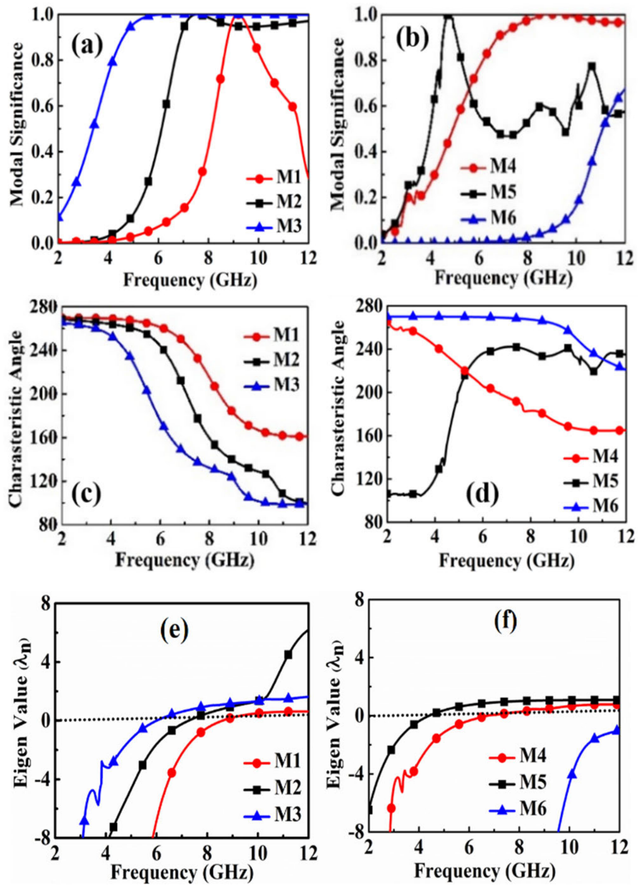


FIGURE 7. **Modal Significance: (a) Modes M1-M3, (b) Modes M4-M6, Characteristics Angle: (c) Modes M1-M3, (d) Modes M4-M6, Eigenvalue (λ_n): (e) Modes M1-M3, and (f) Modes M4-M6.**

Moreover, the approach of CMT provides a clear insights into antenna resonance, radiation mechanism, and serves as a pivotal tool to accumulate the existing modes inherent in the reported antenna geometry [32]. Besides, the adoption of CMT by various commercial electromagnetic solvers contributes to a more deterministic approach to antenna design, markedly distinct from the conventional arbitrary or trial error methods. In recent years, the use of characteristic modes for bandwidth enhancement has also been investigated [33], [34]. However, the literature on bandwidth enhancement using CM is minimal, and the physical phenomena have not been discussed. Hence, in this section, the authors have tried to emphasize the existing mode present in the reported antenna by thorough discussion of the design approach using CMs. The CMs simulation for the reported antenna structure is carried out using CST microwave studio. Fig. 7 demonstrates that the suggested antenna is exciting six different modes, out of which five modes are considered to be significant modes that contribute strong radiation.

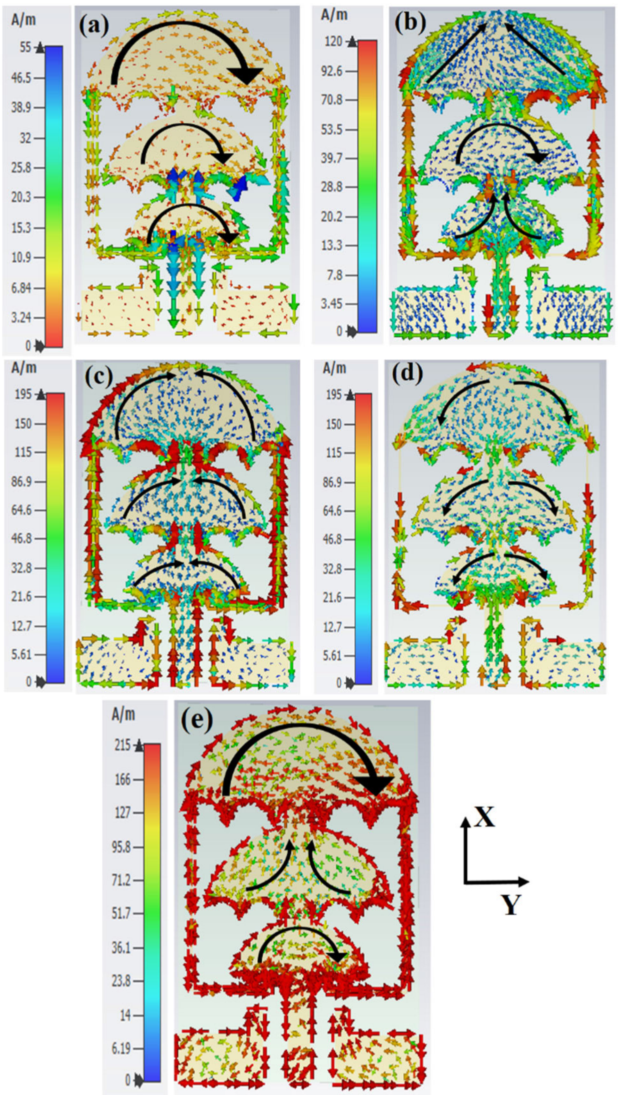


FIGURE 8. Simulated modal Current distributions at their respective mode: (a) J_1 at 9.2 GHz, (b) J_2 at 7.5 GHz, (c) J_3 at 5.9 GHz, (d) J_4 at 8.7 GHz, and (e) J_5 at 4.7 GHz.

Figs. 7(a) and 7(b) depicts the modal significance curves where mode M1 is resonating at 9.2 GHz showing a large modal significance value of 1. Similarly, the modes M2, M3, M4, and M5 also show large modal significance values around 1 at their respective resonant frequency 7.5, 5.9, 8.7, and 4.7 GHz, respectively. Meanwhile, mode M6 is a non-significant mode that provides weak radiation. Besides, utilizing the analysis of characteristic angle (α_n) and Eigen value (λ_n) the radiation properties of the antenna can be determine. This signifies that when $\alpha_\mathrm{n} = 180°$, and $\lambda_\mathrm{n} = 0$ the antenna actively radiates energy, otherwise the antenna stores electric and magnetic energy and behave as a capacitive and inductive. Hence, from Fig. 7(c), and Fig. 7(d) it can be observed that the modes M1-M5 intersect at 180° at their respective resonant frequencies within the UWB (3.1-10.6 GHz) frequency band. This lead to the conclusion that at the resonant frequency, modes M1-M5 demonstrates a tendency to effectively radiate EM energy. Meanwhile mode M6 has a higher value which is beyond the required frequency spectrum. Likewise, the electromagnetic (EM) radiation properties of an antenna can be visualized using the eigenvalues (λ_n). A resonance mode is indicated when $\lambda_n = 0$. It can be clearly visualize from Figs. 7(e) and 7(f) that modes M1 to M5 are resonating modes whose eigenvalues correspond to zero at their respective resonating frequencies. The modal currents for the dominant mode (M1-M5) are examined and represented as J_1, J_2, J_3, J_4, and J_5, for a clear analysis of the antenna's radiation mechanism (see Fig. 8). The dispersal of currents over the antenna structure leads to generating odd and even modes.

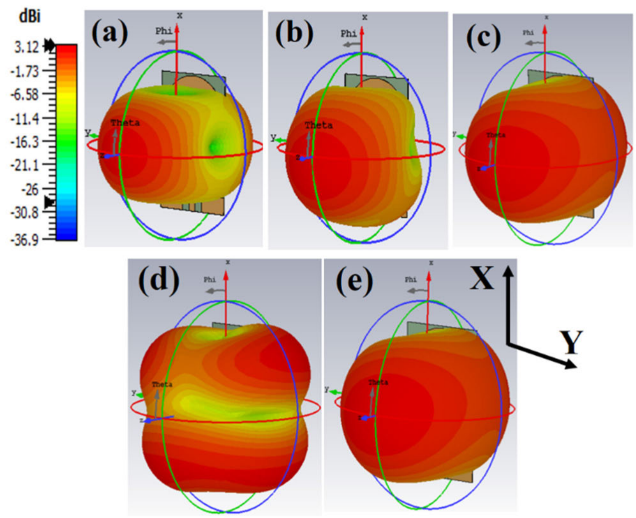


FIGURE 9. Directivity patterns for different frequency modes: (a) 9.2 GHz, (b) 7.5 GHz, (c) 5.9 GHz, (d) 8.7 GHz, and (e) 4.7 GHz.

The distributions of modal currents J_1 in all three umbrella-shaped radiators for mode M1 are in phase, which ensures mode M1 is an even mode [35]. Similarly, modes M3 and M4 are also the even modes that follow identical distributions of modal currents (J_3 and J_4) in the antenna radiator (See Figs. 8(c), and 8(d)). However, in modes M2 and M5 antiphase modal current (J_2 and J_5) patterns are noticed, rendering odd modes. Hence, the strategic excitation of consecutive odd and even modes within the suggested antenna design emerges as a key factor contributing to its wideband performance within the UWB spectrum of 3.15-10.55 GHz [36]. From Fig. 8, the modal currents J_1 to J_5 are mainly concentrated on the L -shaped stubs followed by the feedline and gently flow through the antenna radiators. In the case of mode M1, the current is horizontally directed in all three umbrella-shaped radiators marked with a black arrow. In modes M3 and M4, the current direction is vertical, upward, and downward. An arbitrary flow of current in modes M2 and M5 is observed. Despite a strong current concentration at the ground layer in the form of a loop that tends to achieve broadside radiation behavior. The 3D radiation patterns for the reported antenna at five different modes are depicted in Fig. 9. It is obvious that Mode M1 and M2 provide maximum radiation in the z-direction appearing null at the central position in Y-axis. Whereas Mode M3 and M5 provide a good omnidirectional radiation pattern, and Mode M4 presents a radiation pattern with minimum radiations in X and Y-axis. Therefore, as a result, these five modes contribute more radiation in wideband operations.

III. SIMULATED PERFORMANCE

A. PARAMETRIC ANALYSIS

As the L-shaped stubs and ground plays an important role in obtaining the targeted frequency response of the proposed antenna, therefore, to observe the effect of the width of L-shaped stubs on the reflection coefficient of the proposed antenna, parametric variation of the stub width (C_1) has also been performed and mapped in Fig. 10(a).

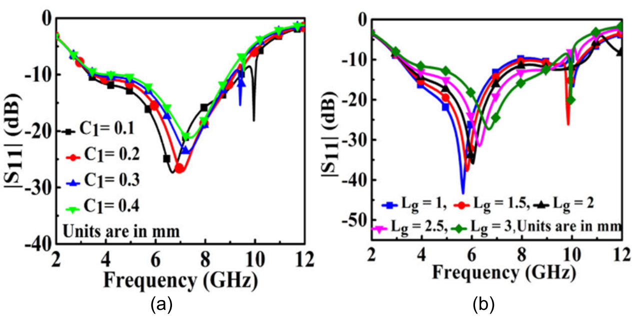


FIGURE 10. Comparison of simulated $|S_{11}|$ for parametric variation of (a) C_1 (width of L-shaped strip), and (b) Lg (length of ground plane).

It can be seen, even slight increment in the value of C_1 can detune and simultaneously shift the overall resonance towards higher frequency; and moreover, stub width has the potential to mismatch the impedance drastically, if width would not be optimized. Hence $C_1 = 0.1$ mm is considered to be the optimized width. Further, Fig. 10(b) shows the tuning effect on $|S_{11}|$ due to parametric variation of the ground plane's length (L_g). With an increment of 0.5 mm in the value of L_g from 1 to 3 mm, the overall resonance is shifting towards high frequency with the potential impedance mismatch. Thus, the optimized value of L_g is 2 mm, which makes the suggested antenna operate in a designated frequency band in order to be applicable for appropriate transfer of data related to the human body physiological statistics.

B. INTEGRATED ANTENNA SYSTEM ROBUSTNESS

In order to analyze sensitivity of the wearable patch, simulated performance of the proposed integrated antenna system is scrutinized by loading a coaxial feed of different cable length (L_f = 5 mm, 10 mm and 15 mm), as shown in Fig. 11 (a-c). Such analysis could support the actions to be taken in measurement procedure to validate this in-house prototype for the real-time application. The simulated $|S_{11}|$ comparison for different coaxial cable length (L_f) is mapped in Fig. 12(a).

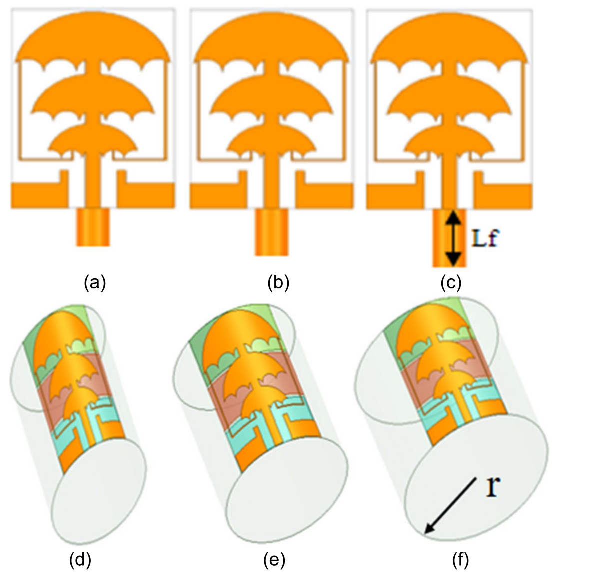


FIGURE 11. Coaxial feed length: (a) $L_f = 5$ mm, (b) $L_f = 10$ mm, (c) $L_f = 15$ mm, Antenna bending radii: (d) $r = 85$ mm, (e) $r = 150$ mm, (f) $r = 250$ mm.

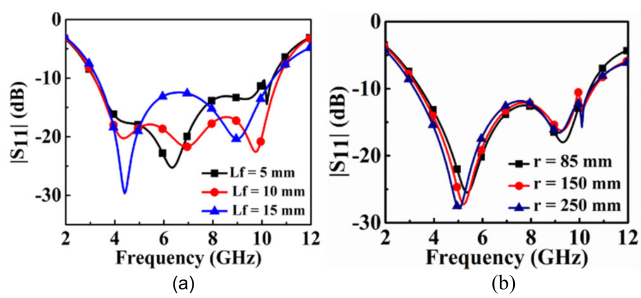


FIGURE 12. Comparison of simulated $|S_{11}|$ for parametric variation of (a) L_f (coaxial feed length) and, (b) r (antenna bending radii).

The comparative results suggest that the overall target impedance bandwidth remains intact due to the UWB profile of the antenna. Note input impedance is varying throughout the bandwidth for different cable lengths, as the intensity of the coupled current from the patch to the cable depends on the coaxial feed length. Further, robustness of the wearable patch is also analyzed due to the curvature effects which could arise in its real-time application. As the proposed antenna system is built on flexible polyimide substrate, it could easily adapt to the curved surface of its intended location (wrist, biceps and thighs) on the human body. Fig. 11(d-f) represents the bending scenario with approximate curvature radii (r) of the human body parts: 85 mm (wrist), 150 mm (biceps), and 250 mm (thigh). The simulated $|S_{11}|$ comparison is plotted in Fig. 12(b). The proposed wearable antenna seems to be robust as both, the overall impedance bandwidth and input impedance throughout the bandwidth stays intact; even though an increase in bending angle decreases the effective resonating length which could shift the resonant frequency. Hence, the comparative results ensure that changing the location (on human body) of operation will not hamper the resonance characteristics of our wearable system.

IV. FABRICATION AND MEASUREMENT

This section presents the comparison of simulated and measured performance characteristics of the reported antenna (Ant-6) in the vicinity of modeled integrated circuit system. The circuit components are assembled at the backside of the antenna where battery (cell) is metallic and other components are PCB board models cased with dielectric (PVC) cover. Further, the whole integrated system is packaged with the biocompatible Polyimide layer and SMA connector (Female-Co-795-D) is used for power delivery. The fabricated prototype of the reported antenna with integrated system and the near-field (reflection coefficient) measurement setup (mimic the simulation scenario) in the laboratory environment is shown in Fig. 13.

FIGURE 13. Experimental setup (a) Fabricated prototype with integrated circuit, (b) assembled electronic circuitry (c) near-field measurement setup for on-wrist scenario, (d) on-bicep scenario and, (e) on-thigh scenario, (f) on-forearm for validation of flexible characteristics.

For validation of the simulated results, Anritsu vector network analyzer (VNA) is used to perform the measurement of S-parameters in different scenarios, where the fabricated wearable patch prototype is placed on the wrist, biceps and thigh of the volunteer subject (human body). Fig. 14(a-b) presents the comparison of simulated and measured $|S_{11}|$ in different scenarios as discussed above. It is noticed that the measured impedance bandwidth for the proposed antenna (Ant-6) in free space scenario follows the simulation behavior in close proximity. It is also observed that for on-wrist, on-bicep, and on-thigh scenario, the proposed antenna seems to be robust as measured $|S_{11}|$ is not deflecting considerably from the simulation, and the overall $|S_{11}|$ behavior is also preserved throughout the bandwidth (UWB) even though the circuit assembling and packaging is done manually and prone to human handling and fabrication errors. Noted, in measurement the proposed wearable patch is placed at 0.25 mm height (thickness of fabric) above the skin surface in case of on-bicep, and on-thigh scenario; whereas for on-wrist scenario the wearable patch is placed just on the bare skin surface of the volunteer. The relative permittivity (typical range, 1.0-2.1) of the conventional fabric layer such as cotton, polyester, and nylon beneath the wearable patch is also believed to influence the $|S_{11}|$ of the antenna. In a comparable manner, the validation of the flexible characteristics for the proposed antenna for real-time applications is demonstrated by placing the antenna structure on the forearm, as illustrated in Fig. 13(f). The measured behavior of $|S_{11}|$ is compared in Fig. 14(a). Table 3 summarizes the simulated and measured -10 dB bandwidth for all the scenarios where, the comparable bandwidth results promisingly validate the strong robustness of the suggested wearable system.

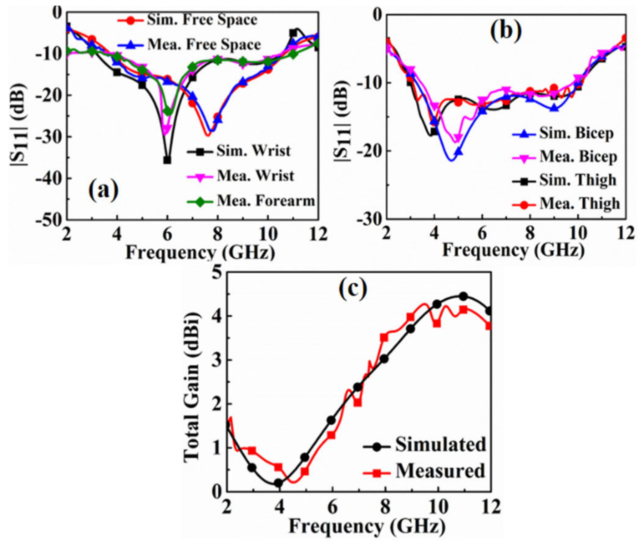


FIGURE 14. Comparison of simulated and measured performance (a, and b) $|S_{11}|$ for different scenarios, and (c) Total gain.

For far-field gain calculation, the measurement system in anechoic chamber is used, as shown in Fig. 15. In an anechoic chamber, the antenna under test (AUT) is positioned at distance > 3m from the reference standard horn antenna (for UWB spectrum) to measure the radiation characteristics (plane, $\varphi = \theta = 0°$) of the antenna in the proposed wearable patch system. Noteworthy, to avoid the risk of EM radiations on the volunteer subject (human body), antenna system is placed over the customized four-layer phantom

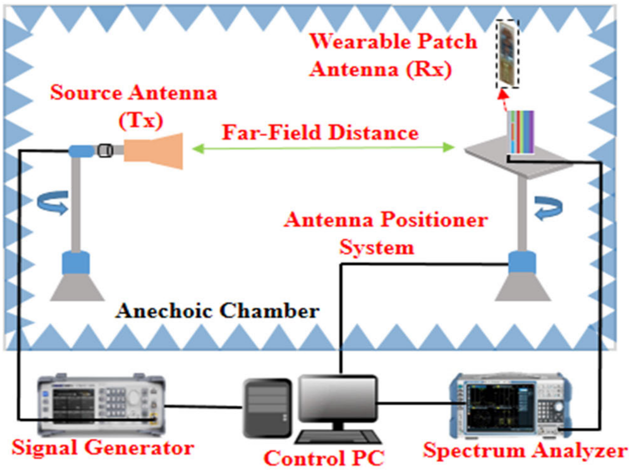


FIGURE 15. Schematic of far-field measurement set-up in an anechoic chamber, where AUT (proposed wearable patch) resides on the customized tissue mimicking four-layer phantom.

which emulates the skin-fat-muscle-bone tissue culture to mimic the rough approximation of on-wrist configuration (same as simulation enclosure). The phantom recipe formulation is referenced from the co-author's [37] but for this measurement setup the ingredients' proportion is scaled to obtain the average electrical properties in the UWB spectrum (3.1 – 10.6 GHz). The relative permittivity and conductivity of the tissue phantom is measured by dielectric probe (open ended high temperature probe) measurement kit (Keysight's 85070E). The total gain of the proposed wearable patch is shown in Fig. 14(c). The simulated and measured gain curves of the reported antenna are comparable and showing exponential increment throughout the frequency band. At 10.4 GHz, peak gain of 4.2 dBi, whereas, at 3.8 GHz lowest gain of 0.3 dBi is observed. This exponential behavior of the gain curve is believed to be activated due to the radiation from different surface areas on the antenna.

As evident from Fig. 8, currents with varying intensities are localized on different surface areas at different modes throughout the UWB spectrum. Fig. 16(a-b) outlines the simulated far-field radiation characteristics (gain) of the proposed on-body antenna system in the absence of integrated circuitry. Noted, gain $\boldsymbol{\Phi}(\boldsymbol{\Phi} = 0°)$ and gain $\boldsymbol{\theta}(\boldsymbol{\Phi} = 90°)$ are the co-polarized, whereas gain $\boldsymbol{\Phi}(\boldsymbol{\Phi} = 90°)$ and gain $\boldsymbol{\theta}(\boldsymbol{\Phi} = 0°)$ are the cross-polarized patterns. Without circuitry, radiation of the proposed antenna is bidirectional. Fig. 16(c-d) outlines the comparison of simulated and measured co-polarized far-field radiation characteristics (received power) of the proposed on-body antenna system in the presence of integrated circuitry, in both E-plane ($\boldsymbol{\Phi} = 0°$) and H-plane ($\boldsymbol{\Phi} = 90°$); at two different frequencies within the achieved UWB spectrum. Circuitry is acting as a reflector and thus, maximum radiation is in the broadside direction ($°\boldsymbol{\theta} = \mathbf{0}$).

V. SPECIFIC ABSORPTION RATE

The proposed on-body antenna is designed to operate just above the bare skin of the human body; thus, the

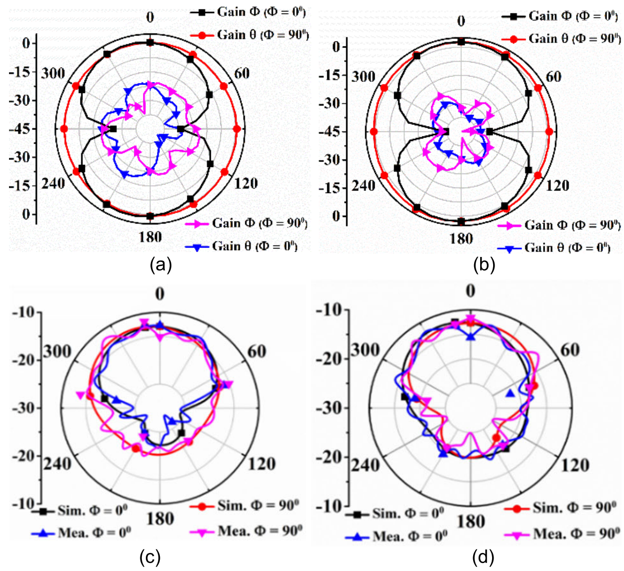


FIGURE 16. Far-field patterns at 5.8 GHz (left side) and 9.0 GHz (right side); (a-b) simulated co-pol. and cross-pol. patterns (gain) without circuitry, (c-d) comparison of simulated and measured co-pol. patterns (received power) with circuitry.

TABLE 3. Comparison of impedance bandwidth.

Sim. Enclosure	Free Space	Wrist	Bicep	Thigh
Sim. $\lvert S_{11}\rvert$ (GHz)	3.95-10.62	3.15-10.55	3.16-10.12	3.01-10.21
Meas. $\lvert S_{11}\rvert$ (GHz)	3.9-10.59	3.34-10.51	3.31-9.98	3.07-10.24

EM radiations of the antenna could raise the temperature of the circumambient tissue cells and pose the life-threatening issues. The dosimetry quantity, specific absorption rate (SAR) quantifies the rate of EM radiations exposed to the body. In this work, the average SAR (ASAR) is evaluated numerically in the simulator when the prototype (antenna without integrated circuit) is placed just above (no gap) the bare skin of the anatomical HFSS model (wrist, biceps, thighs). Noted, the comparative analysis is also done with the 0.25 mm gap to account for the presence of fabric layer ($\boldsymbol{\varepsilon}_r = 1.0 – 2.1$) between the skin surface and the wearable prototype. In this regard, the ASAR calculation for the suggested antenna is performed at the central frequency of the targeted ultra-wideband (5.8 GHz) based on the anatomical model, consisting of tissue layers: skin, fat, muscles, and bone. As the typical wearable devices could be delivered maximum input power of 50 mW, therefore, for the on-wrist scenario (no gap case) the simulated 1-g and 10-g ASAR value is 1.99 W/Kg and 1.56 W/Kg respectively. The ASAR distribution on human wrist is shown in Fig. 17(a-b). For on-biceps and on-thighs case, SAR distribution is not shown for brevity but, the calculations are summarized in Table 4. The tabulated data shows that the thigh tissues are highly penetrated by the EM radiations, thereby, gives the highest ASAR values.

As per the IEEE, FCC, and ICNIRP guidelines [26], ASAR is restricted to 1.6 W/Kg and 2 W/Kg for 1 g and 10 g

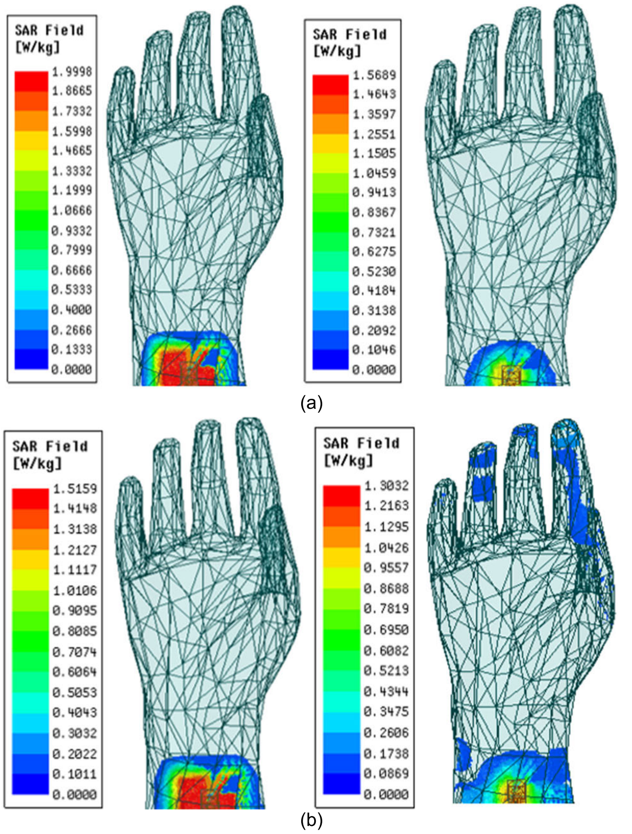


FIGURE 17. Simulated ASAR distribution at 5.8 GHz for the on-wrist scenario, (a) no gap, and (b) 0.25 mm gap case.

of cubic tissue, respectively. To meet such guidelines, max. input power that could be delivered to the proposed antenna are given in Table 4 for thigh tissues. As the transmitter power delivered to the wearable devices is in the order of 0.1 mW [38] which is even less than 1% of the maximum input power (see Table 4) needed for the proposed wearable antenna to reach the SAR limits. Therefore, the reported antenna can be a strong contender for practical use in wearable wireless systems operated within the UWB frequency bands.

TABLE 4. SAR values for different body parts.

Body Parts			Wrist	Biceps	Thigh	Input Power
SAR (W/Kg)	Gap (0 mm)	1-g	1.99	1.96	2.04	78.43
		10-g	1.56	1.51	1.62	123.45
	Gap (0.25 mm)	1-g	1.51	1.49	1.57	101.91
		10-g	1.30	1.27	1.44	138.88

Max. input power: mW (values given for only thigh tissues for briefness).

VI. CONCLUSION

Ultra-miniaturized umbrella-shaped UWB antenna bearing body-worn wearable patch has been designed and fabricated in this paper for health care monitoring applications. Based on the principle of characteristics mode theory, wideband behavior has been studied. The performance has been examined in terms of resonating frequency, operating bandwidth, average SAR, surface current distribution, radiation pattern, and gain. Further, parametric studies regarding robustness of the proposed wearable patch has also been carried out to monitor the sensitivity issues. It is concluded that the reported antenna is ultra-compact and has flexible geometry that can easily adapt to the curvature of the human body. Such wearable characteristics render the reported prototype an excellent candidate for e-healthcare monitoring applications in both indoor and outdoor environments.

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(Sumon Modak and Vikrant Kaim are co-first authors.)

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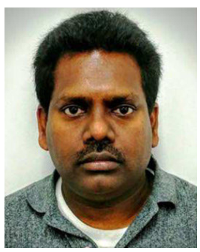

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