

A Compact Wearable Asymmetric U-Shaped Microstrip Patch Antenna for Biomedical Applications

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ABSTRACT: The proposed antenna is a flexible, wearable antenna designed for smart clothing applications, operating in the 2.4 GHz band. To make it truly wearable, we used jeans (denim) fabric as the substrate, with a compact size of $50 \times 36 \text{ mm}^2$ and a thickness of 1 mm. We focused on how the antenna performs when placed on the human body. We tested it using hand and leg phantom models, and the results were excellent. The Specific Absorption Rate (SAR) remained well below the safety limit of 1.6 W/kg — measuring 0–0.345 W/kg on the hand and 0–0.245 W/kg on the leg. We also achieved strong 3D radiation gains of 4.95 and 4.81 dBi. Because clothes naturally fold and move, we also analyzed the antenna's performance under vertical and horizontal bending with 0° , 30° , 45° , and 60° . Graphical analysis confirmed that the antenna remained stable and efficient even when bent, proving that it is a reliable and safe choice for real-world wearable technology.

1. INTRODUCTION

We are living in a time when the Internet of Things (IoT) and technologies such as 5G and 6G are changing everything. Wearable technology refers to devices that can be worn. Now, it is like systems that are connected to our bodies [1]. We no longer have only smartwatches or fitness bands. The IoT and fast internet, such as 5G and 6G, have made them more complex. Currently, researchers are looking into Smart Textiles or Electronic Textiles. Smart Textiles, or Electronic Textiles, are a way of making technology [2, 3]. In this approach, the antenna is no longer a separate or externally attached component; instead, it is seamlessly integrated into the user's everyday clothing, making it unobtrusive and comfortable to wear. These wearable systems are important for applications such as health monitoring and elderly care. They are also used for battlefield coordination and tracking the performance of professional athletes [4–6]. IoT and fast internet, such as 5G and 6G, have made it possible to create systems connected to our bodies. However, developing these systems is not easy. One major challenge is designing an antenna that works well while being worn on the body.

The human body can affect antenna performance [7]. When an antenna is placed near the skin, it can suffer from frequency detuning, which can reduce its efficiency and communication range. Traditional antennas are unsuitable for these systems. However, conventional wearable antennas may not provide suf-

ficient comfort, breathability, and mechanical durability for prolonged daily use. To address these limitations, researchers have explored various materials. Among these materials, jeans have emerged as a popular choice. They have low cost and properties for microwave applications [10, 11]. In this study, we propose an antenna designed on a jeans substrate. The antenna was optimized to operate in the 2.4 GHz band. This band is compatible with Bluetooth, ZigBee, and Wi-Fi protocols used in IoT devices [12–14]. We conducted a performance analysis using hand and leg models. This was done to simulate real-world usage scenarios. User safety is an important aspect of wearable technology.

We ensure that our design meets the safety limit for the Specific Absorption Rate (SAR) [15–17]. A flexible antenna using a highly conductive silver/graphene oxide (Ag/GO) nanocomposite was developed for SAR applications at 2.47 GHz [18]. The proposed antenna demonstrated good radiation performance and acceptable SAR characteristics, highlighting its suitability for flexible and wearable applications. Our results show that these values are below the safety limit. We also tested our design under these conditions. These conditions included folding, stretching, and crumpling. The antenna performance remained stable despite deformation [19]. Silver-graphene oxide nanocomposites with hybrid fillers were investigated for their electrical conductivity and morphological characteristics for wearable antenna applications [20]. The results demonstrate the potential of these nanocomposites as highly conductive and flexible materials for wearable antenna fabrication.

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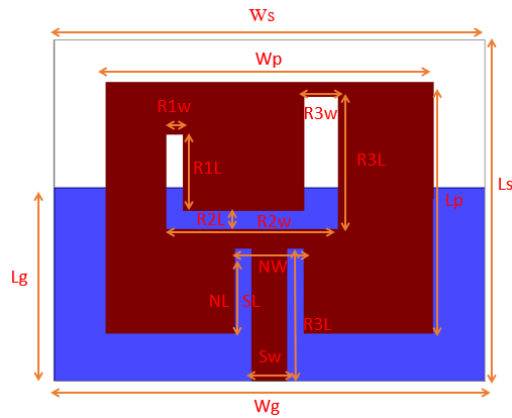


FIGURE 1. Geometry of the proposed antenna.

IoT and fast internet, such as 5G and 6G, have made it possible to create systems connected to our bodies. These systems can withstand such activities [21–22]. A flexible wearable antenna based on a graphene nanoplatelet-silver-copper tri-nanocomposite was developed for wearable electronic applications [23]. The proposed antenna exhibited high conductivity and flexibility, demonstrating its suitability for efficient wearable communication devices.

The Internet of Things (IoT) and fast internet, such as 5G and 6G, have changed the way we use technology. A compact dual-band syringe-inspired wearable antenna was optimized using machine learning for efficient wireless body area network (WBAN) applications [24, 25]. The proposed antenna provides improved performance with a compact structure suitable for wearable medical communication systems. This paper provides a detailed deep dive into the design methodology [26], simulation environment, and robust performance metrics that make this denim-based antenna a reliable solution for the next generation of smart wearable electronics. A dual-band, linearly polarized lamp-shaped wearable antenna was designed and fabricated for ISM and public safety band applications [27]. The proposed antenna demonstrated suitable radiation performance and compact characteristics for wearable communication systems. Wearable antennas are widely studied for healthcare, IoT, and wireless communication applications. Flexible textile and leather substrates enable lightweight, conformal antenna designs, while bending and SAR ensure reliable on-body performance. Graphene-based MIMO and wideband Vivaldi antennas further improve the potential of wearable systems for 5G, medical, and IoT applications [28–32]. The manuscript is organized as follows. Section 2 describes the antenna design. Section 3 presents simulated results of the parametric analysis of antenna bending losses, both vertical and horizontal, along with SAR analysis. Section 4 presents measured results. Finally, Section 5 includes the key findings and possible improvements in future work as the conclusion.

2. PROPOSED ANTENNA DESIGN

The development of wearable technology has created a growing need for flexible, small, and high-performance antennas. The proposed antenna was designed using a U-slot cut on a patch

TABLE 1. Antenna parameters and their respective values.

Parameter	Symbol	Value (mm)
Substrate $W \times L$	$W_s \times L_s$	50×36
Ground $W \times L$	$W_g \times L_g$	50×20.4
Patch $W \times L$	$W_p \times L_p$	38×26.5
Feed $L \times W$	$L_f \times W_f$	4×1
Strip $W \times L$	$W_{s1} \times L_{s1}$	4×14
R1 $L \times W$	$L_{r1} \times W_{r1}$	2×10
R2 $L \times W$	$L_{r2} \times W_{r2}$	20×2
R3 $L \times W$	$L_{r3} \times W_{r3}$	4×14
Notch $L \times W$	$L_n \times W_n$	4×4

with Jeans as the substrate with relative permittivity $\epsilon_r = 1.67$ and a loss tangent of $\tan \delta = 0.025$. Fig. 1 illustrates the geometry of the proposed antenna, and Table 1 lists the notations. Ansys High Frequency Structural Simulator (HFSS) Licensed software 2017 version is used for the simulation process [33]. Initial dimensions of the patch antenna were calculated using the standard transmission-line model [21].

$$\text{width} = \frac{c}{2f_0 \sqrt{\frac{\epsilon_r + 1}{2}}} \quad (1)$$

where c is the light velocity, and ϵ_r is the relative permittivity.

Effective dielectric constant:

$$(\epsilon_{eff}) = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[\frac{1}{\sqrt{1 + 12 \left(\frac{h}{w} \right)}} \right] \quad (2)$$

where h is the height of the substrate.

Calculation of the Patch Length:

$$\text{length} = \frac{c}{2f_0 \sqrt{\epsilon_{eff}}} - 0.824h \left(\frac{\epsilon_r (\epsilon_{eff} + 0.3) \left(\frac{w}{h} + 0.264 \right)}{(\epsilon_{eff} - 0.258) \left(\frac{w}{h} + 0.8 \right)} \right) \quad (3)$$

3. RESULTS AND DISCUSSIONS

3.0.1. Using Various Iterations

The antenna design was realized through various iterative steps, with step-by-step improvements aimed at improving its performance for wearable applications. Fig. 2(a) shows the basic rectangular monopole from iteration 1, which has a limited bandwidth and single-band operation. The design was first improved by incorporating three vertical and horizontal slots in the second iteration, as shown in Fig. 2(b). This modification significantly improved the S_{11} characteristics and resulted in multiband operation. In the last structure shown in Fig. 2(c), the slot geometry was further optimized in length, width, and spacing, which led to better impedance matching and wider bandwidth. S_{11} plot in Fig. 3 clearly shows the improvement, where the final structure (red curve) exhibits single-band performance

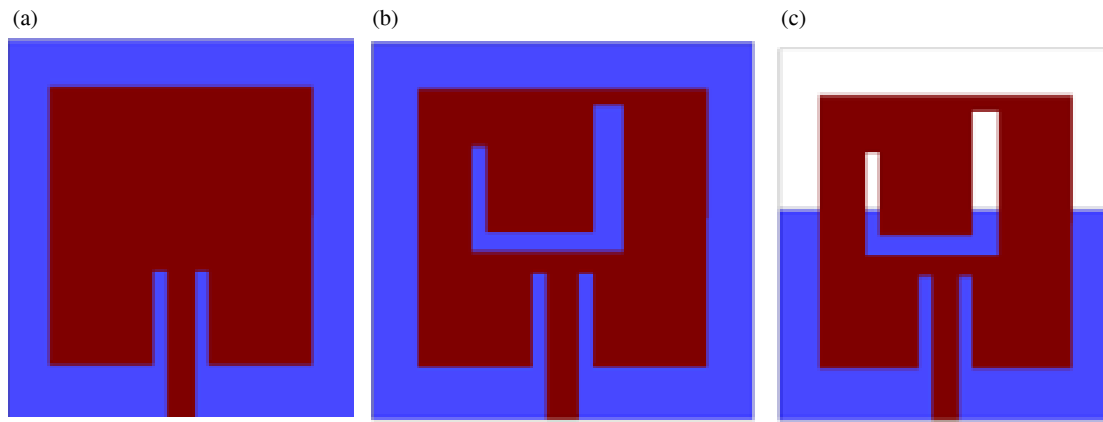


FIGURE 2. (a) Iteration 1, (b) Iteration 2, and (c) Iteration 3.

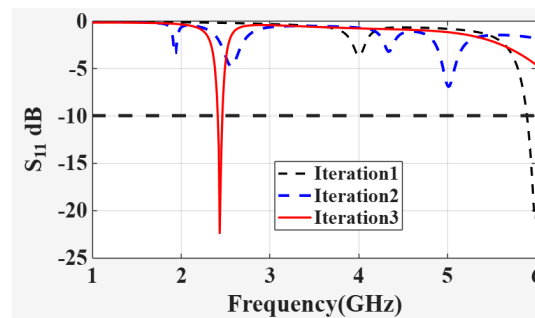


FIGURE 3. Return loss for three iterations.

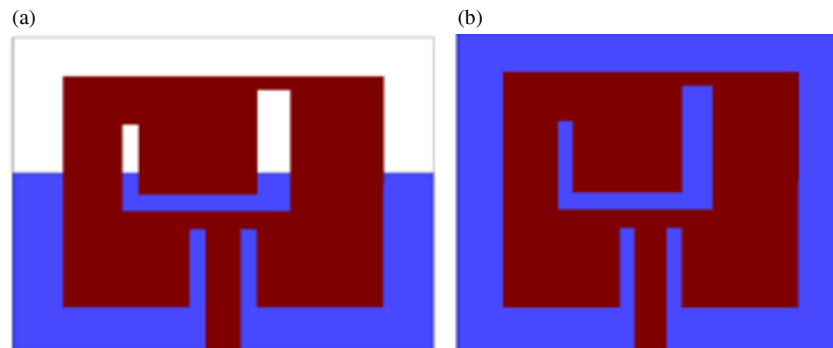


FIGURE 4. Proposed antenna. (a) With DGS and (b) without DGS.

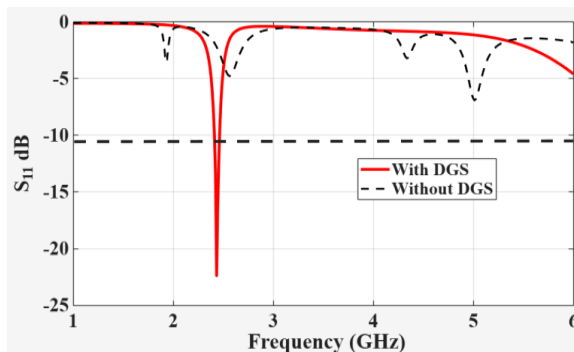


FIGURE 5. Simulated return loss comparison of the proposed antenna with and without DGS.

and deep resonance at approximately 2.4 GHz, which is suitable for body-centric wireless communication. The proposed antenna shows a compact size, excellent flexibility, and low SAR, making it highly suitable for wearable devices operating in the ISM frequency bands.

3.0.2. Return Loss Curves with and without Defected Ground Structure

Fig. 4(a) shows the introduced design with Defected Ground Structure (DGS), and Fig. 4(b) shows another design without a DGS. The return loss S_{11} is taken from the graph in Fig. 5. The operating frequency is found to be 2.4 GHz, while the S_{11} value lies in the range of approximately 25 dB for the antenna with the DGS.

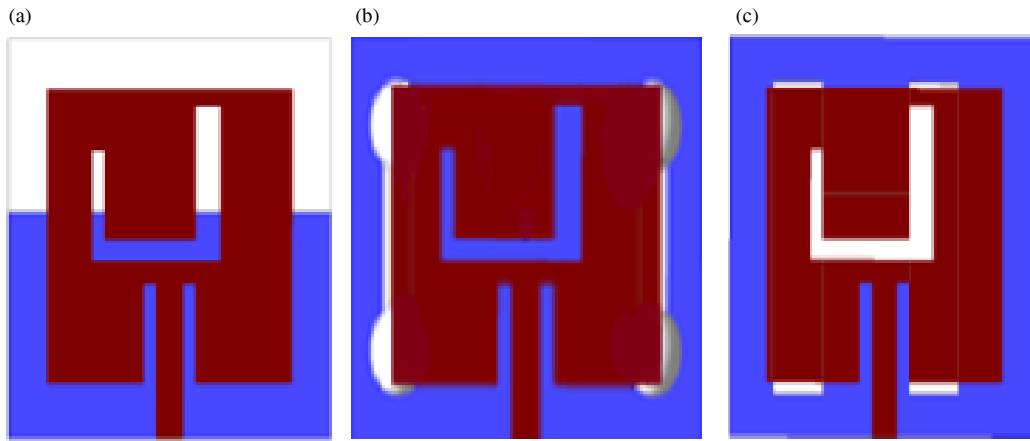


FIGURE 6. (a) Proposed DGS, (b) dumbbell-shaped DGS, and (c) H-shaped DGS.

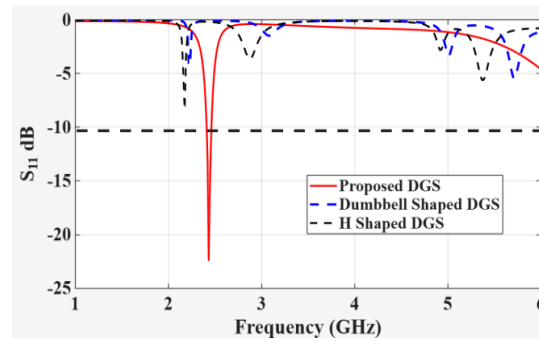


FIGURE 7. Simulated return loss curves for different DGS.

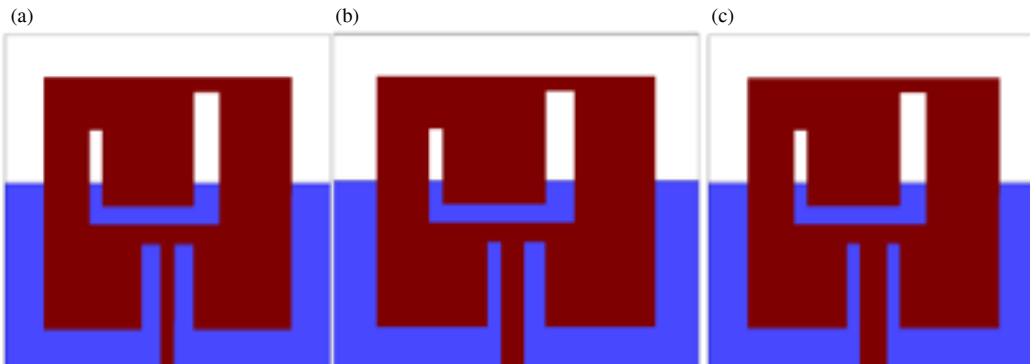


FIGURE 8. Strip widths. (a) $W_s = 2$ mm, (b) $W_s = 3$ mm, and (c) $W_s = 4$ mm.

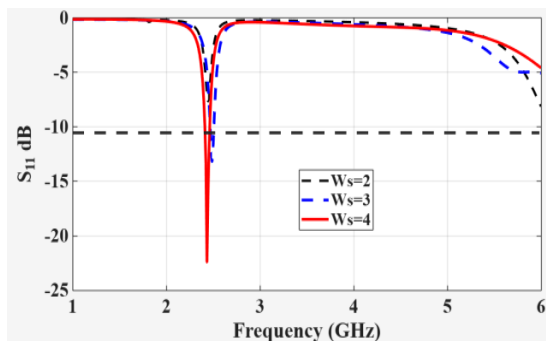


FIGURE 9. S_{11} for strip widths $W_s = 2, 3$, and 4 mm.

3.0.3. Variability in Return Loss for Various DGSs

Three DGS configurations, namely dumbbell-shaped, H-shaped, and the proposed DGS shown in Fig. 6, were investigated under the same antenna dimensions and operating conditions. Fig. 7 compares their simulated S_{11} responses. The different DGS geometries modify the ground-current path and effective inductive-capacitive loading, resulting in different impedance characteristics. The proposed comb-shaped DGS provides the strongest perturbation of the ground-current path and consequently achieves the best impedance matching, with a minimum S_{11} of approximately -22.5 dB at 2.4 GHz. Therefore, the comb-shaped DGS was selected for the final antenna design.

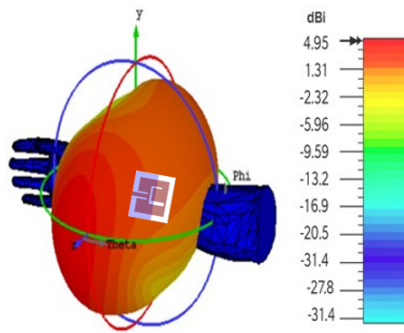


FIGURE 10. Simulated radiation pattern and realized gain with hand phantom.

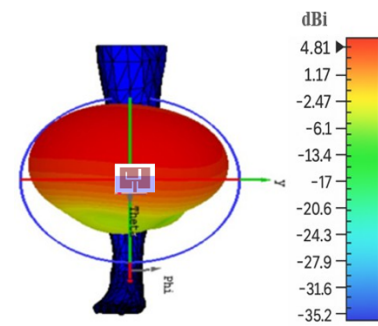


FIGURE 11. Simulated radiation pattern and realized gain with Leg phantom.

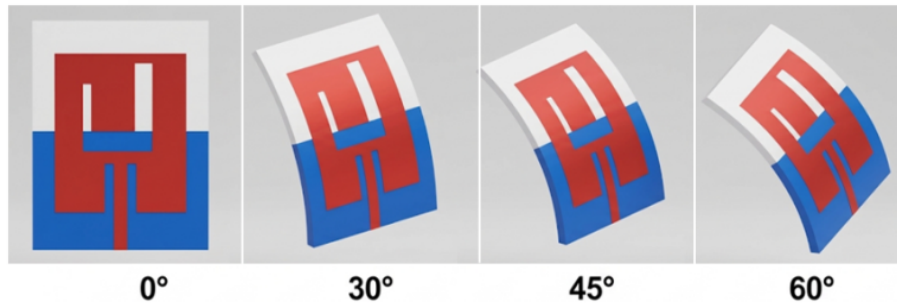


FIGURE 12. Antenna performance at a 0°, 30°, 45°, 60° vertical bend, respectively.

3.0.4. Return loss Variation with Different Strip Widths

Strip width W_s was swept over 2, 3, and 4 mm, as shown in Figs. 8(a), 8(b), 8(c). It can be seen that when $W_s = 4$ mm, the antenna shows the deepest resonance at 2.4 GHz (≈ -25 dB) with an S_{11} value of approximately -25 dB.

It can be observed that when $W_s = 4$ mm, the antenna exhibits the deepest resonance at 2.4 GHz,

3.1. Radiation Performance Analysis and Gain Plots

The radiation performance of the proposed antenna was evaluated under hand- and leg-phantom loading conditions. Simulated three-dimensional radiation patterns and realized gain were analyzed to characterize on-body radiation behaviour.

3.1.1. Hand Phantom Analysis

Fig. 10 shows the simulated three-dimensional radiation pattern of the proposed antenna with the hand phantom. The antenna achieves a maximum realized gain of 4.95 dBi in the principal radiation direction, indicating predominantly directional radiation under hand-phantom loading.

3.1.2. Leg Phantom Analysis

Fig. 11 shows the simulated three-dimensional radiation pattern of the proposed antenna with the leg phantom. A maximum realized gain of 4.81 dBi is obtained in the principal radiation direction. The antenna maintains a predominantly broadside radiation characteristic in leg-phantom loading, with slight variation in the radiation distribution due to the different phantom geometry.

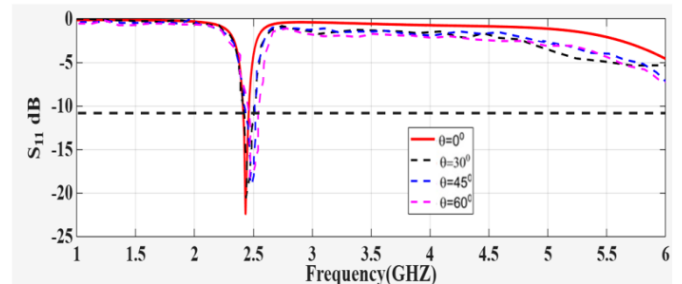


FIGURE 13. Return loss plot at 0°, 30°, 45°, 60° vertical bending angles.

Bending is unavoidable in wearable antennas because fabrics are flexible. It changes antenna performance, mainly shifting the resonant frequency (e.g., 2.4 GHz may move slightly), affecting S_{11} (return loss) and reducing or distorting the radiation pattern and gain. When the proposed antenna is bent, the current path length changes, which can affect the resonant frequency. The effective dielectric environment changes (due to the body + curvature), which causes detuning. In this bending analysis, there are two types: 1. Vertical bending and 2. Horizontal bending. These two types were analysed at various angles such as 0°, 30°, 45°, and 60°. The details are presented in the following section.

3.1.3. Vertical Bending Losses

Vertical bending refers to the antenna deformation along its length, in which the antenna is bent about an axis parallel to its width. This bending mode has a significant impact, as it stretches the antenna's electrical length and causes a change in

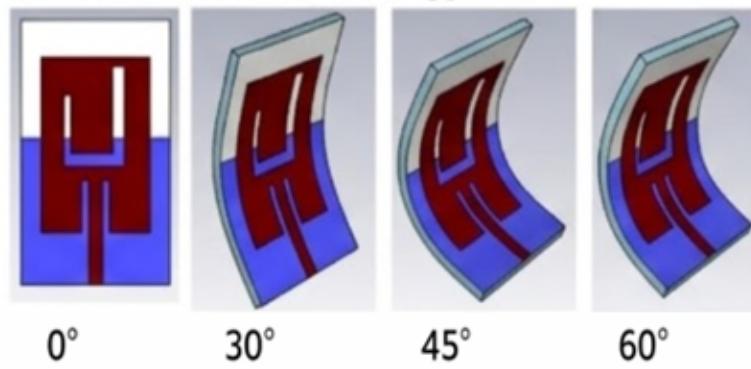


FIGURE 14. Antenna performance at a 0° , 30° , 45° , and 60° horizontal bending angles.

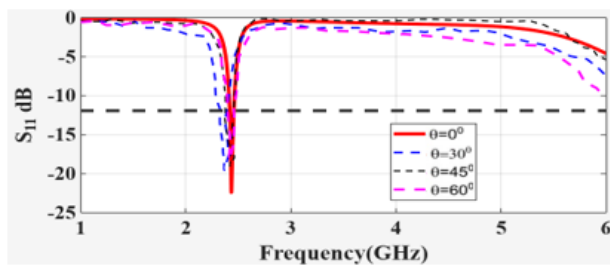


FIGURE 15. Return loss plot at 0° , 30° , 45° , and 60° horizontal bending angles.

the current distribution. Therefore, the resonant frequency also varies. Vertical bend experiments were performed at 0° , 30° , 45° , and 60° bends. Fig. 12 and Fig. 13 show the results.

3.1.4. Horizontal Bending Losses

Horizontal bending refers to deformation along the width direction, in which the antenna is bent about an axis parallel to its length. In horizontal bending, the antenna undergoes deformation along its width direction, with the bending occurring about an axis parallel to its length. We ran the numbers for horizontal bending at 0° , 30° , 45° , and 60° angles, and Fig. 14 and Fig. 15 show the results.

3.2. Specific Absorption Rate (SAR) Analysis

SAR is a measure to determine how electromagnetic energy from an antenna is absorbed by the human body. Wearable antennas are very closer to the body (on clothes, skin, etc.); therefore, some radiation can enter the body tissues. High SAR means that more energy is absorbed, which can be unsafe for humans. SAR is important for wearable antennas because it ensures that the radiation absorbed by the human body remains within safe limits, making the device suitable for safe daily use.

3.2.1. Hand-Phantom SAR Analysis

Fig. 16 shows the hand-phantom SAR analysis, where the proposed antenna is placed on a realistic arm, and Fig. 16(b) shows an SAR value of 0.345 W/kg.

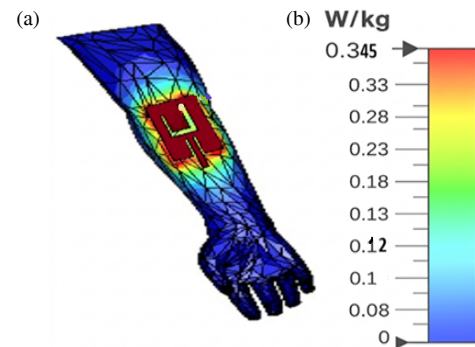


FIGURE 16. (a) Hand phantom and (b) hand-phantom SAR values.

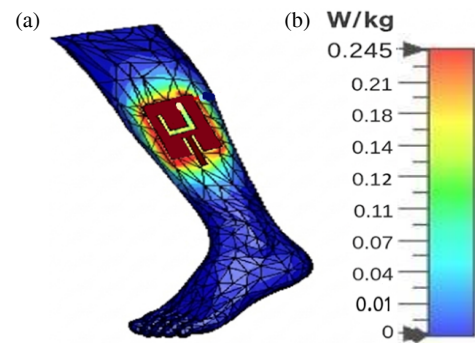


FIGURE 17. (a) Leg phantom and (b) leg-phantom SAR values.

3.2.2. Leg-Phantom SAR Analysis

The SAR analysis for the leg phantom was performed to evaluate the safety of the proposed wearable antenna. Fig. 17(a) shows the proposed antenna placed on the leg phantom. Fig. 17(b) shows the corresponding SAR distribution, where the maximum SAR value is observed to be 0.245 W/kg.

3.3. Field Distribution Analysis

E -field, H -field, and surface current density (J_{surf}) distributions were evaluated at 2.4 GHz to identify regions responsible for the antenna resonance, as shown in Figs. 18–20. In Fig. 18, the E -field is concentrated mainly around the U-shaped radiating element and feed region, indicating strong excitation of

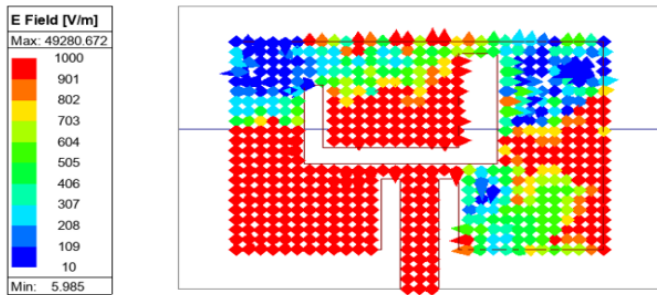


FIGURE 18. E -field distribution at 2.4 GHz to the intended antenna.

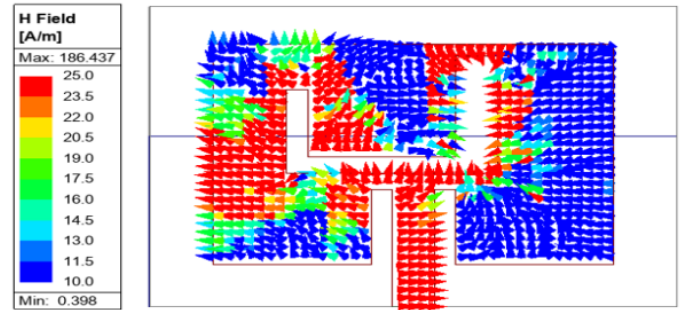


FIGURE 19. Distribution of H -field to the designed antenna at 2.4 GHz.

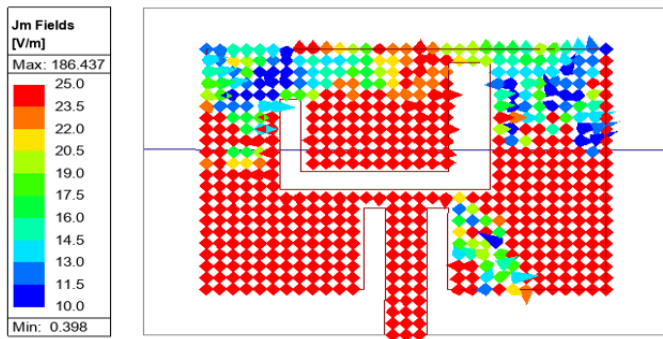


FIGURE 20. Distribution of J_{srf} to the designed antenna at 2.4 GHz.

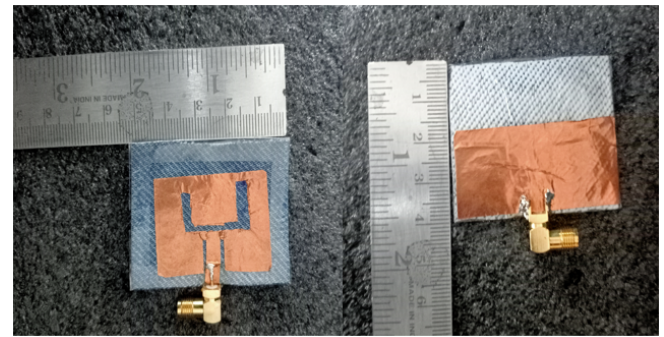


FIGURE 21. Fabricated antenna top and bottom views.

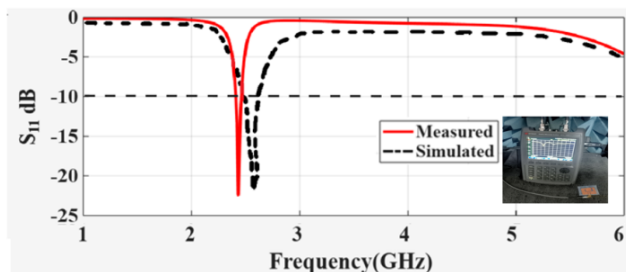


FIGURE 22. Measured and simulated return loss for the proposed antenna.

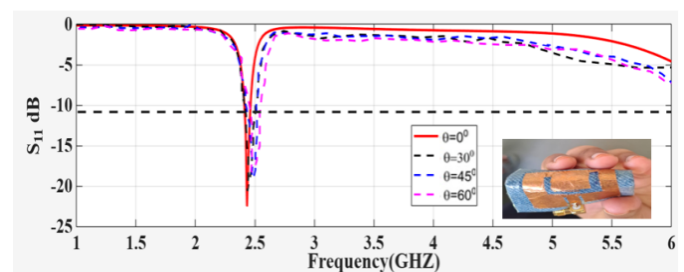


FIGURE 23. Measured return loss plot at 0° , 30° , 45° , 60° vertical bend.

the radiator. The U-shaped path increases the effective electrical length, supporting resonance at 2.4 GHz. In Fig. 19, the H -field is concentrated around the U-shaped element, feed region, and modified ground area, confirming strong electromagnetic interaction in these regions. Fig. 20 shows high J_{srf} mainly along the feed line and ground conductor, with noticeable current concentration around the U-shaped path and DGS discontinuities. Thus, the combined modification of the radiator and ground structure contributes to the impedance matching and establishment of the 2.4-GHz resonant mode.

4. MEASURED RESULTS AND DISCUSSIONS

Figure 21 depicts the manufactured prototype of the proposed U-shaped microstrip antenna. We conducted tests to illustrate its simulated behaviour. Using high-precision etching, the antenna was created on a 1 mm-thick jeans (denim) cloth substrate and connected using SMA. Return loss, gain, and radiation pat-

terns were measured using an anechoic chamber and a Vector Network Analyser (VNA).

4.1. Measured and Simulated Return Losses

Figure 22 displays the S_{11} , or return loss, for the proposed antenna. The results are in good agreement. The proposed antenna operates at a frequency of approximately 2.4 GHz. This difference can be attributed to fabrication tolerances, variations in the dielectric properties of the denim substrate, and parasitic effects associated with the SMA connector and soldering. The results show that the proposed antenna operates as expected. This means that it can be used for things that people wear, such as devices that operate at 2.4 GHz. VNA was used to measure the S_{11} .

The prototype produces measured bending results at various degrees 0° , 30° , 45° , 60° . Here, we plot the measured S_{11} return loss graph as shown in Fig. 23.

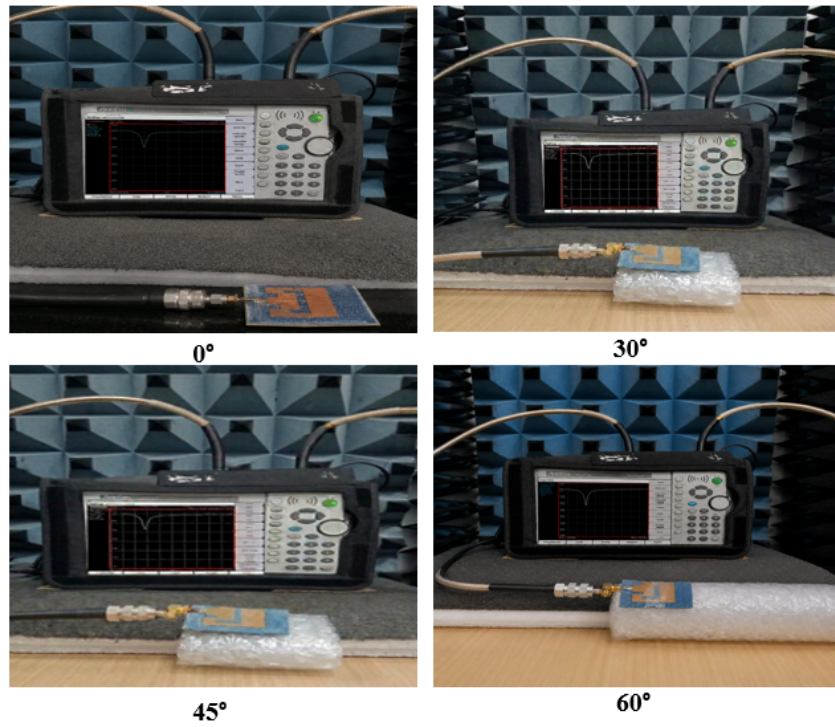


FIGURE 24. Horizontal bending measurement setup of the proposed antenna at 0° , 30° , 45° , and 60° .

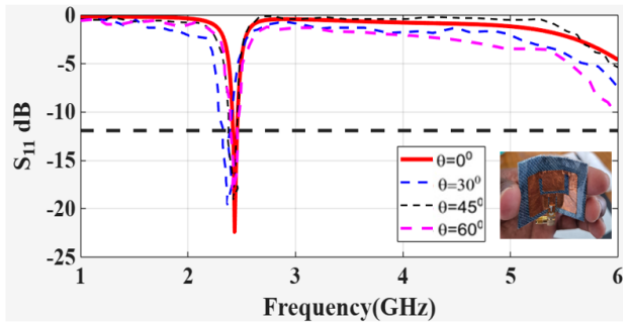


FIGURE 25. Measured return loss plot at 0° , 30° , 45° , 60° horizontal bend.

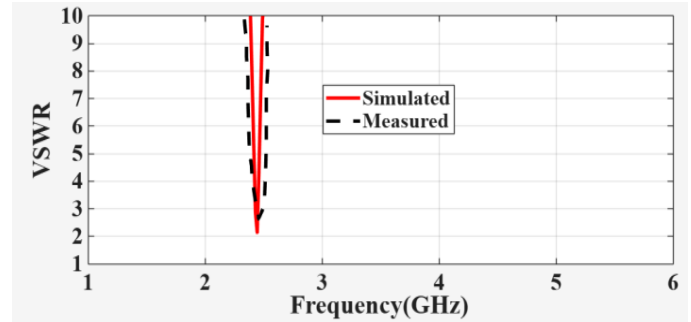


FIGURE 26. VSWR of the designed antenna.

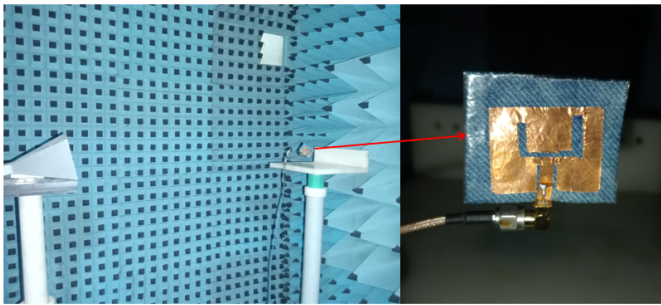


FIGURE 27. Photograph of an anechoic chamber setup.

Furthermore, horizontal bending analysis was performed on the fabricated antenna at bending angles of 0° , 30° , 45° , and 60° , while maintaining proper VNA connectivity, as illustrated in Fig. 24. To ensure reproducibility of the mechanical defor-

mation, corresponding bending radii were considered as ∞ (flat condition), 191 mm, 127.3 mm, and 95.5 mm for bending angles of 0° , 30° , 45° , and 60° , respectively. Fig. 25 shows measured return-loss responses for different bending conditions.

4.2. Voltage Wave Standing Wave Ratio (VSWR)

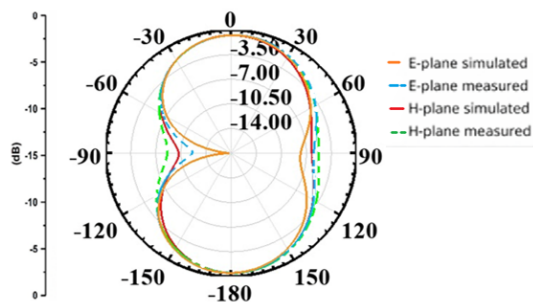
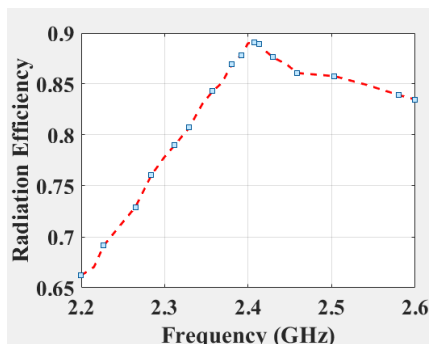
The designed antenna exhibited good signal strength. The VSWR is greater than 2, as shown in Fig. 26. This figure shows the antenna's simulated and measured results. The designed antenna performed well.

4.3. Polar Plot Analysis

The radiation characteristics of the fabricated antenna were examined in a test room referred to as an anechoic chamber, as shown in Fig. 27. This aids in creating a testing environment devoid of any disturbance. The minimum far-field distance (R)

TABLE 2. The comparison of the recommended antenna work with existing works.

Ref No	Operating Frequency (GHz)	Dimensions (mm)	Bandwidth (GHz)	SAR (W/kg)	Gain (dBi)
[12]	2.45	$31 \times 42 \times 0.6$	0.379 GHz	0.054	2.627
[16]	3.5–14.3	$52.8 \times 60 \times 1.07$	6.5	0.99	4.6
[17]	2.4/3.5 (Dual-band)	$60 \times 50 \times 3.24$	0.35 GHz at 2.4 GHz	0.85	4.38 & 2.4 GHz
[19]	2.41	$80 \times 60 \times 1$	0.09 GHz	0.576	~ 2.1
[30]	2.45	$34 \times 32 \times 1$	0.50 GHz	Compliant (IEEE limit)	~ 2.0
Proposed Antenna	2.4 (ISM Band)	$50 \times 36 \times 1$	0.379 GHz	0.345 (hand) 0.245 (leg)	4.95/4.81

**FIGURE 28.** Measured and simulated E and H plane radiation patterns at 2.4 GHz.**FIGURE 29.** Simulated radiation antenna efficiency.

was calculated as 40 mm using $R \geq 2D^2/\lambda$, for an antenna size of $D = 50 \times 36 \text{ mm}^2$ at 2.4 GHz. Fig. 28 shows radiation patterns in the E - and H -planes at 2.4 GHz. The antenna radiation was examined in an anechoic chamber to achieve accurate results. The proposed antenna achieves a high simulated radiation efficiency of approximately 0.89 or 89%, as shown in Fig. 29.

In this way, the data are retained while a more readable description of the results is created. With our proposed design, we break away from the notion of wearables being bulky and stiff. This was made possible by using a denim substrate, which helped us create an incredibly thin antenna of only 1 mm thickness that can easily merge with the material. However, there was an additional concern regarding consistency when building the wearable antenna. The antenna performance did not falter even during repeated bending or positioning around various body areas, such as the hand or leg. Table 2 presents a comparison of the proposed antenna with previously reported wearable antennas.

5. CONCLUSION

In this study, we successfully designed and analysed a flexible wearable antenna for smart clothing applications, specifically operating in the 2.4 GHz band. To make it truly wearable, we used jeans (denim) fabric as the substrate, with a compact size of $50 \times 36 \text{ mm}^2$ and a thickness of 1 mm. We focus on antenna performance when the antenna was placed on the body. We tested it using hand and leg phantom models, and the results were excellent. The SAR stayed well under the safety limit of 1.6 W/kg — measuring 0–0.345 W/kg on the hand and 0–0.245 W/kg on the leg. We also achieved strong 3D radiation gains of 4.95 dBi and 4.81 dBi, respectively. Because clothes naturally fold and move, we also analysed the antenna's performance under vertical and horizontal bending at 0° , 30° , 45° , and 60° . The graphical analysis confirms that the antenna remains stable and efficient even when bent, proving that it is a reliable and safe choice for real-world wearable technology.

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