

Flexible Conformal Textile-Based ETSRP Wearable Antenna for Wireless and Biomedical Applications

Yarram Uma Maheswari and Bappadittya Roy*

School of Electronics Engineering, VIT-AP University, Inavolu, Andhra Pradesh 522241, India

ABSTRACT: This paper presents a low-profile, flexible, and wideband conformal wearable antenna for biomedical and wireless applications, including Internet of Things (IoT). The proposed antenna is based on an edge-truncated and slotted rectangular patch structure (ETSRP) developed on a jeans textile substrate, with compact overall dimensions of $0.163 \times 0.269 \times 0.006\lambda^3$. The antenna offers a peak gain of 6.3 dBi with an impedance bandwidth of 2.32 GHz to 8.84 GHz, corresponding to a fractional bandwidth of 116.5%, with a reflection coefficient (S_{11}) of -42.4 dB covering the ISM bands. The antenna's performance was evaluated using a human phantom and showed minor frequency detuning across different placement conditions. The specific absorption rate (SAR) was evaluated at 2.45 GHz and 5.8 GHz, with values of 0.7 W/kg and 0.8 W/kg, respectively, which are within accepted safety limits. The measured results were in good agreement with the simulated results in terms of impedance bandwidth, gain, and resonance characteristics. The proposed textile antenna offers wideband operation, low SAR, and compact size, making it suitable for wearable biomedical devices and IoT-based on-body communication systems.

1. INTRODUCTION

Wearable antennas for biomedical applications have gained significant attention due to their integration with wireless communication and healthcare technologies. These antennas are integrated into clothing or accessories, allowing continuous, noninvasive health monitoring in a comfortable, low-profile manner. The main design requirements include flexibility, lightweight structure, biocompatibility, and stable performance under a complex electromagnetic environment around the human body. In addition, these radiators must withstand body movements and environmental effects such as moisture while minimizing signal loss and interference, making them suitable for various healthcare applications, as illustrated in Fig. 1.

Several studies have focused on the growth of flexible and wearable antennas for wireless communication and wireless body area network (WBAN) applications. In [1], a rectangular patch antenna with triangular notches and a slot was built to enhance impedance matching and radiation performance. A millimeter-wave super-wideband antenna operating from 24 to 64 GHz was reported in [2], in which bending effects, human body interaction, and SAR were investigated. In [3], a flexible two-element multiple-input multiple-output (MIMO) antenna was designed for Wi-Fi 7 and 5G systems, achieving good isolation using a complementary split-ring resonator. A comb-shaped antenna operating at 2.45 GHz was presented in [4], and its performance under conformal conditions was studied while maintaining SAR within IEEE limits. In [5], a compact textile penta-band antenna was developed for off-body communica-

tion, indicating stable radiation characteristics and acceptable SAR performance.

Fabric-based and textile antennas have also been widely explored for WBAN systems. In [6], a textile ultra-wideband (UWB) MIMO antenna supporting worldwide interoperability for microwave access (WiMAX), wireless local area network (WLAN), and industrial, scientific, and medical (ISM) bands was presented with good isolation and acceptable SAR levels. A metamaterial-based textile antenna was proposed in [7] to enhance near-field coupling while suppressing far-field radiation, thereby better communication security. In [8], an antenna integrated with an artificial magnetic conductor (AMC) was developed to minimize surface waves and enhance bandwidth and gain. A circularly polarized broadband fabric-based antenna with a metasurface structure was reported in [9] for WBAN applications. Similarly, [10] presented a cavity-backed substrate-integrated waveguide (SIW) textile antenna operating at the 2.45 GHz ISM band, in which fractal slots were used to reduce size and improve isolation from the human body.

Further research has focused on polarization control and filtering characteristics. In [11], a reconfigurable coplanar waveguide (CPW)-fed metasurface antenna was developed for WBAN systems using PIN diodes for polarization switching. In [12], a flexible filtering antenna with steady on-body performance was introduced under bending conditions. In [13], a dual-mode and dual-polarized textile antenna operating at 2.45 GHz and 5.8 GHz was designed for both on-body and off-body communication. A flexible two-port MIMO antenna incorporating a frequency-selective surface (FSS) was described in [14] to improve gain and isolation while maintaining low SAR. Additionally, [15] presented a triangular bowtie textile

* Corresponding author: Bappadittya Roy (bappadittya.roy@vitap.ac.in).

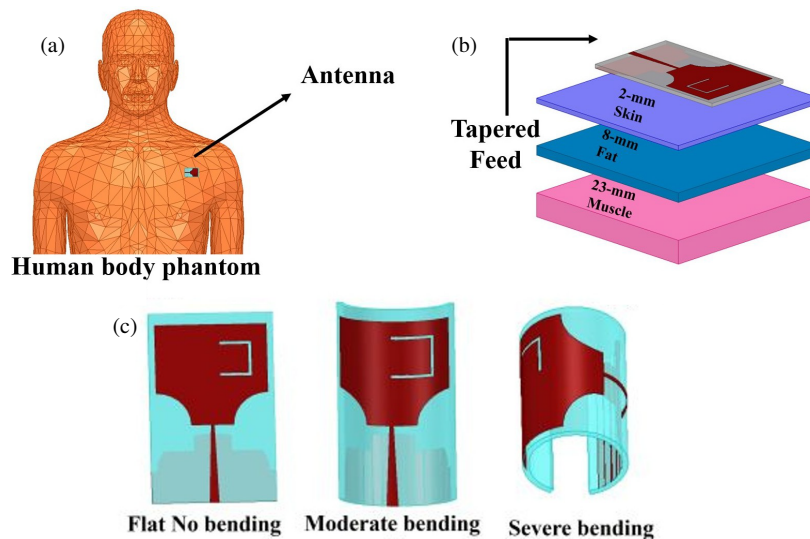


FIGURE 1. Wearable antenna evaluation under realistic conditions: (a) on-body placement on a human body phantom, (b) multilayer tissue model made up of skin, fat, and muscle, and (c) antenna behavior under flat, moderate, and severe bending conditions.

antenna employing jute material for ISM-band healthcare applications.

Recent studies have also focused on compact, flexible antennas intended for wearable use. In [16], a jeans-based antenna with a defective ground structure (DGS) was proposed to perform reliably under bending conditions while keeping SAR below 1.6 Watts/kg. In [17], a dual-band planar antenna operating at 2.4 GHz and 5.8 GHz was presented, where both bands were independently controlled using an electromagnetic band gap (EBG) structure to achieve low SAR. A metasurface-based antenna supporting tri-band and tri-polarization operation for body-centric communication was reported in [18].

Other compact antenna designs have also been investigated for wearable systems. In [19], a diamond-shaped patch antenna was designed by rotating a square patch to increase the current path and achieve wideband operation. In [20], a UWB MIMO antenna was developed incorporating split-ring resonators and a DGS to enhance bandwidth and gain. In [21], an SRR-based antenna was designed for on-body communication covering UWB, ISM, and medical body area network (MBAN) bands for medical monitoring. Finally, in [22], compact UWB textile antennas were reported with wide bandwidth and acceptable SAR performance for wearable IoT applications.

Although significant progress has been made in wearable antenna technology, several challenges remain. Many existing designs suffer from impedance mismatch and radiation degradation under bending and body movement due to variations in current distribution. In addition, most textile antennas are limited to narrowband or dual-band operation, limiting their use in wideband biomedical communication systems. Achieving low SAR and substantial gain often requires multilayer structures, AMC, EBG structures, or shielding elements, which increase fabrication complexity and reduce the flexibility and the wearer's comfort.

To address these challenges, this work proposes a compact, fully flexible wearable antenna for biomedical and body-centric wireless communication applications. The antenna is

designed on an inexpensive jeans textile substrate, providing a lightweight and conformal structure suitable for garment integration. An edge-truncated rectangular monopole with an inverted C-shaped slot, a partial defected ground structure, and a tapered feed is employed to improve surface current distribution and achieve wideband impedance matching. Unlike existing approaches, the proposed antenna avoids using complex multilayer configurations or additional structures, such as AMC, EBG, or shielding layers, maintaining structural simplicity and flexibility. The antenna performance is evaluated under free-space, bending, and on-body conditions, demonstrating consistent radiation properties and low SAR, which makes it suitable for practical wearable healthcare and biomedical monitoring applications.

2. DEVELOPMENT AND ANALYSIS FRAMEWORK

2.1. Configuration and Design Methodology of the Antenna

The proposed antenna is designed to improve impedance bandwidth and mechanical durability for wearable biomedical applications. It is fabricated on a jeans textile substrate with an overall size of $0.163 \times 0.269 \times 0.006\lambda^3$, having a dielectric constant of $\epsilon_r = 1.7$ and a loss tangent of $\tan \delta = 0.085$, as

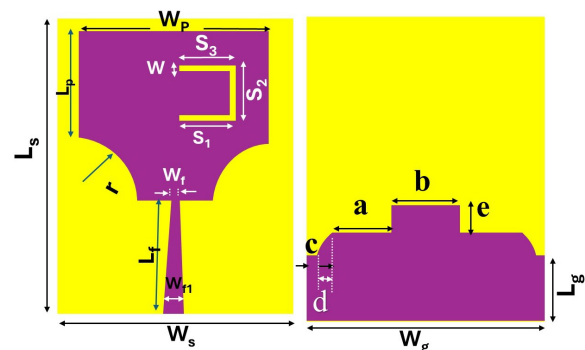


FIGURE 2. Structure of the antenna showing the front and back views.

shown in Fig. 2. The antenna geometry is based on a patch with concave edge truncations and a tapered feed, incorporating an inverted C-shaped slot. The refined design parameters of the proposed wideband (WB) radiating element are listed in Table 1. The radiator consists of a feed line, an inverted C-shaped slotted radiating patch, and a ground structure. The tapered feed provides a smooth impedance transition, thus improving impedance matching and achieving wideband performance. The proposed antenna is designed and simulated using Ansys High Frequency Structure Simulator (HFSS) 2021 R2.

TABLE 1. Optimized antenna design parameters.

Parameters	Dimensions (mm)	Parameters	Dimensions (mm)
L_s	33	W_{f1}	0.5
W_s	20	L_g	20
L_p	17.5	W_g	5.5
W_p	18	S_1	6
L_f	13.5	S_2	6
W_f	1.48	S_3	6
r	5	b	6
a	4.8	c	0.5
d	1	e	1.5
L_{eff}	20	W	0.5

The flowchart shown in Fig. 3 illustrates the systematic design and validation procedure. Initially, the electromagnetic properties of the flexible substrate are characterized. The operating frequency and antenna dimensions are then determined based on application requirements. The dielectric gap is adjusted to optimize the matching, gain, and radiation efficiency. If the performance criteria are not satisfied, iterative optimization is performed. Once the desired performance is achieved, the antenna is fabricated and tested experimentally. Finally, on-body performance analysis is conducted, and the results are documented.

2.2. ETSRP Antenna Design for Wideband Operation

The edge truncated and slotted rectangular patch (ETSRP) antenna has evolved with a partial ground surface, as illustrated in Fig. 4. The design evolution of the proposed ETSRP is illustrated in Fig. 4. Antenna 1 (Fig. 4(a)) represents a conventional rectangular radiating element with a full ground plane and serves as the reference configuration. The feed is placed at the center to achieve $50\ \Omega$ impedance matching. In Antenna 2 (Fig. 4(b)), the ground plane is modified to a partial configuration, resulting in improved impedance matching and a change in the resonant frequency. In Antenna 3 (Fig. 4(c)), an elliptical groove is introduced beneath the radiating patch, and the lower edges are truncated with a radius of 5 mm. These modifications increase the effective current path and improve bandwidth performance. Further enhancement is achieved in Antenna 4 (Fig. 4(d)) by incorporating curved rectangular slots and a stub in the ground plane, forming a defected ground structure (DGS) that introduces additional resonances. Finally, in An-

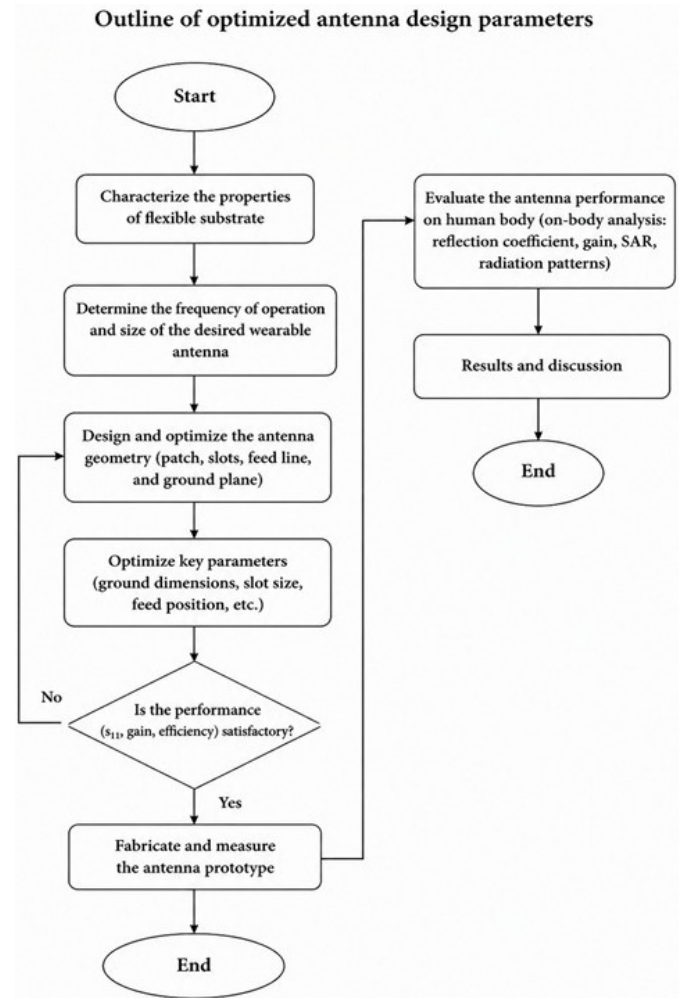


FIGURE 3. The antenna simulation flowchart in HFSS.

tenna 5 (Fig. 4(e)), an inverted C-shaped slot is engraved on the radiating patch, resulting in the proposed ETSRP antenna. This configuration provides significantly improved impedance bandwidth and gain as a result of the combined effects of current path extension and slot-induced resonance.

3. SIMULATION-BASED PERFORMANCE ANALYSIS

This section discusses the results obtained for the antenna developed in this work and compares their performance using evaluation metrics. It also includes free-space analysis to evaluate basic performance, examines design variations, performs parametric and SAR analysis for safety, and evaluates bending performance under different deformation conditions.

3.1. A Free-Space Antenna Analysis

The simulated reflection coefficients (S_{11}) for Antenna 1 to Antenna 5 are illustrated in Figs. 5(a) and (b). They show that impedance bandwidth and gain improve progressively, making the antenna capable of wideband wearable purposes, including the ISM bands. The reference antenna (Antenna 1) resonates at higher frequencies, from 11.57 to 11.86 GHz, and has a very narrow impedance bandwidth of about 2.5%,

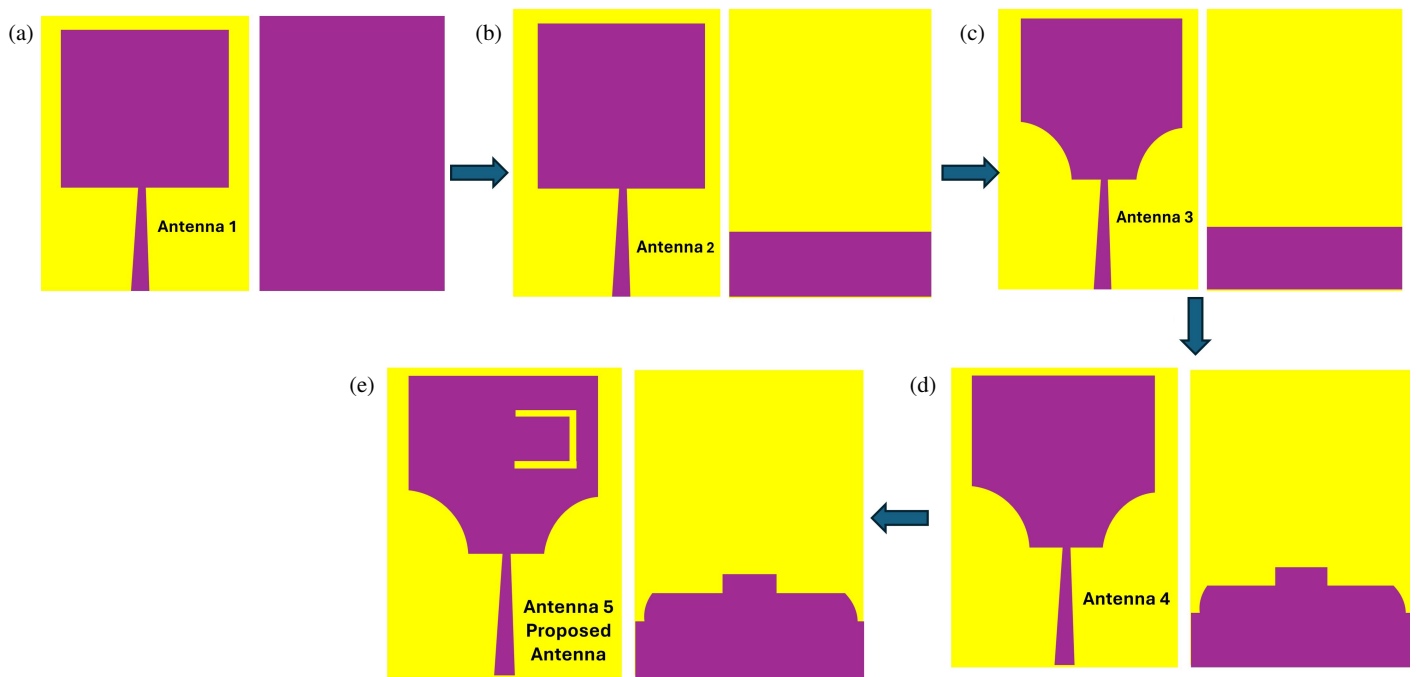


FIGURE 4. (a) Conventional rectangular monopole reference geometry, (b) rectangular radiator with ground modification, (c) edge-truncated radiating structure, (d) electrically extended radiator achieved through edge truncation, and (e) final optimized wearable antenna incorporating a slot.

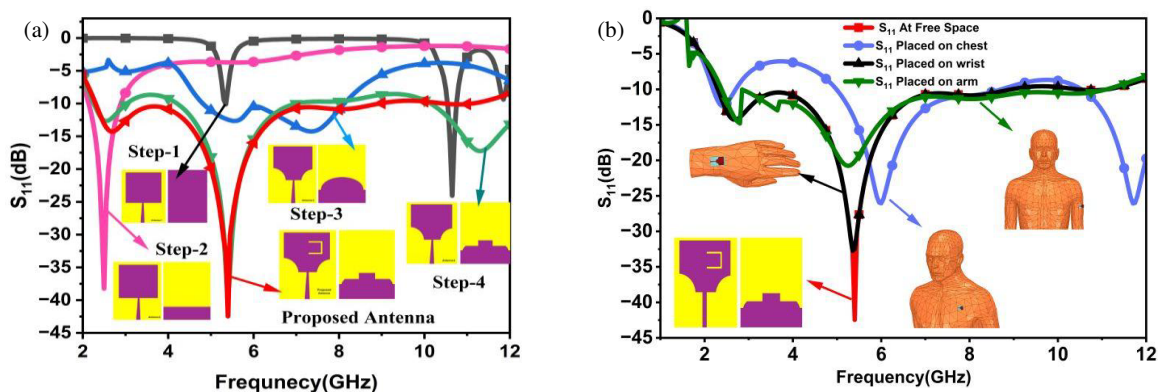


FIGURE 5. (a) Simulated S_{11} -parameter response for design variation evolution stages of the proposed antenna, illustrated impedance matching improvement and (b) comparison of (S_{11}) characteristics in free space and under on-body conditions (wrist, arm, and chest), demonstrating stable performance.

which makes it unsuitable for wearable devices using the ISM band. Antenna 2 moves its resonance to the 2.18–2.80 GHz range by changing the ground plane to a partial configuration. This yields an impedance bandwidth of about 25% centered near 2.45 GHz. Adding an elliptical ground slot and cutting off the edges of the radiating patch on Antenna 3 makes the impedance bandwidth much wider, ranging from approximately 51% (4.82 to 8.12 GHz). Antenna 4 has dual-band behavior because it has rectangular curved slots and a ground stub. The lower band (2.26–3.02 GHz) has an impedance bandwidth of approximately 29% around 2.45 GHz, and the upper band (4.2–6.97 GHz) has a bandwidth of approximately 49% around 5.8 GHz. The final ETSRP antenna (Antenna 5) has an impedance bandwidth of almost 116.84% (2.32–8.84 GHz) because it has an inverted C-shaped slot etched into the radiating patch. This fully covers both the 2.45 and 5.8 GHz ISM bands.

The gain also improves, going from 0.6 to 1.8 dBi at 2.45 GHz and reaching 6.3 dBi at 5.8 GHz. These results show that the proposed ETSRP antenna has better impedance matching and radiation performance, as observed in Table 5, making it suitable for wideband wearable applications covering ISM bands. The reflection coefficient (S_{11}) of the proposed antenna in free space and under different conditions on the body are compared, including placement on the wrist, arm, and chest in Fig. 5(b).

The performance illustrates that the antenna maintains good impedance matching across the operating band, with only minor frequency shifts due to proximity to the body. The stable reflection coefficient ensures radiator performance when placed on the human body, demonstrating its suitability for on-body applications. Table 2 summarizes the reflection coefficients for the proposed ETSRP antenna under various body conditions.

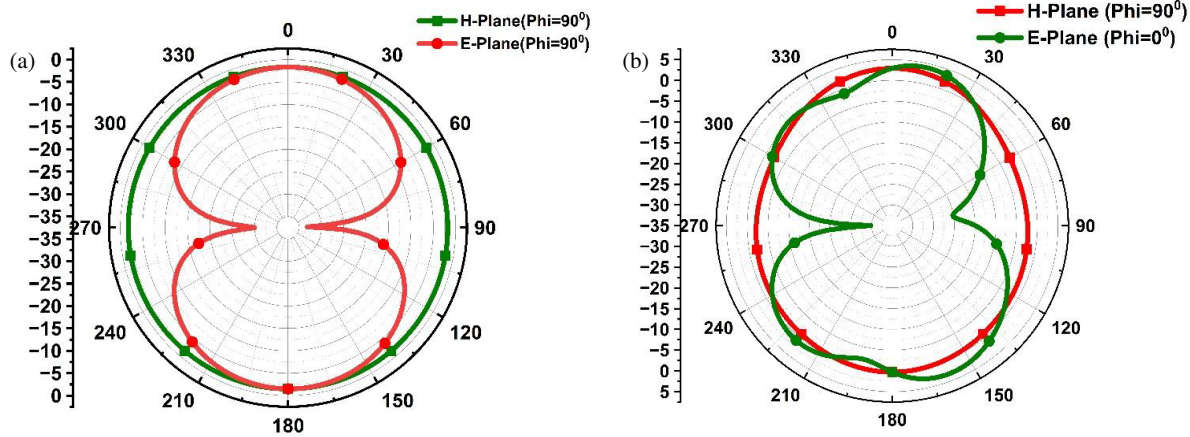


FIGURE 6. 2D radiation patterns of the antenna at (a) 2.45 GHz and (b) 5.8 GHz.

TABLE 2. On-body S_{11} performance of the proposed ETSRP antenna.

Antenna Placement	Band (GHz)	S_{11} (dB)
Free space	2.32, 5.8	-42.2
Chest	2.45, 5.8	-25.23
Wrist	2.45, 5.8	-30.14
Arm	2.45, 5.8	-20

The antenna demonstrates acceptable impedance matching in the 2.45 GHz and 5.8 GHz ISM bands across all tested placements, which was placed on the chest, wrist, and arm. Only minor variations are observed in the minimum values S_{11} due to body-loading effects, indicating stable body operation suitable for wearable electronic systems.

2D radiation patterns of the reported ETSRP radiator in the E -field ($\phi = 0^\circ$) and H -plane ($\phi = 90^\circ$) at 2.45 GHz are represented in Fig. 6(a). The H field exhibits quasi-omnidirectional radiation suitable for body-centric wireless communication, and the E field shows a bidirectional pattern, characteristic of monopole-type antennas. Fig. 6(b) presents the corresponding radiation patterns at 5.8 GHz, where a similar radiation trend is maintained with slightly increased pattern distortion due to higher-order modes and substrate effects. Despite these variations, the antenna ensures stable radiation behavior in both principal planes. The suggested radiator achieves a peak gain of 6.3 dBi, confirming effective radiation performance across the ISM bands.

The moderate gain at 2.45 GHz is attributed to quasi-omnidirectional radiation, while radiation efficiency remains high due to minimal dielectric loss and effective ground isolation, as shown in Fig. 7(a). At 2.45 GHz, the gain increases from approximately 0.6 dBi in Step-1 to 0.3 dBi in Step-2 and 0.8 dBi in Step-3, followed by significant enhancement to approximately 1.7 dBi in Step-4. The final ETSRP antenna achieves a peak gain of nearly 1.8 dBi, which is suitable for short-range, low-power real-time wearable biomedical communication. A similar improvement is observed at 5.8 GHz, where the gain is improved from around 2 dBi in the initial design to 3.8 dBi in Step-4, reaching nearly 4 dBi in the suggested antenna. At 5.8 GHz, the gain is further enhanced from nearly

3.7 dBi to about 6.3 dBi in the final configuration. Fig. 7(b) illustrates the variation of realized gain across frequencies for successive design stages. The antenna exhibits higher gain at lower frequencies, which is more suitable for real-time biomedical sensing, patient monitoring, and body-centric data transmission. As the operating frequency increases, a gradual reduction in gain is observed as a result of the excitation of additional resonant modes and increased dielectric and conductor losses, which reduce radiation efficiency. Incorporating the inverted C-shaped slot in the final design effectively improves both gain and impedance bandwidth, particularly in the upper frequency, compared with earlier configurations. The reported antenna achieves a radiation efficiency of 88% in the operating band, while maintaining a moderate-to-high radiation efficiency (70–85%), considering textile losses within the primary ranges of the wearable biomedical frequencies depicted in Fig. 7(c). This high efficiency ensures reliable real-time wireless data transmission with low power loss, indicating that the antenna is suitable for wearable biomedical devices such as health-monitoring sensors, body communication, and continuous patient care systems.

The simulated electric-field vector distribution of the ETSRP antenna at operating frequencies is illustrated in Fig. 8. The arrows represent the surface current density (J_s), where the direction indicates current flow and the length of the arrow represents the magnitude, while the color bar corresponds to the intensity of the electric field ($|E|$ in V/m) shown in Fig. 8(a).

The vectors propagate from the feed to the radiating patch and extend to the truncated edges, indicating the flow of electromagnetic energy across the patch surface. The magnitude of the electric field in this case varies approximately from 24.40 V/m to 12,662.64 V/m. This distribution supports stable radiation at the fundamental resonant frequency. At 5.8 GHz, the electric field vectors spread over a larger portion of the radiating patch, as illustrated in Fig. 8(b). An increased electric-field intensity is observed around the inverted C-shaped slot, indicating the excitation of a higher-order resonant mode. The electric-field magnitude ranges approximately from 54.54 V/m to 24,985.61 V/m. The slot modifies the electromagnetic (EM) distribution, indicating the excitation of a higher-order resonant mode. The electric field magnitude ranges approximately from 54.54 V/m

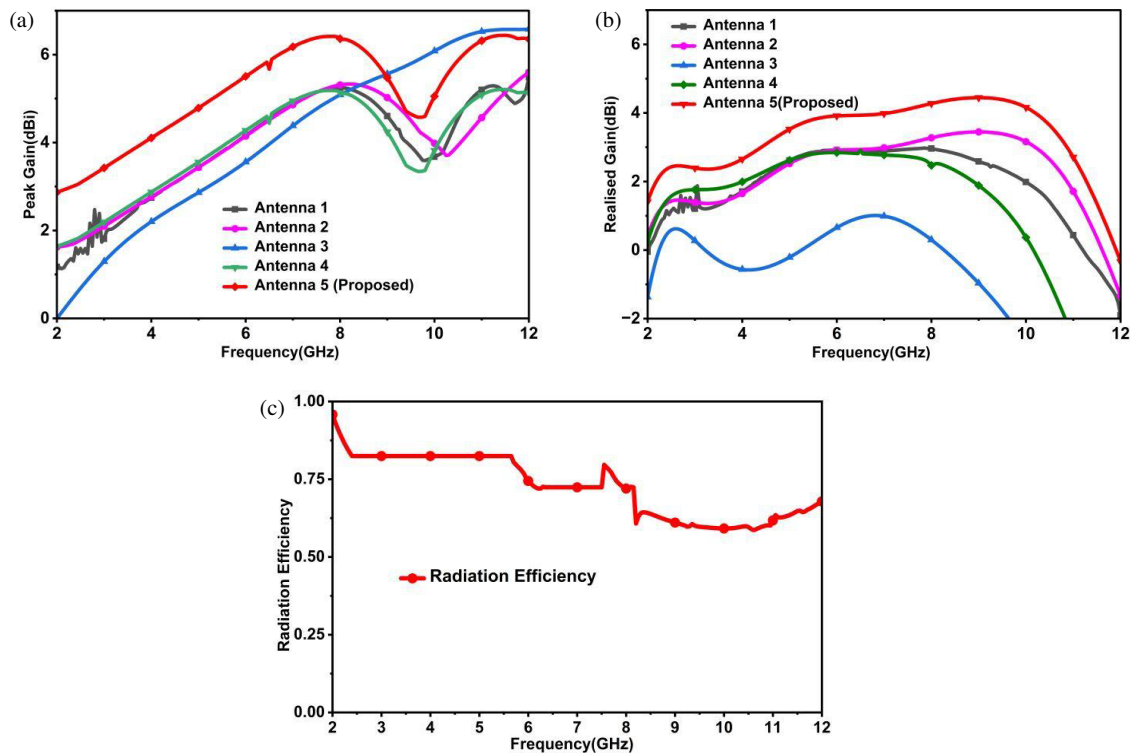


FIGURE 7. (a) Peak gain, (b) realized gain, and (c) radiation efficiency of the ETSRP antenna.

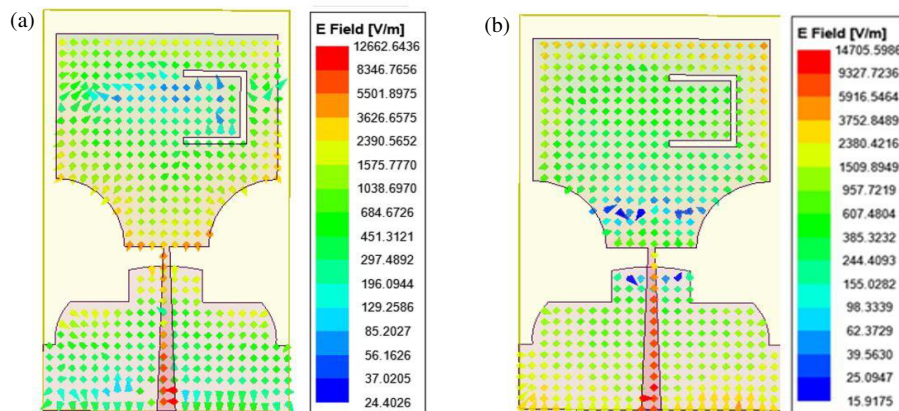


FIGURE 8. Vector current distribution of the proposed ETSRP antenna at (a) 2.45 GHz and (b) 5.8 GHz.

to 24,985.61 V/m. The slot modifies the EM distribution and contributes to improved impedance characteristics. Lower field magnitudes are observed in the non-radiating regions, showing efficient radiation from the main patch.

The 3D radiation pattern, which exhibits omnidirectional characteristics, ensures uniform radiation across all directions within the specified plane. The analysis, in Fig. 9, shows that the ETSRP antenna achieves a maximum gain of 6.3 dBi. However, this gain may require further optimization to meet stringent performance requirements of advanced wearable applications, where higher gain and improved efficiency are critical to optimal functionality. For on-body applications, achieving a stable peak gain is essential for maintaining reliable communication and reducing signal loss caused by proximity to the human body.

3.2. Impact of Geometrical Parameters on Antenna Performance

The parametric investigation is performed to analyze how variations in key antenna dimensions affect impedance bandwidth and gain, which are critical to reliable performance in wearable and biomedical applications. The simulated reflection coefficient of the proposed antenna for different substrate materials is shown in Fig. 10. The antenna performance is studied using cotton, polydimethylsiloxane (PDMS), Bakharam, and jeans substrates. It can be seen that the substrate material has a noticeable effect on impedance matching characteristics. Among the considered materials, the antenna designed on the jeans substrate shows the deepest resonance, particularly near the 5.8 GHz band, indicating better matching than the other substrates. The Bakharam substrate produces a res-

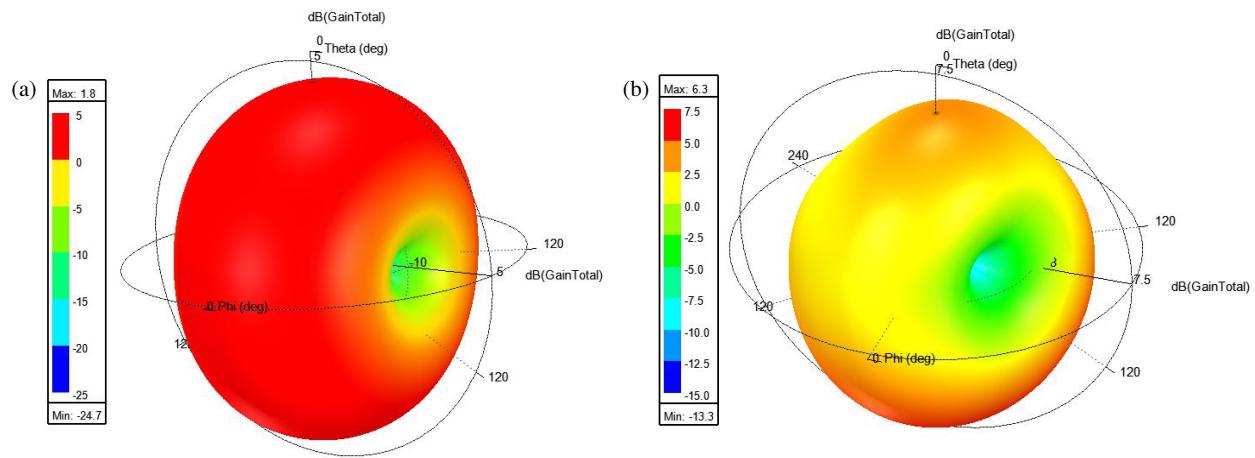


FIGURE 9. 3D radiation patterns of the reported radiator at (a) 2.45 GHz and (b) 5.8 GHz.

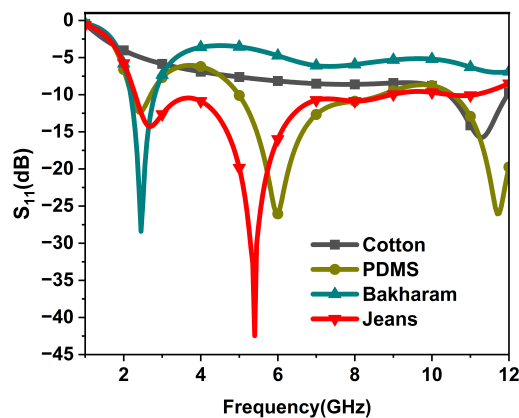


FIGURE 10. Simulated (S_{11}) characteristics of the proposed wearable antenna on different flexible substrates.

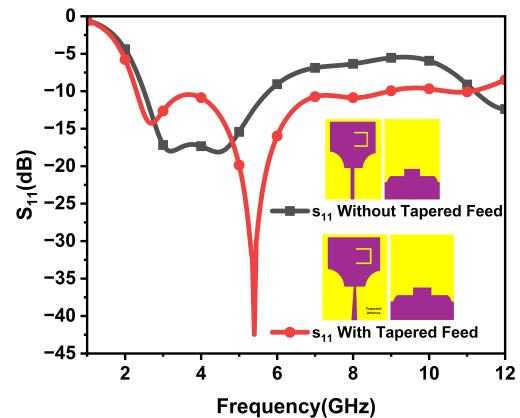


FIGURE 11. S_{11} parameter of ETSRP antenna with and without tapered.

onance around 2.45 GHz, while the PDMS substrate exhibits additional resonant behavior at higher frequencies. In contrast, the antenna with the cotton substrate has relatively shallow resonances in the operating range. Because of its stable impedance response and flexible nature, the jeans substrate is more suitable for WBAN applications.

Figure 11 presents the simulated S -parameter of the suggested ETSRP antenna with and without the tapered feed. The antenna has a narrow impedance bandwidth of 3 to 5 GHz and a minimum (S_{11}) of -17.34 dB when the tapered feed is not used. By incorporating a tapered feed, the impedance bandwidth is significantly extended from 2.3 to 8.84 GHz, achieving a deep resonance of -33.5 dB during the intermediate optimization stage before the final ETSRP configuration reached -42.4 dB. Improved impedance matching is observed in the 2.45 and 5.8 GHz ISM bands, which are widely used for wearable biomedical devices, WLAN, and short-range wireless communication systems. The tapered feed provides a smooth impedance transition that minimizes reflection losses, thereby improving power transfer efficiency and making the proposed antenna suitable for multi-band wearable and continuous health monitoring. Fig. 12 presents the simulated S -parameters of the proposed antenna for three slot positions: a slot in the center, a slot in the left orientation, and a slot in the right orientation. The

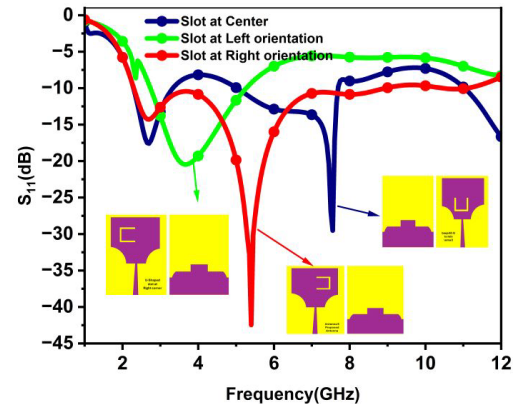


FIGURE 12. S -parameter characteristics of the ETSRP antenna for different slot positions.

results show that changing the slot position alters the antenna's resonant frequencies and impedance matching characteristics. The center-slot configuration produces a clear resonance in the higher-frequency region. When the slot is shifted to the left, the resonance shifts toward the lower-frequency band with moderate matching. The right-oriented slot provides a good reflection coefficient in the 5.8 GHz frequency range, indicating im-

proved impedance matching. This study confirms that the slot position plays a key role in tuning the antenna response. A parametric study is performed to further refine the antenna performance.

Figure 13 shows the reflection coefficient (S_{11}) of Antenna 5 for different values of gap parameter G , ranging from 1 to 3 mm. The results show that changes in G cause noticeable shifts in the resonant frequencies, thereby influencing the impedance match. For all evaluated cases, the values of (S_{11}) remain below -10 dB, indicating preferable impedance matching. Among the configurations considered, the gap value of $G = 2$ mm exhibits good performance, providing improved matching and a wider impedance bandwidth, as shown in Fig. 13. Therefore, this G value is selected for optimized antenna design, ensuring stable operation for wearable biomedical applications.

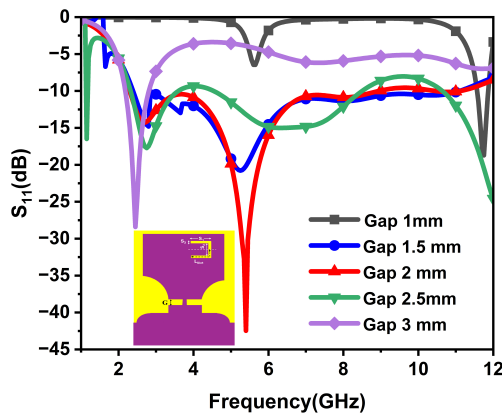


FIGURE 13. Parametric analysis gap between patch and ground.

Radiation pattern analysis compares components E_θ and H_ϕ for configurations of the slot at the left and right corners depicted in Fig. 14. In the E_θ plane, both configurations exhibit broad radiation, although the right slot demonstrates marginally higher gain than the left corner slot. In the H_ϕ plane, the right corner slot orientation shows more noticeable directional radiation with a well-defined dipole-like pattern, and the center slot provides symmetric H - and E -plane patterns with uniform gain distribution, while the left corner slot orientation produces a wider, less concentrated radiation pattern with lower gain. This highlights the good directional performance and enhanced radiation characteristics resulting from the orientation of the right-corner slot. The inverted C-shaped slot in the proposed antenna serves as a resonator, and its dimensions also play a crucial role in defining the resonant frequency. The metallic slots contribute to achieving a WB band by acting as resonating elements. The wave-length can be determined using the provided Eq. (1) [23]

$$\lambda = \frac{C}{f_r \sqrt{\epsilon_{eff}}} \quad (1)$$

In the proposed antenna design, the inverted C-shaped hole operates as a quarter-wavelength resonator ($\lambda/4$). The slot dimensions are denoted as S_1 , S_2 , and S_3 for its segments, along with its width playing a critical role in determining the antenna's resonant frequency (f_r). The resonant frequency can be approxi-

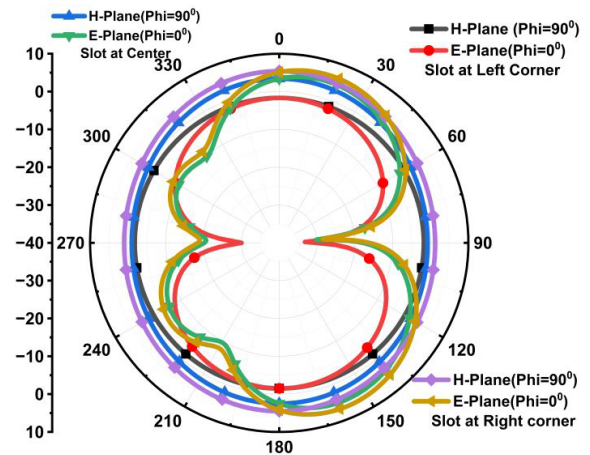


FIGURE 14. 2D far-field patterns of the ETSRP proposed antenna U-slot with different slot orientations.

mated using the following Eqs. (2) and (3) [23].

$$f_r = \frac{C}{4 \times L_{eff} \sqrt{\epsilon_{eff}}} \quad (2)$$

$$\epsilon_{eff} = \frac{(\epsilon_r + 1)}{2} \quad (3)$$

The symbol “ c ” represents the speed of light in free space (3×10^8 m/s). The effective permittivity of the substrate is denoted by ϵ_{eff} . For a resonant frequency of 2.45 GHz, the slot length (L_{eff}) is defined as λ to achieve optimal compactness and effective impedance tuning. Taking into account the speed of light (c) and the relative dielectric permittivity of the substrate (ϵ_r), L_{eff} is calculated as 24 mm. After varying several design parameters to achieve the desired WB performance, the values of S_1 , S_2 , S_3 , and W are finalized as listed in Table 1. The physical length of L_{eff} , as shown in Fig. 15(a), can be expressed as

$$L_{eff} = (S_1 + S_2 + S_3) + 13.5 \times w \quad (4)$$

The calculated (L_{eff}) from Eq. (2) is approximately 24 mm, which closely matches the geometrically estimated slot by Eq. (4), where S_1, S_2, S_3 represent the primary slot path lengths, and each length is 6 mm. Due to tapered feed current spreading directly to the radiation boundary. The feed length (L_f) and slot width (w) are important and used to find the effective length. Thus, the total effective resonant length becomes $L_{eff} = (S_1 + S_2 + S_3) + L_f \times w$, which improves the estimation of the resonant path length and provides better agreement with the simulated operating frequency.

The ECM (Equivalent Circuit Modeling) of the developed antenna is represented in Fig. 15(b), where each structural element is represented by its corresponding electrical component. The radiating patch is modeled as an inductive element, as a result of the current flow along its surface, whereas the inverted C-shaped slot introduces a capacitive effect that improves impedance tuning. The DGS is represented by a parallel RLC network consisting of L_g , C_g , and R_g , which describes the stored magnetic energy, electric coupling, and radiation losses,

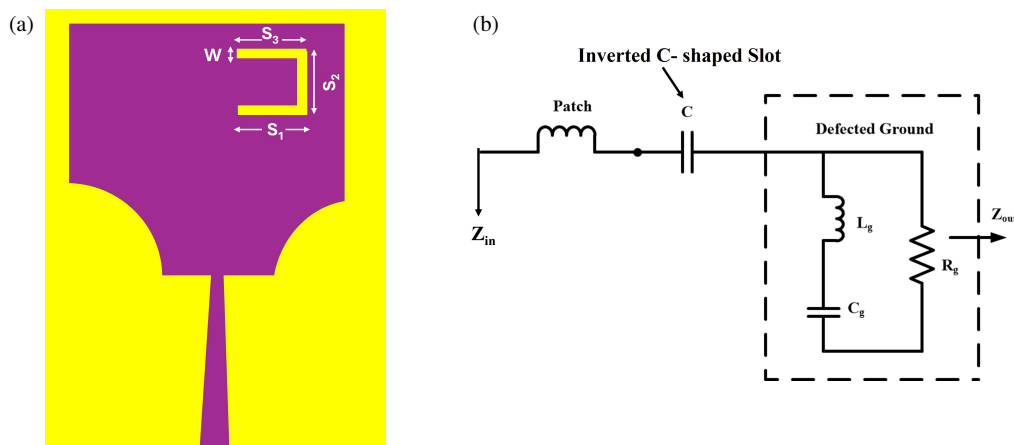


FIGURE 15. (a) Representation of slot length L_{eff} and (b) equivalent circuit model of the designed antenna.

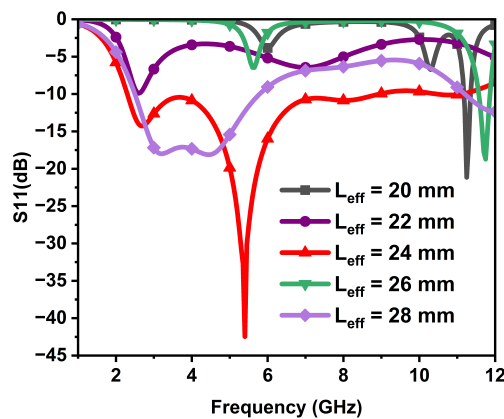


FIGURE 16. S_{11} variation with different L_{eff} .

respectively. The interaction of these inductive and capacitive elements produces multiple resonances around 2.45 GHz, 5.8 GHz, and 8.37 GHz, leading to the wide impedance bandwidth in the antenna.

The influence of effective slot length (L_{eff}) on the reflection coefficient of the proposed ETSRP antenna is illustrated in Fig. 16. It is observed that the variation in (L_{eff}) produces nonlinear resonance behavior due to the strong electromagnetic coupling between the slot, truncated edges, defected ground structure, and feed line. As L_{eff} increases from 20 to 28 mm, the resonant frequency decreases, indicating that a longer slot length enhances the effective current channel, thereby facilitating lower-frequency operation, ISM (2.45/5.8 GHz), WiMAX (2.5/3.5 GHz), LTE (2.3/2.5 GHz), exhibiting remarkable wideband efficiency. Furthermore, a larger L_{eff} impedance matching by reducing S_{11} values, enhancing wideband (WB) characteristics. In particular, optimal wideband performance is achieved when L_{eff} is set to 24 mm.

3.3. Textile Substrate and Its Impact on Antenna Performance

Textile antennas have emerged as a key enabling technology for wearable applications due to their inherent flexibility, lightweight nature, and seamless integration with clothing materials. These characteristics ensure high conformability to the

human body, thereby maintaining stable electromagnetic performance even under bending and deformation conditions. In Fig. 17(a), generally, textile-based antennas are also widely employed, particularly in wireless body area networks (WBANs), where they enable continuous health monitoring and real-time data transmission. Compact, low-profile, and highly suitable for next-generation healthcare systems, the proposed antenna is shown in Fig. 17(b).

3.4. Assessment of Antenna Performance under Bending

Bending analysis plays a crucial role in wearable antennas because they are designed to conform to the human body and experience continuous deformation. Bending impacts key antenna properties such as operating frequency and impedance match. Figs. 18(a)–18(b) present S_{11} of the radiating element in free space and under bending conditions.

HFSS was used to test how well the flexible antenna bent at angles of 30°, 45°, and 60°, along the E - and H -planes. The antenna exhibits stable performance in an empty space, with stable resonant frequencies of 2.45 GHz and 5.8 GHz and wide bandwidth spanning 2.5 to 6.8 GHz. This meant that it could be used for WBAN, continuous health monitoring, and other similar systems. At bends of 30° and 45° along the E -plane, the antenna barely changes its frequencies. A slight improvement in the reflection coefficient was observed, and the bandwidth remained nearly the same at 2.45 to 7 GHz. It shows the robustness of the radiator under moderate bending conditions, making it ideal for wearable use. At 60° bending, the antenna exhibited a shift in the lower band to 2.45 GHz with a bandwidth of 2.32 to 8.84 GHz. Despite these changes, it maintained good performance and stable operation in both bands. Similar behavior was observed with H -plane bending, where dual-band functionality was preserved with only moderate frequency variations. Overall, the antenna shows strong stability under moderate bending and retains operational capability even at extreme bending angles, making it well-suited for flexible and wearable applications.

The radiation characteristics of the proposed antenna under bending conditions are presented in Figs. 19(a), (b), (c), and

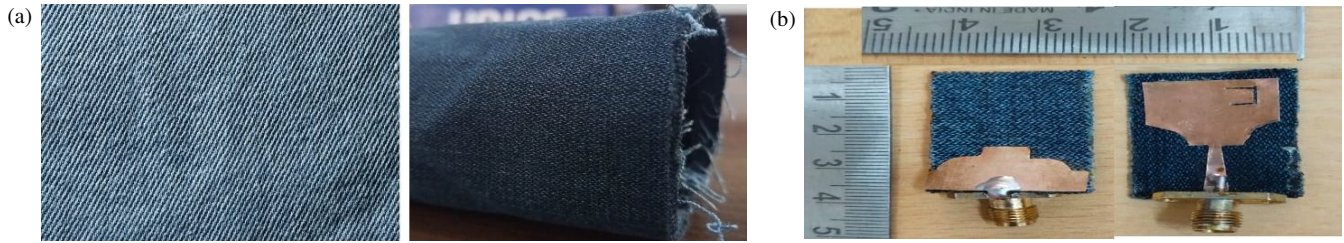


FIGURE 17. Proposed antenna: (a) substrate micro-image and (b) fabricated prototype (top and bottom layers).

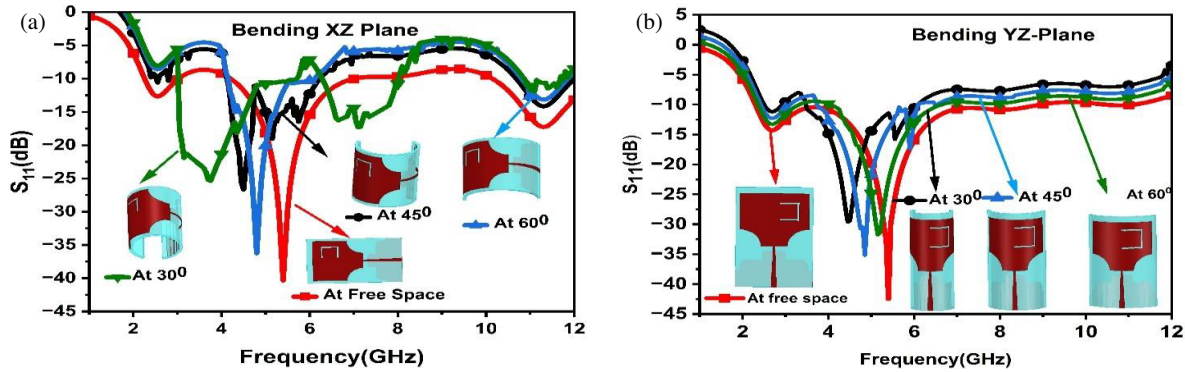


FIGURE 18. Return loss at various bending angles of the radiator (a) along the E -plane and (b) along the H -plane.

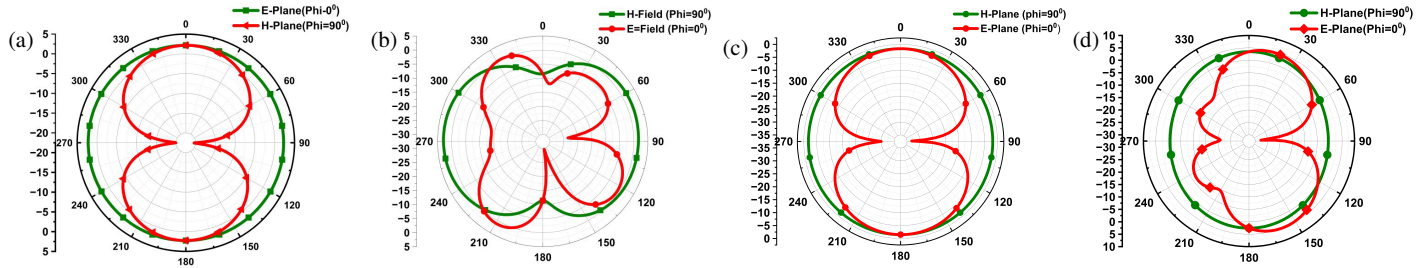


FIGURE 19. 2D radiation patterns of the designed antenna XZ -plane under bending at (a) 2.45 GHz and (b) 5.8 GHz and YZ -plane under bending at (c) 2.45 GHz and (d) 5.8 GHz.

(d) for the E -plane and H -plane at 2.45 GHz and 5.8 GHz. At 2.45 GHz, the H -plane maintains a near omnidirectional radiation pattern in both bending planes, while the E -plane exhibits stable bidirectional behavior with only minor distortion due to bending. At 5.8 GHz, small changes in the E -plane lobes are observed; however, the overall radiation pattern remains consistent. In both E - and H -plane bending conditions, the antenna maintains stable radiation characteristics within the operating bands, showing its suitability for wearable and biomedical purposes.

3.5. SAR Characteristics of the ETSRP Antenna

The Specific Absorption Rate (SAR) is defined [16] as the rate at which radio-frequency energy is absorbed per unit mass of biological tissue. The calculation is performed using Eq. (5).

$$\text{SAR} = \frac{\sigma E^2}{\rho} \left(\frac{\text{W}}{\text{kg}} \right) \quad (5)$$

where σ is the tissue's electrical conductivity (S/m); E is the electric field strength (V/m); ρ is the tissue density (kg/m^3). In HFSS simulations, SAR is evaluated by calculating the electric field around the antenna placed near human tissue, as illustrated in Figs. 21 and 22. The average SAR for a specific mass of tissue, say 1 gram or 10 grams, is

$$\text{SAR average}(r, \omega) = \frac{1}{v} \int \frac{\sigma(r, \omega) |E(r, \omega)|^2}{2\rho(r)} dV \quad (6)$$

Equation (6) ensures that the antenna operates safely near the human body (1.6 Watts/kilogram in the US and 2 Watts/kilogram in Europe).

The primary concern for WBAN antennas when placed near or on the body phantom is calculating the amount of radiation absorbed by surrounding tissues. This is quantified by the SAR, which measures the absorption extent of EM energy by human tissue. The SAR safety limit is 1.6 W/kg averaged over 1 g tissue (FCC) and 2 W/kg averaged over 10 g tissue (IEEE). To

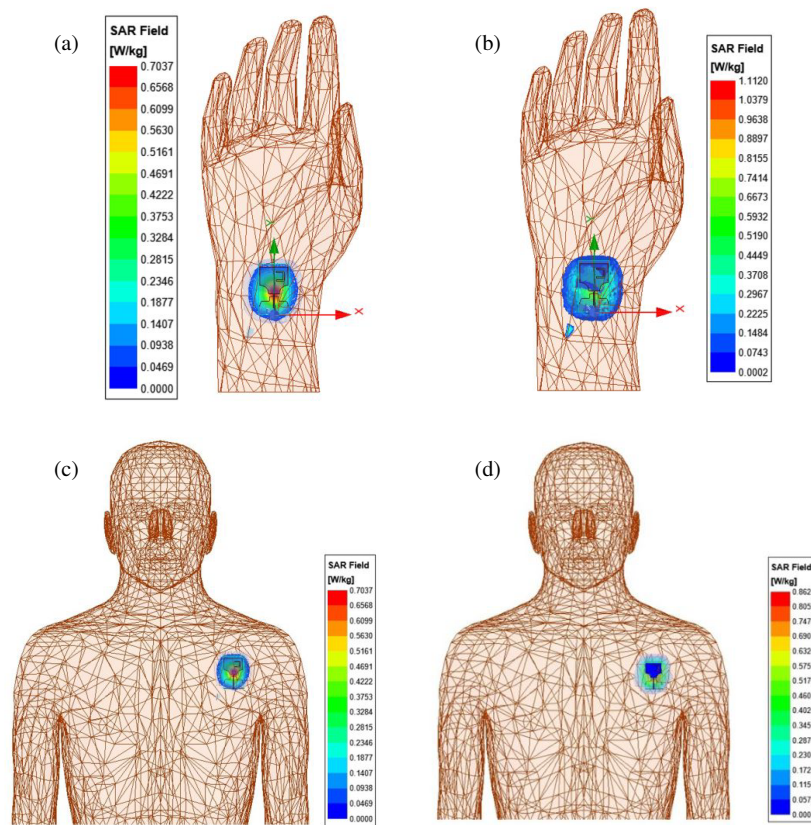


FIGURE 20. Simulated 1-g SAR distribution of the proposed antenna at (a) 2.45 GHz on hand and (b) 5.8 GHz on hand, (c) 2.45 GHz on chest, and (d) 5.8 GHz on chest.

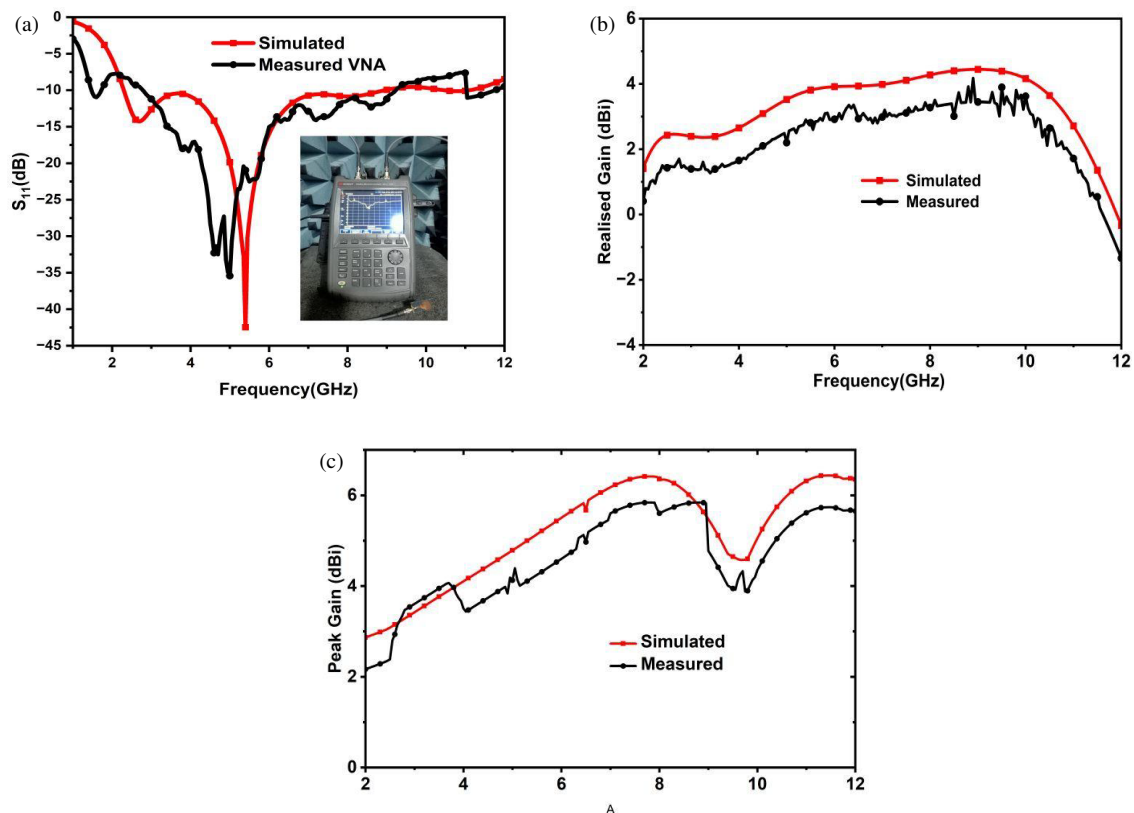


FIGURE 21. Simulated versus measured performance of the ETSRP antenna: (a) reflection coefficient S_{11} , (b) realized gain, and (c) peak gain characteristics.

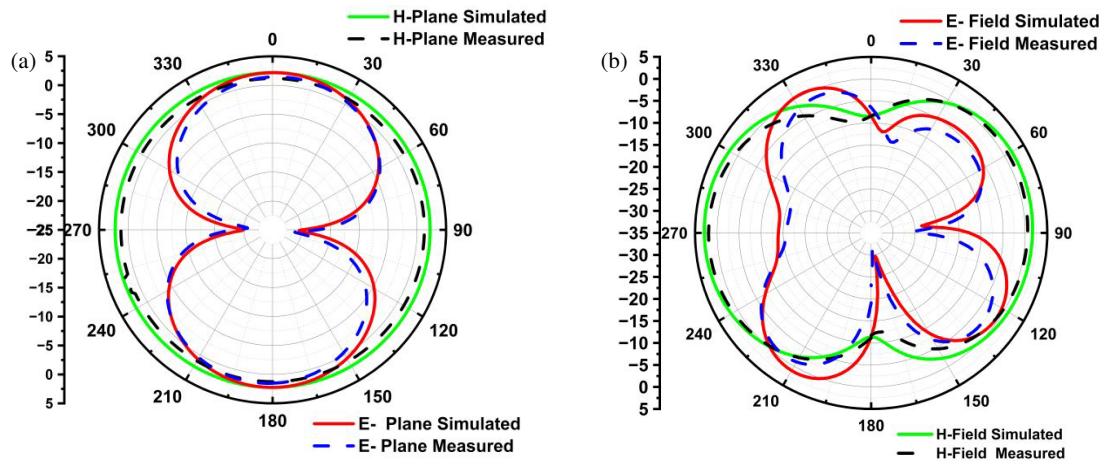


FIGURE 22. 2D far-field pattern *E*-plane: simulated versus measured results at (a) 2.45 GHz and (b) 5.8 GHz.

TABLE 3. Specifications of the human body tissue model.

Parameters	Skin	Fat	Muscle
Conductivity (S/m)	1.49	0.11	1.77
Density (kg/m ³)	1001	900	1006
Thickness (mm)	1	5	15
Permittivity (ϵ_r)	37.95	5.27	52.67

TABLE 4. Tissue thickness values of the human phantom model.

Body Location	Skin (mm)	Fat (mm)	Muscle (mm)
Wrist	4	10	11
Head	3.5	5	6
Chest	4.5	15	25

assess compliance, the antenna was simulated in a planar configuration on a human tissue model. As shown in Figs. 20(a) and (b), the maximum SAR values were 1.0 W/kg at 2.45 GHz and 1.1 W/kg at 5.8 GHz. For comparison, the maximum SAR values observed in the human chest were 0.7 W/kg at 2.45 GHz and 0.8 Watt/kg at 5.8 GHz based on an input power of 0.2 W, as shown in Figs. 20(c) and (d). This antenna can be placed directly on the skin but is intended to be integrated into clothing or coats, ensuring a gap of at least 5 to 10 mm between the antenna and the body using a non-conductive spacer or the clothing itself. This setup protects the wearable device from the effects of nearby tissue and reduces performance variations during operation. Therefore, there are no direct biocompatibility concerns with this application.

Table 3 presents the thicknesses of skin, fat, and muscle layers in different parts of the human body, selected to represent typical anatomical conditions for realistic modelling with the body. Based on this, Table 4 summarizes the tissue thickness values at the body's various locations considered in this study, which are used to evaluate antenna performance in practical wearable scenarios. Table 5 shows the antenna's peak SAR values at 2.45 and 5.8 GHz for chest and wrist positions. The SAR is slightly higher on the wrist and at a higher frequency. However, all values are below the limit of 1.6 W/kg, which confirms safe operation.

TABLE 5. Simulated peak SAR (1 g) values of the proposed antenna at different frequencies and on-body locations.

On-Body Location	Frequency (GHz)	Peak SAR (W/kg, 1 g)
Chest	2.45	0.7
Chest	5.8	0.8
Wrist	2.45	1.0
Wrist	5.8	1.1

4. MEASURED RESULT

The antenna was constructed and evaluated to confirm its practical performance. Measurements were performed using a vector network analyzer and an anechoic chamber. Relevant results, including impedance matching, radiation patterns, and gain, have been recorded and compared with simulations to confirm their consistency. The good agreement between the measured and simulated results of the suggested antenna confirms its suitability for ultra-wideband wearable applications.

The effective impedance matching is evident from the simulated and measured characteristics, as shown in Fig. 21(a), which compares the simulated and measured S_{11} over the frequency range of 2.32 GHz to 8.84 GHz. Distinct peaks appear at specific resonant frequencies, namely 2.45 GHz and 5.8 GHz, which align well with the simulated response and validate the accuracy of the antenna's physical implementation. As depicted in Fig. 21(b), the realized gain remains positive throughout the operating band, with a measured peak of approximately 5.5 dBi, closely matching the simulated peak of 5.8 dBi. As depicted in Fig. 21(c), simulated and measured results follow a similar trend, with slight variations caused by practical factors.

Minor discrepancies between measured and simulated results arise due to fabrication tolerances, SMA connector losses, cable effects, and measurement uncertainties.

The simulated and measured *E*- and *H*-plane patterns at 2.45 and 5.8 GHz are shown in Figs. 22(a)–24(b). The patterns exhibit a significant correlation, showing stable antenna performance. At 2.45 GHz, the two planes exhibit close symmetry with minimal discrepancies. At 5.8 GHz, small differ-

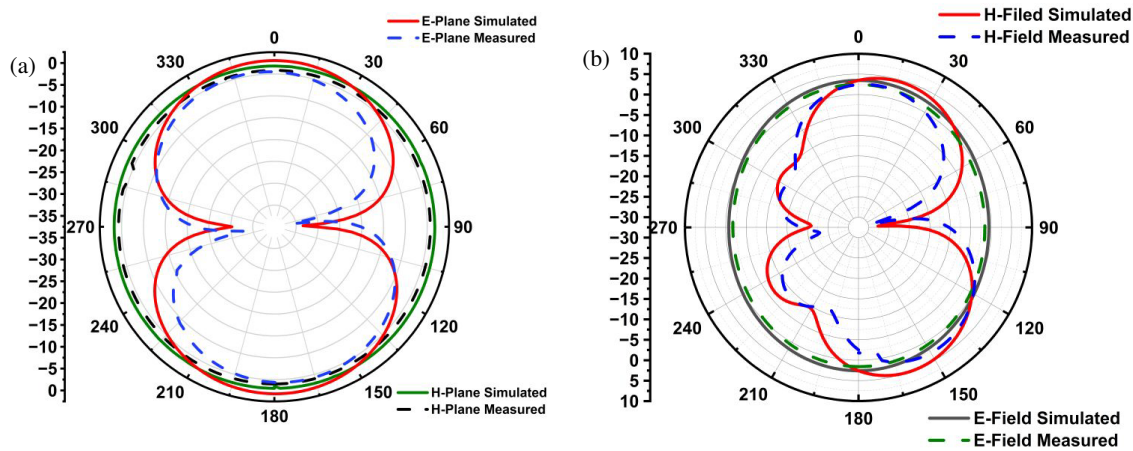


FIGURE 23. 2D far-field pattern H -plane: simulated versus measure results at (a) 2.45 GHz and (b) 5.8 GHz.

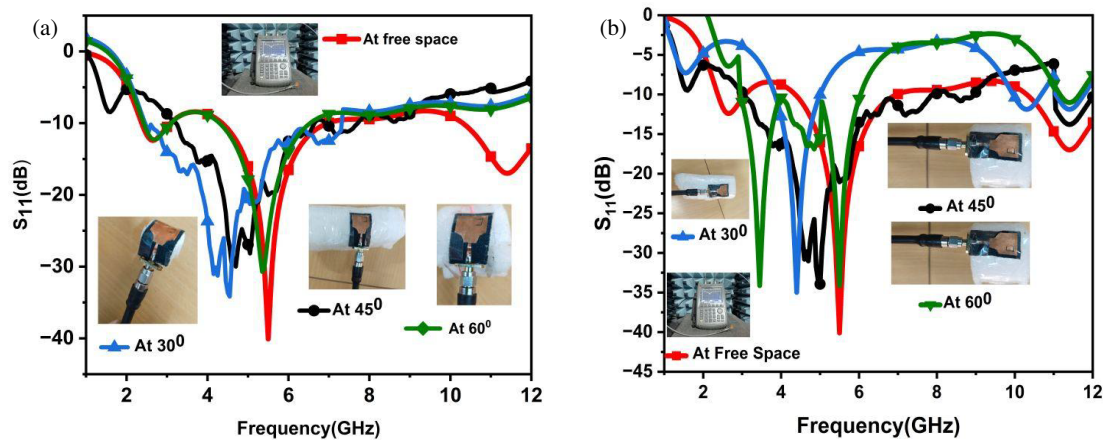


FIGURE 24. Measured S_{11} characteristics of the antenna at various bending angles along (a) the E -plane and (b) the H -plane.

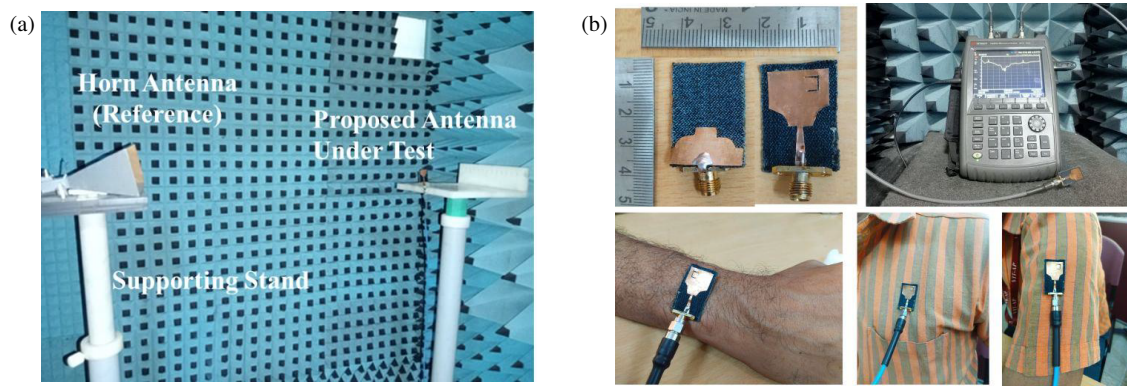


FIGURE 25. (a) Far-field radiation measurement arrangement in the anechoic chamber using a horn antenna as the reference and the fabricated antenna as the AUT. (b) Measurement setup: fabricated prototype (top and bottom), assembled circuitry, on wrist, on chest, and on arm.

ences in the E -plane result from manufacturing or alignment constraints, as shown in Figs. 23(a) and 23(b).

Comparison between simulated and measured results S_{11} for an antenna or resonator system over a frequency spectrum of 2.32 to 8.84 GHz. The good agreement between measured and simulated results of the suggested antenna confirms its suitability for wideband wearable applications.

The structural deformation of the wearable antenna was evaluated by bending it over a cylindrical surface of 50 mm radius and mounting it on a human arm. Figs. 24(a) and 24(b) present the simulated and measured S_{11} under flat, E - and H -plane conditions throughout the 2.32–8.8 GHz frequency range. The antenna consistently exhibited good impedance matching, with S_{11} below -42.4 dB ISM band (5.8 GHz). A minor fre-

TABLE 6. Comparison of selected wearable antennas with the proposed design.

Ref.	Dimensions (λ_0^2)	Freq. (GHz)	Substrate	BW (GHz)	Gain (dBi)	Conformal	SAR (W/kg)	Applicable Band
[1]	0.487×0.581	2.45	Jeans	1.21	5.6	Yes	1.24	ISM, WBAN
[4]	0.26×0.22	2.45	RT/Duroid	0.41	5.0	Yes	0.26	ISM, WBAN
[6]	0.58×0.77	5.8	Felt	7.5	4.81	No	1.37	UWB, WLAN, WiMAX
[8]	0.32×0.26	2.45	Denim + AMC	0.51	7.15	Yes	-	ISM, WBAN
[10]	0.42×0.42	2.45	SIW Textile	0.6	3.61	Yes	0.3	ISM, WBAN
[13]	0.28×0.28	2.45/5.8	Felt	0.16/0.27	7.15	Yes	0.05	ISM, WBAN
[16]	0.25×0.35	2.45	Jeans	0.379	2.6	Yes	0.05	ISM, WBAN
[17]	0.23×0.33	2.4/5.8	Textile	0.38	1.0/9.0	Yes	1.62/0.91	ISM, WBAN
Proposed	0.163×0.269	2.45/5.8	Jeans	7.92	6.3	Yes	0.52/0.90	ISM, WBAN

quency shift was observed during bending, which was more pronounced in the E -plane than in the H -plane. Minor variations between simulation and measurement are attributed to fabrication tolerances and human body loading effects. These results confirm the antenna's mechanical flexibility and stable performance, affirming its suitability for portable use.

In Figs. 25(a) and 25(b) show the measurement setup and performance evaluation of the fabricated antennas on jeans substrates, respectively, revealing significant variations due to the substrate material.

The jeans-based antenna exhibits pronounced resonance shifts and degraded matching, likely due to inherent permittivity variations and fabrication inconsistencies. Overall, the good electromagnetic stability of the jeans substrate underscores its suitability for high-precision applications, ensuring minimal performance discrepancies between the simulated and measured results. Finally, Table 6 presents a comparative analysis of the designed ETSRP antenna compared to other conventional wearable antennas. The studied design demonstrates good bandwidth and gain relative to similar structures. In addition, it features a more compact form factor than many WBAN antennas reported in existing research. Although using the same substrate has led to slight variations in size and gain, the radiating element still exceeds the performance of [6], establishing it as a good choice for WBAN applications.

5. CONCLUSION

In conclusion, the low-profile suggested wearable antenna incorporating an inverted C-shaped slotted ETSRP design exhibits high performance for WB communication applications. It does a great job of matching impedance throughout the frequency range, from 2.32 to 8.84 GHz. Both simulations and real-world data confirm the design's accuracy. The antenna proficiently decreases backward radiation, yielding SAR values of the wrist and chest, 1.0/0.7 Watts/kilogram at 2.45 GHz and 1.1/0.8 Watts/kilogram at 5.8 GHz, while maintaining elevated gain and effective radiation performance. The bending study verifies the antenna's reliability during bending, con-

firming its suitability for wearable technology. The proposed antenna, characterized by its compact size, straightforward design, low profile, and extensive bandwidth, presents considerable promise for practical application in different communication systems.

ACKNOWLEDGEMENT

We would like to thank the School of Electronics Engineering and V-Lunch and RGEMS Project (VIT-AP/SpoRIC/RGEMS/2024-25/009) to support lab work and complete this research work. Author contributions B. Roy and Y. U. Maheswari conceived the structure and scope of the review. Y.U.M. wrote the initial draft of the manuscript. B. Roy provided main supervision and contributed to the technical discussion on microwave wearable platforms, dielectric characterization methods, etc. All authors contributed to manuscript revisions, provided critical feedback, and approved the final version of the manuscript.

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