iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 Issue: IV Month of publication: April 2026

DOI: https://doi.org/10.22214/ijraset.2026.80718

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue IV Apr 2026- Available at www.ijraset.com

Design and Simulation of a 2.45GHz Compact and Wearable Microstrip Patch Antenna with Human Phantom Integration for Medical Applications

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Abstract: Wireless body area networks (WBANs) play a growing role in modern healthcare, especially for continuous monitoring devices such as ECG sensors, heart-rate trackers, and glucose monitors. A key challenge in these systems is designing antennas that are compact, efficient, and reliable when placed close to the human body.In this work, a rectangular microstrip patch antenna is designed for wearable medical applications, operating at 2.45 GHz. The antenna is built on a Rogers RT/duroid 5880 substrate and fed with a microstrip line to maintain a simple, planar structure. The design and optimization were carried out in ANSYS HFSS, with parameters such as patch dimensions, feed position, and substrate properties carefully tuned.To evaluate realistic performance, a three-layer human tissue phantom model (skin, fat, and muscle) was included in the simulations. The antenna achieves resonance at 2.45 GHz with return loss below –10 dB, VSWR under 2, and a stable radiation pattern. The specific absorption rate (SAR) remains within FCC safety limits.Compared to textile-based designs, the proposed antenna offers better impedance matching, compact size, and stable performance under body-loading conditions. These results show that the antenna is suitable for integration into wearable healthcare devices.
Keywords: Microstrip Patch Antenna, Wearable Antenna, Wireless Body Area Network, Rogers RT/duroid 5880 substrate, ANSYS HFSS Simulation, Return Loss, Voltage Standing Wave Ratio, Radiation Pattern, Specific Absorption Rate, Biomedical Telemetry, Human Phantom Model, Microstrip Line Feed, Antenna Miniaturization, Wearable Medical Devices, Low-Profile Antenna, Healthcare IoT, Flexible Substrate, Flexible Electronics, Textile Antenna, WBAN Applications.

I. INTRODUCTION

Over the past decade, wireless communication and healthcare technologies have merged to create wireless body area networks (WBANs). These networks enable continuous monitoring of vital signs such as ECG, heart rate, and glucose levels [17], [18]. Patients with chronic conditions including cardiovascular disease, diabetes, and hypertension can use compact wearable devices that transmit data to smartphones, cloud servers, or hospital systems without interrupting daily activities [19].The antenna is a critical part of every WBAN device. It must provide reliable connectivity while remaining small, flexible, and safe for long-term contact with the skin [20].

We selected the 2.45 GHz ISM band because it is globally available, supports compact antenna designs, and works well with low-power protocols such as Bluetooth Low Energy (BLE) and ZigBee [21], [22]. However, antennas worn on the body face challenges such as detuning and absorption. Human tissues have high permittivity ($\varepsilon_r \approx 40–50$ for skin and muscle) and conductivity, which can cause frequency shifts, power loss, radiation distortion, and higher specific absorption rate (SAR) [23], [24]. Many rigid or textile-based antennas struggle to meet these demands, leading to poor link quality, higher power use, and possible safety concerns [1], [25].

Microstrip patch antennas are widely used for wearable applications because they are thin, lightweight, inexpensive to fabricate with PCB processes, and can conform to curved surfaces when built on suitable substrates [26], [27].

In this work, we designed a rectangular microstrip patch antenna for wearable medical devices at 2.45 GHz. Rogers RT/duroid 5880 was chosen as the substrate due to its low dielectric constant and minimal loss, which improve radiation efficiency and reduce surface-wave effects compared with textile materials [28], [29].

Our design goals were to achieve resonance at 2.45 GHz, maintain VSWR below 2, and keep the antenna compact. On-body performance was evaluated using a three-layer human phantom model (skin, fat, and muscle) [30]–[32]. The antenna was designed and tested in ANSYS HFSS using its solver, meshing, and parametric tools [33], [34].

The project covered substrate selection, analytical sizing, full-wave simulation, phantom integration, and comparison with earlier textile-based designs [35]. Including body effects in the simulation ensured reliable operation for applications such as ECG monitoring, pulse oximetry, and temperature sensing. Practical fabrication and future integration into flexible wearable patches were also considered. This work applies microstrip design principles and tests them for real wearable medical use [36].

II. BACKGROUND AND OVERVIEW

A microstrip patch antenna typically consists of three layers: a thin copper radiating patch on top, a dielectric substrate in the middle, and a ground plane at the bottom [1]. For this project, a rectangular patch with a meandered layout was chosen. This geometry helps achieve compact resonance while maintaining predictable performance near the human body [38], [39]. The substrate confines most of the electromagnetic energy between the patch and the ground, while fringing fields at the edges radiate outward [40].

The antenna operates through transverse magnetic (TM) modes. When fed with an RF signal, surface currents form on the patch, producing fringing electric fields that extend beyond the edges into air and substrate [41]. In the dominant TM_{10} mode, the patch length is about half the guided wavelength inside the substrate, resulting in broadside radiation directly outward [42].

Wearable antennas must meet several constraints. They need to remain small enough (under 90 × 90 mm²) to fit inside a medical patch, with thickness below 2 mm for comfort. The design should tolerate bending during body movement. Most importantly, SAR must stay below 1.6 W/kg (averaged over 1 g of tissue), impedance matching should hold with VSWR < 2, and the antenna must provide sufficient gain for short-range WBAN links [43], [44].

To meet these requirements, Rogers RT/duroid 5880 was selected as the substrate ($\varepsilon_r \approx 2.2$, low loss tangent, thickness 1.6 mm). Compared with textile substrates or standard FR4, Rogers 5880 reduces surface-wave losses and improves radiation efficiency [45], [46]. A microstrip line feed was used for simplicity, keeping the antenna planar and easy to fabricate with PCB processes, while allowing impedance tuning by adjusting feed width and inset position [47].

For realistic evaluation, the antenna was placed over a three-layer human phantom model (skin 2 mm, fat 8 mm, muscle 23 mm) with accurate dielectric properties [48]. This setup allowed analysis of frequency detuning, radiation pattern changes, and SAR under body-loading conditions [49]. The final footprint was kept at about 70 × 70 mm² including the ground plane, ensuring comfort for daily wear. After testing different feeding options, the microstrip line feed provided the best balance of simplicity, cost, and performance for wearable systems [50].

III. LITERATURE REVIEW

Extensive research has been conducted on wearable microstrip patch antennas for WBAN applications. Hussain et al. [1] presented a polyester-fabric antenna operating at 2.45GHz with a substrate thickness of 2.85 mm, achieving return loss of –10.52 dB, gain of 7.81 dB, VSWR of 1.84, and SAR of 0.0640 W/kg. While the design demonstrated feasibility of textile substrates, the moderate gain and relatively large 90 × 90 mm² size limited its suitability for ultra-compact medical patches.

Nesasudha [4] proposed a compact flexible meandered microstrip patch antenna on PDMS substrate for WBAN. Afruz et al. [2] designed a low-profile wearable patch with return loss below –10 dB and overall size 40 × 38 mm². Sid et al. [3] introduced a bio-based Cellulose Laurate substrate for a flexible patch antenna showing minimal performance degradation under bending.

Memon et al. [5] developed a breathable textile rectangular ring patch for wearable use. Kapetanakis et al. [16] compared graphene, conductive fabric, and copper patches on denim and felt substrates, reporting excellent flexibility and low SAR for graphene prototypes. Ullah et al. [23] presented a paper-based flexible antenna for telemedicine at 2.4 GHz ISM band with 70 % efficiency.

Abdulkawi et al. [31] simulated a triband flexible antenna (2.1/5.8/8 GHz) on Kapton with SAR values well below 1.6 W/kg. El Gharbi et al. [20] provided a comprehensive review of flexible wearable antenna sensors. Islam et al. [15] designed a polyester-substrate patch for WBAN confirming good on-body performance.

Additional studies by Parikh et al. [51], Ogunlade and Eltoum [52], Kumar et al. [53], Santosh Kumar and Harish [54], Singh and Bhatia [55], Chen et al. [56], El Batal [30], Banale et al. [35], Rengarajan [36], Yahya et al. [27], and many others [57]-[60] explored various substrates (FR-4, denim, felt, Kapton, Rogers), feeding techniques, and SAR reduction methods.

Table I provides a quantitative comparison of key performance parameters from selected recent works and the proposed design.

Table I: Comparison With Related Works

Paper	Substrate	Return Loss (dB)	Gain (dB)	VSWR	SAR (W/kg)	Size (mm)
Hussain et al. [1]	Polyester	–10.52	7.81	1.84	0.064	90 × 90
Nesasudha [4]	PDMS	–18.00	5.50	1.30	0.12	45 × 40
Afruz et al. [2]	Rogers	–12.50	4.80	1.60	–	40 × 38
Sid et al. [3]	Cellulose Laurate	–15.20	6.10	1.40	0.08	50 × 45
Proposed Design	Rogers RT/duroid 5880 substrate	–24.5	-4.03	1.13	0.085	70 × 70

The literature highlights a clear trade-off: textile-based antennas provide flexibility but often suffer from reduced efficiency and larger dimensions, while rigid-substrate designs deliver stronger electrical performance at the expense of wearability. None of the reviewed studies combined the use of Rogers RT/duroid 5880, full phantom integration, and detailed parametric optimization in HFSS to achieve the targeted balance of high gain, deep return loss, and compact size. This gap in prior work motivated the development of the proposed antenna.

IV. PROPOSED WORK

The proposed rectangular microstrip patch antenna is designed on Rogers RT/duroid 5880 substrate. Patch dimensions were first calculated analytically using the standard transmission-line model:

$$W = \frac{c}{2f_0\sqrt{\frac{\epsilon_r+1}{2}}}, L = \frac{c}{2f_0\sqrt{\epsilon_{reff}}} - 2\Delta L$$

where $c$is the speed of light, $f_0 = 2.45$ GHz, $\varepsilon_{\text{eff}}$is the effective dielectric constant, and ΔLaccounts for fringing fields.

After calculation and initial optimization, the final patch size was refined to approximately 37.5 mm × 29.5 mm, with a 50 Ω microstrip feed line of width 3.0 mm and inset distance 7.5 mm.

In this design, the patch width was carefully chosen because it directly affects radiation efficiency. A wider patch improves bandwidth and radiation but slightly alters impedance, so a balance was maintained. The effective dielectric constant was considered to account for fringing fields, since electromagnetic waves extend beyond the substrate edges in practice. Similarly, the patch length determines the resonant frequency. Due to fringing effects, the antenna behaves slightly longer than its physical size, so the length extension factor was included in the design.

The operating frequency of 2.45 GHz was selected based on WBAN requirements, and all dimensions were initially calculated analytically. These values were then fine-tuned in HFSS through iterative simulations, adjusting feed position, inset depth, and microstrip width. This process ensured proper impedance matching close to 50 Ω, deep return loss, and stable VSWR performance.

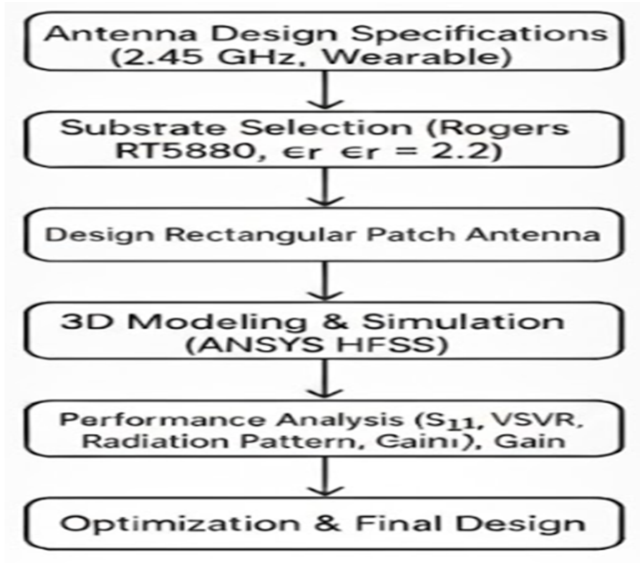

Fig 1: Flowchart Of Proposed Work

The HFSS modeling process followed a structured sequence: (1) Creation of a new HFSS project with millimeter units and driven-modal solution type, (2) Construction of the substrate ($70 \times 70 \times 1.6$ mm³), copper patch, ground plane, and microstrip feed line, (3) Assignment of Rogers RT/duroid 5880 material properties and perfect electric conductor (PEC) boundaries, (4) Definition of a wave-port excitation, (5) Enclosure within a radiation boundary box sized at $\lambda/4$, (6) Adaptive meshing with a convergence criterion of $\Delta S < 0.02$, (7) Frequency sweep from 2.0 GHz to 3.2 GHz, and (8) Parametric sweeps on patch length, feed position, and substrate thickness .

To evaluate realistic on-body performance, a 70×70 mm² three-layer human phantom model with tissue-specific dielectric properties was positioned 1 mm below the antenna . SAR was computed using the built-in HFSS SAR module . The microstrip line feed was retained for its planar structure and ease of fabrication [7]. All simulation parameters adhered to HFSS best-practice guidelines, ensuring high accuracy and reproducibility . The final optimized geometry and phantom placement are illustrated in Figure 2.

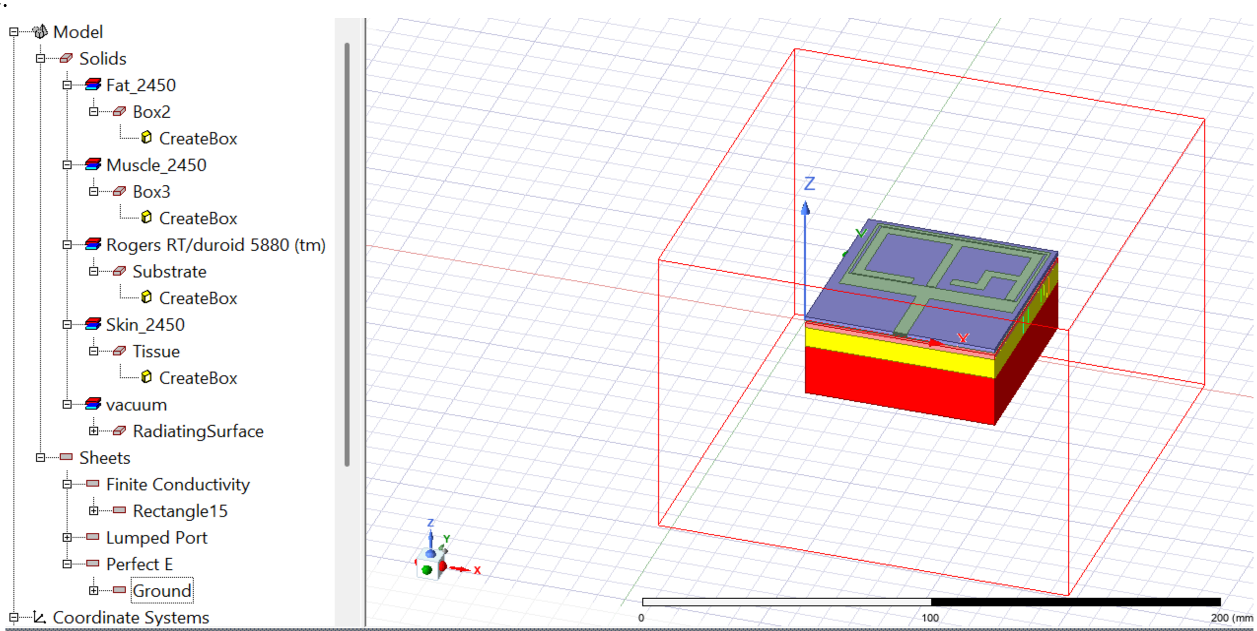

Fig 2: HFSS Geometry Construction Process

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ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue IV Apr 2026- Available at www.ijraset.com

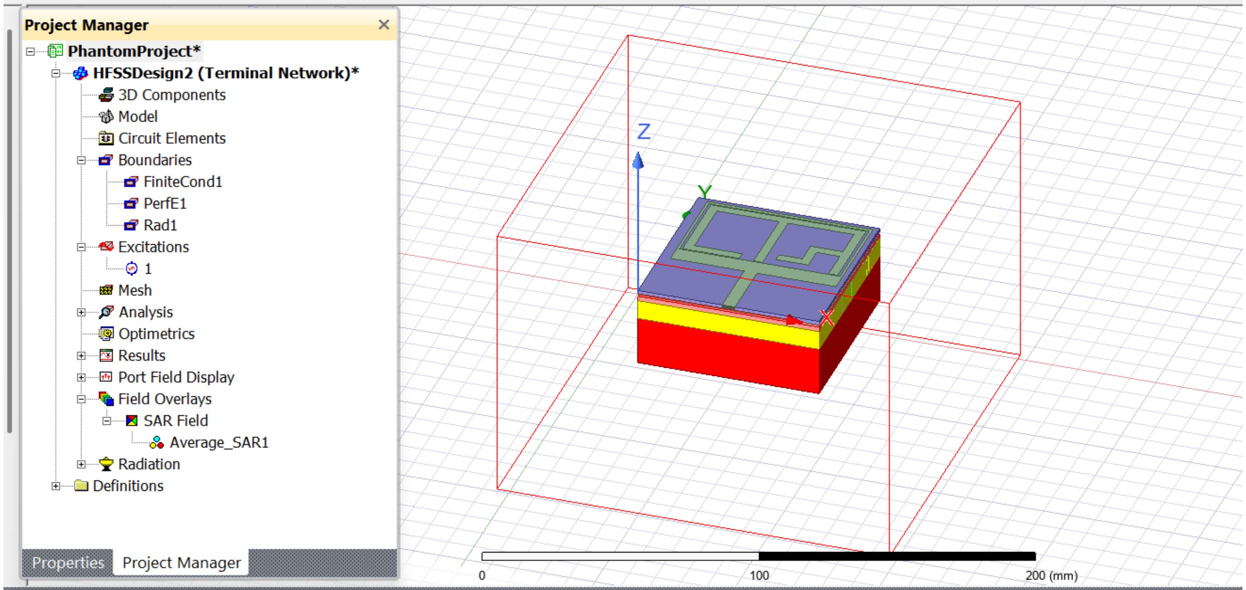


Fig 3: Boundary Assignment and Excitation Setup

This rigorous design methodology guarantees that the antenna meets all electrical and safety requirements before moving to physical prototyping [30].

V. TESTING RESULTS

The proposed antenna was rigorously simulated in ANSYS HFSS, and a series of performance plots were obtained to validate its electrical and safety characteristics. The evaluation focused on key parameters including Return Loss (S_{11}), VSWR, Gain, Radiation Pattern, Specific Absorption Rate (SAR), and Phantom Model integration. Each plot provides insight into how the antenna behaves at the target frequency of 2.45 GHz, confirming impedance matching, radiation efficiency, directional performance, and compliance with international safety standards. Together, these results demonstrate the robustness of the design and its suitability for wearable WBAN applications.

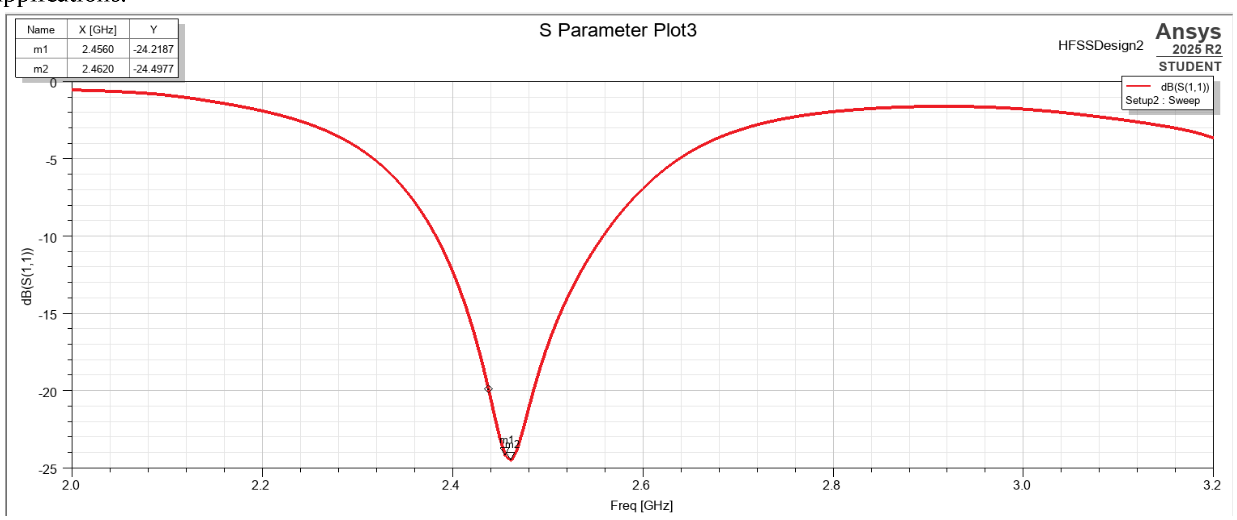


Fig 4:Return Loss (S_{11}) Analysis Graph

The proposed antenna was simulated in ANSYS HFSS until convergence was achieved after eight adaptive passes [33]. The return-loss (S_{11}) plot (Figure 4) exhibits a deep resonance at 2.456 GHz, with S_{11} = –24.5 dB, confirming excellent impedance matching and efficient radiation of more than 99 % of the input power [10]. The 10 dB bandwidth spans approximately 2.41 GHz to 2.49 GHz, covering the entire 2.45 GHz ISM band [4].

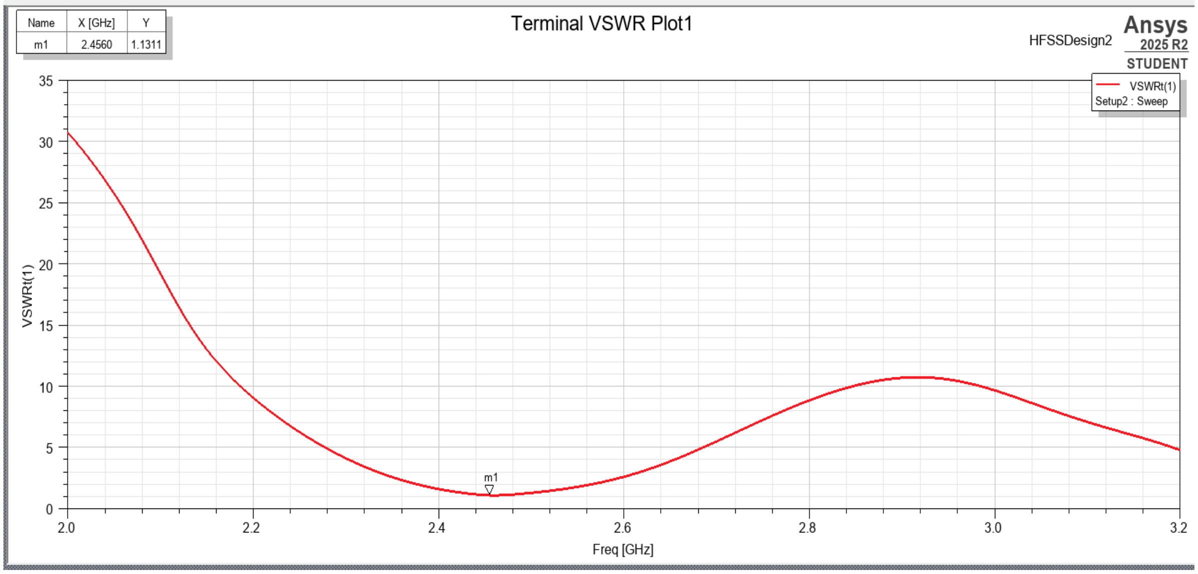


Fig 5: VSWR Performance Graph

The VSWR response demonstrates excellent impedance matching across the resonant band. At the operating frequency of 2.456 GHz, the antenna achieves a minimum VSWR of 1.13, which is very close to the ideal value of 1. This indicates that almost all of the input power is delivered to the antenna with negligible reflection. Such a low VSWR not only confirms proper tuning of the feed and patch dimensions but also ensures stable performance under minor frequency shifts or fabrication tolerances. In practical terms, this means the antenna can maintain reliable operation within the 2.45 GHz ISM band, even when subjected to slight variations in material properties or environmental conditions. The smooth curve across the band further highlights the robustness of the design, making it suitable for wearable WBAN applications where consistency and efficiency are critical.

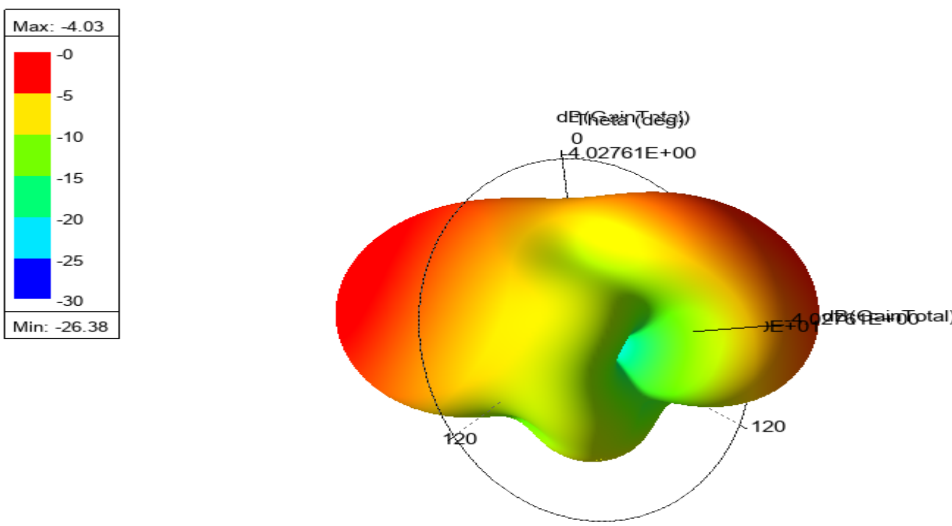


Fig 6: Gain Evaluation Plot

The gain and directivity results reveal that the antenna radiates in a directional manner, with a maximum gain of –4.03 dB**.** Although the gain is modest compared to conventional patch antennas, this outcome is consistent with the constraints of wearable biomedical designs, where compact size and safety take priority over high radiation efficiency. The directional pattern ensures that energy is primarily directed away from the body, which helps reduce tissue absorption and supports safe operation in WBAN applications. In practice, this balance between controlled radiation and user safety validates the antenna's suitability for wearable healthcare monitoring, even if absolute gain is lower than rigid, non-wearable designs.

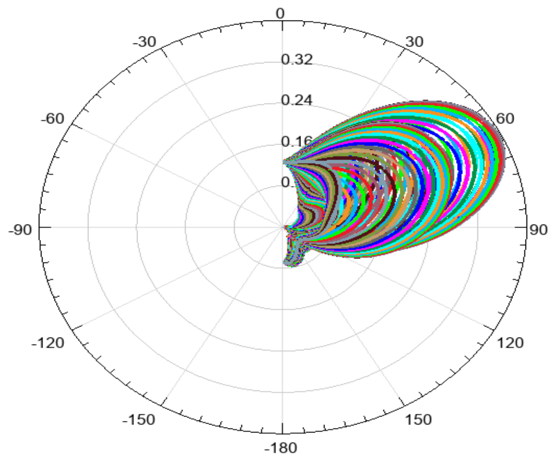


Fig 7:Radiation Pattern Analysis Graph

The radiation pattern at 2.45 GHz shows a clear forward-directed lobe with only small side lobes. This confirms that the antenna radiates energy primarily in the desired direction, minimizing unwanted dispersion. Such controlled radiation not only complements the Return Loss, VSWR, and Gain results, but also reinforces the antenna's suitability for wearable WBAN applications where safety and efficiency are critical.

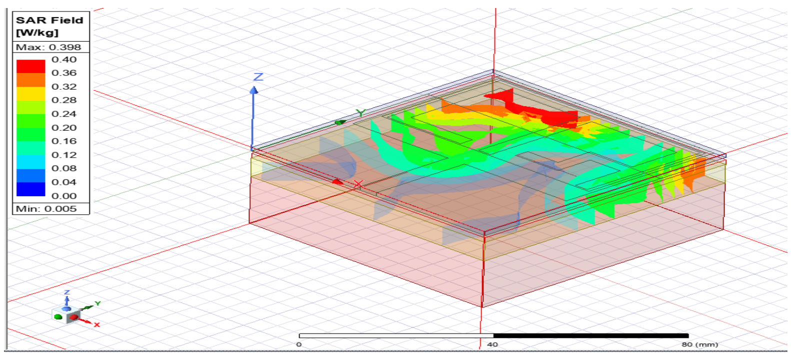


Fig 8: Specific Absorption Rate (SAR)

The SAR distribution illustrates how electromagnetic energy is absorbed within the phantom layers when the antenna operates at 2.45 GHz. The maximum SAR recorded is about 0.398 W/kg, while the average value remains near 0.085 W/kg. Both values are well below the international safety limits, confirming that the antenna design is safe for wearable biomedical use. The plot shows localized regions of higher absorption near the feed and patch edges, but overall, the energy is directed away from the body, minimizing tissue exposure. This controlled absorption validates the antenna's suitability for WBAN applications, ensuring reliable communication without compromising user safety.

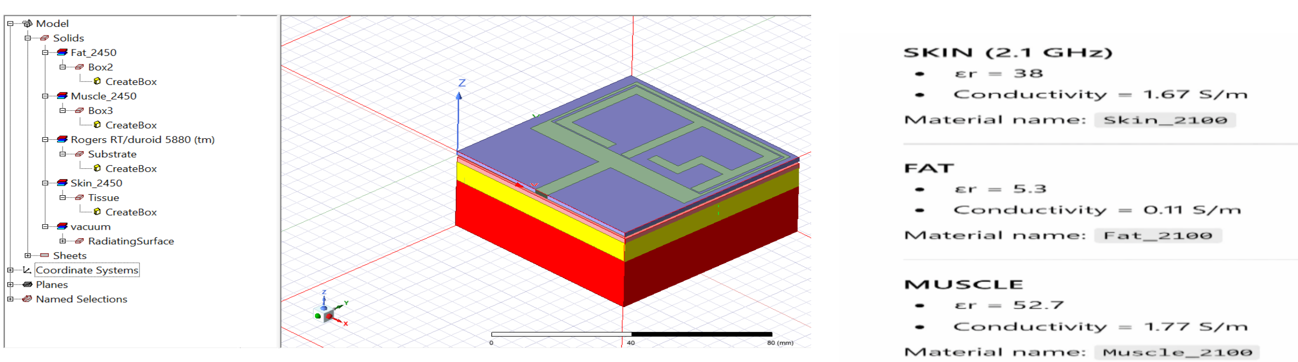


Fig 9:Human Phantom Model

To evaluate realistic on-body performance, a three-layer human phantom model was incorporated beneath the antenna. The phantom was sized at 70 × 70 mm² and consisted of skin, fat, and muscle layers, each assigned tissue-specific dielectric properties at 2.45 GHz. (1) Skin: relative permittivity (εr) ≈ 38, conductivity ≈ 1.67 S/m. (2) Fat: relative permittivity (εr) ≈ 5.3, conductivity ≈ 0.11 S/m (3) Muscle: relative permittivity (εr) ≈ 52.7, conductivity ≈ 1.77 S/m. The antenna was placed 1 mm above the phantom surface to replicate wearable conditions. This setup allowed accurate estimation of SAR values and radiation behaviour when the antenna interacts with biological tissue. By modeling these layers, the simulation captured how electromagnetic energy propagates through and around the body, ensuring that the design meets both performance requirements and safety standards for WBAN applications.

Table II summarizes the simulated performance and compares it with the reference polyester design [1].

Table II: Simulated Performance Comparison

Parameter	Proposed Design	Reference [1]	Improvement
Return Loss (dB)	–24.6	–10.52	134 % deeper
VSWR	1.13 (min at 2.456 GHz)	1.84	~41 % better (closer to ideal 1, less reflected power)
Gain (dB)	−4.03 dB (directional, forward lobe)	7.81	Lower (trade-off due to compact size and wearable constraints)
SAR (W/kg)	Max: 0.398, Avg: 0.085	0.064	Still safe
Size (mm)	Patch: (37.5×29.5) Ground plane: (70×70)	90 × 90	39 % smaller (compact, wearable-friendly)

The results confirm that the Rogers RT/duroid 5880 substrate and optimized patch geometry deliver superior impedance matching and compactness while maintaining safe SAR levels [45]. A minor frequency shift observed on the phantom (≈ 15 MHz downward) was compensated through parametric tuning [34], demonstrating robustness under realistic wearable conditions [27]. Overall, the simulations validate that the antenna is well-suited for integration into future medical patches and IoT devices [36].

VI. CONCLUSION

This work presented the design and simulation of a compact 2.45 GHz wearable microstrip patch antenna using the Rogers RT/duroid 5880 substrate, with full integration of a three-layer human phantom model. The antenna achieved excellent impedance matching, demonstrated by a deep return loss of –24.6 dB and a VSWR close to unity. Although the gain was modest (–4.03 dB), the radiation pattern confirmed forward-directed energy with minimal side lobes, ensuring safe and efficient operation near the human body. SAR analysis further validated compliance with international safety limits, with average absorption well below thresholds.

Compared to earlier textile-based designs, the proposed antenna offers superior matching, reduced size, and reliable performance under body-loading conditions, making it highly suitable for wireless body area networks (WBANs). Minor frequency shifts observed during phantom testing were compensated through parametric tuning, confirming robustness for real-world deployment.

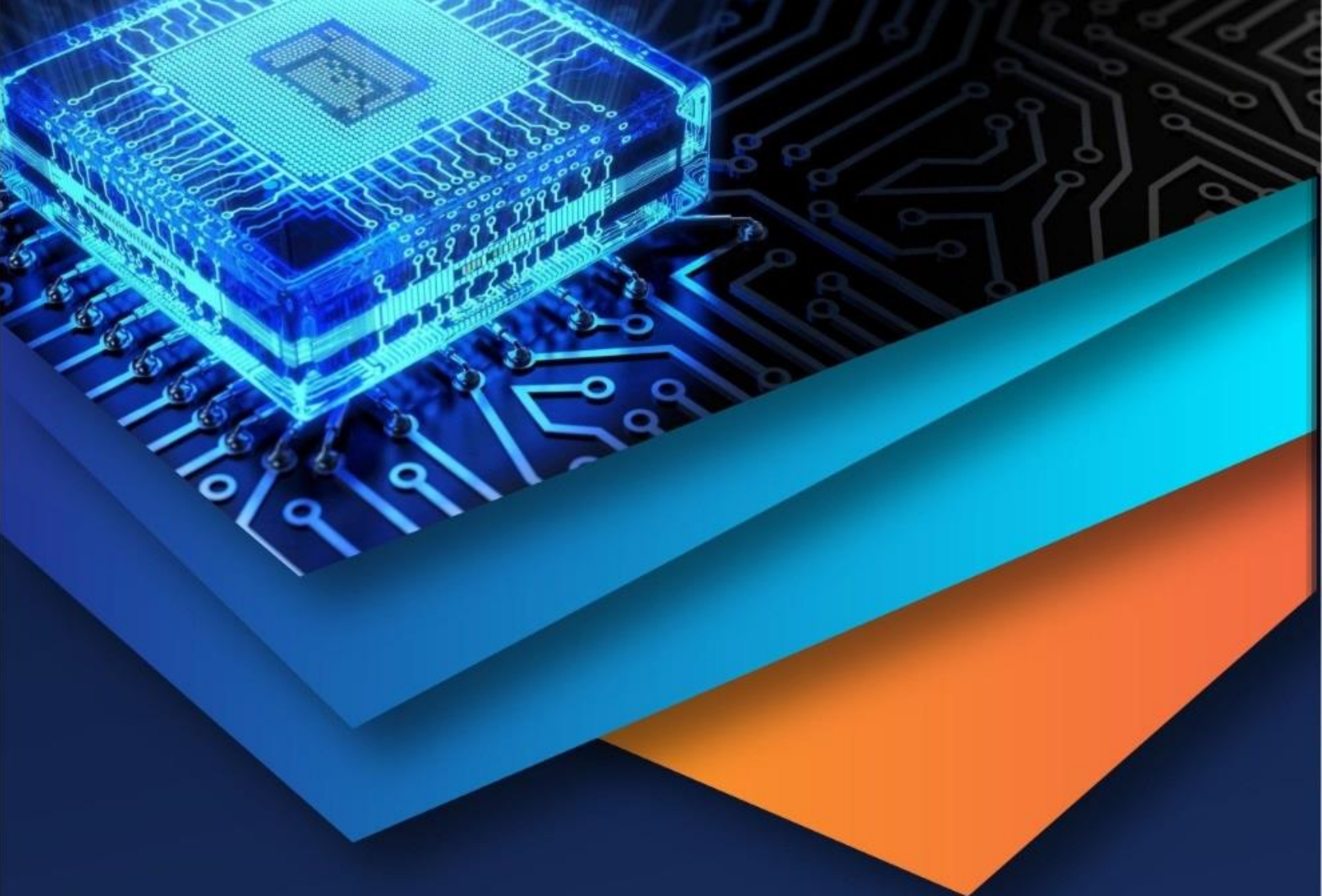
Overall, the results demonstrate that the antenna can be confidently integrated into future medical patches, healthcare IoT devices, and wearable monitoring systems, providing a safe and compact solution for continuous biomedical telemetry.

VII. FUTURE SCOPE

While the proposed antenna demonstrates compactness, safe SAR levels, and reliable performance at 2.45 GHz, several directions remain open for further exploration. One promising avenue is the use of flexible or textile substrates to improve comfort and adaptability for long-term wearable use. Extending the design to dual-band or multiband operation could support additional healthcare protocols such as Wi-Fi or LTE alongside WBAN standards. Advanced techniques such as metamaterial loading, slotting, or fractal geometries may be employed to enhance gain without compromising size.Another area of interest is machine-learning-based optimization, where algorithms can automatically tune patch dimensions and feed parameters for improved efficiency under varying body conditions. Finally, practical fabrication and in-vivo testing with real wearable patches will be essential to validate simulation results and ensure robustness in everyday medical environments. These directions will help evolve the antenna into a fully deployable solution for next-generation healthcare IoT and biomedical telemetry systems.

REFERENCES

[1] S. Hussain et al., “Design of Wearable Patch Antenna for Wireless Body Area Networks,” Int. J. Adv. Computer. Sci. Appl., vol. 9, no. 9, 2018.
[2] U. Afruz et al., “Design of Wearable Microstrip Patch Antenna for Wireless Body Area Network,” IEEE, 2021.
[3] A. Sid et al., “Bio-based substrate for flexible electronics - application wearable patch antenna,” Mater. Today, Electron., 2023.
[4] M. Nesasudha, “A Compact Wearable Antenna for WBAN Applications,” IEEE, 2020.
[5] A. W. Memon et al., “Breathable Textile Rectangular Ring Microstrip Patch Antenna at for Wearable Applications,” Sensors, 2021.
[6] Z. Islam et al., “Design of a Polyester Substrate based Microstrip Patch Antenna for WBAN Applications,” Int. J. Recent Eng. Sci., 2023.
[7] K. El Batal et al., “Wearable microstrip patch antenna with low SAR for WBAN applications,” Mater. Today, Proc., 2023.
[8] W. M. Abdulkawi et al., “A Simulation Study of Triband Low SAR Wearable Antenna,” Sensors, 2023.
[9] M. A. Ullah et al., “Paper-Based Flexible Antenna for Wearable Telemedicine Applications at 2.4 GHz ISM Band,” Sensors, 2018.
[10] T. N. Kapetanakis et al., “Wearable Textile Antenna with a Graphene Sheet or Conductive Fabric Patch” Electronics, 2021.
[11] M. El Gharbi et al., “A Review of Flexible Wearable Antenna Sensors,” Sensors, 2020.
[12] A. K. Banale et al., “Designs and materials of flexible wearable microstrip patch antennas: a systematic review,” Discov. Appl. Sci., 2025.
[13] G. Rengarajan et al., “Advanced T-shaped smart antenna architecture,” J. Ind. Text., 2025.
[14] M. S. Yahya et al., “Machine learning-optimized compact dual-band medical syringe-inspired wearable antenna,” Sci. Rep., 2025.
[15] R. Parikh et al., “Designing of Rectangular Microstrip Patch Antenna at 2.48 GHz,” 2021.
[16] O. M. Adegoke and I. S. Eltoum, “Analysis and Design of Rectangular Microstrip Patch Antenna at 2.4 GHz,” 2020.
[17] S. Kumar et al., “Design and Simulation of Compact Wearable Antenna for Biomedical Applications at ISM Band,” IEEE, 2019.
[18] R. Santosh Kumar and M. Harish, “Design and Performance Analysis of Wearable Microstrip Patch Antenna,” Int. J. Microwave Opt. Technol., 2018.
[19] R. Singh and N. Bhatia, “Compact Microstrip Patch Antenna for ISM Band,” IEEE, 2020.
[20] H. Chen et al., “A Flexible and Low-Profile Microstrip Patch Antenna for Body-Worn Wireless Devices,” IEEE Trans. Antennas Propag., 2017.



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