SSRG International Journal of Electrical and Electronics Engineering
ISSN: 2348-8379/ https://doi.org/10.14445/23488379/IJEEE-V11I3P111

Volume 11 Issue 3, 148-154, March 2024

Original Article

Wearable Textile Antenna on Jean Substrate for On-Body Wireless Communication Applications

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Received: 08 January 2024 Revised: 06 February 2024 Accepted: 06 March 2024 Published: 25 March 2024

Abstract - *This study pioneers a textile-based antenna designed specifically for wireless body communication, drawing inspiration from a square-shaped structure while integrating a partial ground element into its design. The antenna, compact at 30×30×1 mm^3, is meticulously crafted on flexible jean fabric chosen for its exceptional flexibility. Utilizing adhesive conductive copper and silver tape, the radiating elements and grounds achieve the necessary conductivity. Operating seamlessly across 3.75, 5.7 and 7 GHz on the body and ISM band applications, this antenna is meticulously engineered for applications centred around the human body. Rigorous assessments of its wearability involve systematic bending tests at varying vertical and horizontal angles, which remarkably showcase minimal variation in resonating frequencies despite these manoeuvres. Further validation through on-body testing, where the prototype is placed directly onto the subjects' skin, confirms the antenna's effectiveness in facilitating seamless wireless communication on the body. This comprehensive evaluation highlights its potential as a reliable solution for body-centric wireless applications, emphasizing its structural resilience and functional efficiency in real-world scenarios.*

Keywords - *Bending, Body-centric wireless applications, ISM applications, Jean substrate, Textile antenna.*

1. Introduction

In the current era of flexible electronics, the demand for robust and adaptable antennas suitable for wearable technology has skyrocketed [1]. Conventional printed circuit board microstrip antennas, while effective in their functionality, face limitations in today's wearable devices. Their rigid construction and non-skin-friendly design, characterized by sharp edges, render them impractical and uncomfortable for human skin. This has led to an urgent call for innovative approaches in crafting antennas that align with modern wearable devices' comfort and flexibility requirements.

Wearable antennas are crucial in various fields, including emergency operations, medical advancements, military applications, on-body communication systems, and biomedical radio frequency systems. Their significance lies in enabling Wireless Body Area Networks (WBANs), which foster connectivity among personal wearable devices, enabling versatile communication modes encompassing off/on-body and even in-body communication [2]. These antennas form the backbone of seamless connectivity, empowering technological advancements directly impacting healthcare, emergency response, military operations, and personalized communication systems. Textile patch antennas emerge as the foremost choice in crafting wearable antennas due to their exceptional characteristics. Their conformal and skin-friendly attributes guarantee comfort and discretion when incorporated into wearable devices. These antennas typically leverage dielectric fibres for insulation and utilize various innovative techniques. These methodologies include precision methods like inkjet printing [3], traditional yet effective approaches such as screen printing [4], utilization of conductive tapes or fibres [5, 6], intricate methods like embroidery [7], and specialized techniques like wet-etching [8]. These diverse techniques are employed to create the conductive radiating and ground elements, showcasing the versatility and adaptability of textile patch antennas in meeting the demands of modern wearable technology.

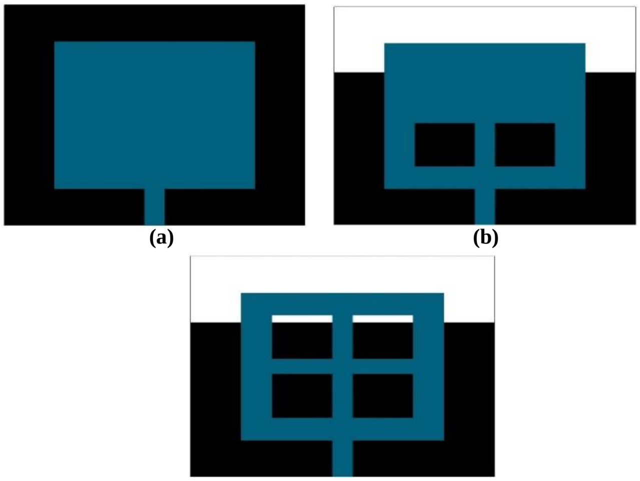
Advanced manufacturing techniques have revolutionized the high-volume production of these antennas, allowing for compact sizing and dual-polarization capabilities while maintaining an impressively unobtrusive. The selection of fabrication methods is a nuanced process, considering various pivotal factors such as antenna size, textile material properties, substrate thickness, flexibility, conformity when worn, scalability in production, and cost-effectiveness. Affectionately dubbed "textennas," these antennas come in diverse shapes, including rectangular, circular, elliptical, triangular, and square forms. Moreover, innovative designs inspired by nature continue to emerge, ensuring enhanced efficiency, flexibility, and safety across a spectrum of bending scenarios. This evolution in shapes ensures better performance and aligns seamlessly with the demands of wearable technology, allowing for optimal functionality in diverse applications.

The precision of fabrication, dimensional accuracy, and structural integrity during bending are critical considerations in antenna development. For instance, developers in [9] utilized embroidery using Shieldex Plated Nylon fibres on cotton textiles for on-body ISM band communications. A wearable antenna was made utilizing Pellon material with dimensions 57×32.1 mm², and conductive layers are realized using the conductive fabrics, operating at 2.45 GHz [10]. In a different approach, engineers in [11] exploited a dual frequency operating textenna on Jean fabric, operating at 2.45 and 5 GHz frequencies using conductive stitching threads. Researchers in [12] developed a wearable antenna utilizing the Jute fabric. A proper pre-investigation [13-17] was made to analyze the fabric, and the antenna was developed with a dimension of 16×20 mm^{2,} and it was rigorously tested by bending in various aspects.

This study delves into the design of wearable textile antennas using a streamlined manufacturing approach tailored for large-scale production. Rigorous analysis of these antennas' functional performance is conducted under on-body scenarios and diverse bending conditions. The paper is meticulously structured into distinct sections that encompass Antenna Design, offering intricate insights into the fabrication methodology; Bending Assessment, providing a comprehensive evaluation of performance amidst on-body interactions and varied bending circumstances; and a Conclusion section that briefly summarizes the outcomes derived from the comprehensive assessments conducted across on-body scenarios and bending evaluations. This systematic approach ensures a holistic understanding of the antenna's functionality in real-world applications and bending scenarios, shedding light on its viability for widespread adoption in wearable technology.

2. The Antenna Design

The design of the textile antenna draws inspiration from a square-shaped structure with a partial ground element. The antenna design was crafted on a jean-based textile substrate. The textenna measures 30×30×1 mm³, as depicted in Figure 1. The antenna's physical parameters were modelled using Ansys High-Frequency Structure Simulator (HFSS) version 19 software. In the first design step, a square patch of 20×20 mm^2 was considered a patch. In the second iteration, two square structures with a dimension of 6×6 mm^2 were opened on the bottom side of the patch. In the final iteration, two more square slots remained launched. In the ground iterations, the whole ground was turned into a partial ground to enhance the radiating characteristics of the proposed model. In the first design step, the antenna functions at a single frequency of 3.7 GHz. In the next step, the antenna operates at 4.5 and 6.7 GHz; in the final step, it functions at 3.75, 5.7 and 7 GHz at the onbody and ISM bands, as seen in Figure 2. The measurements of the propounded antenna components in mm include LS=30, WS=30, L1=20, L2=20, L3=6, and FL=5.


(a) (b)

(c)

Fig. 1 Iterations of the proposed antenna model

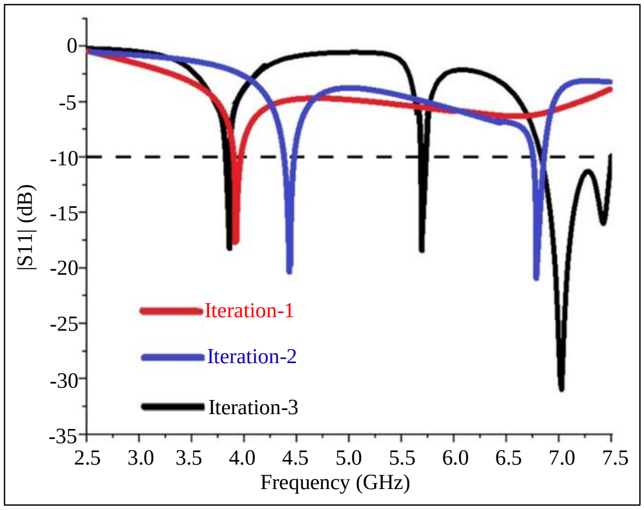
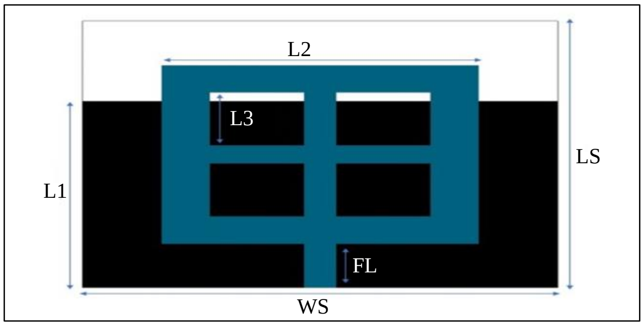
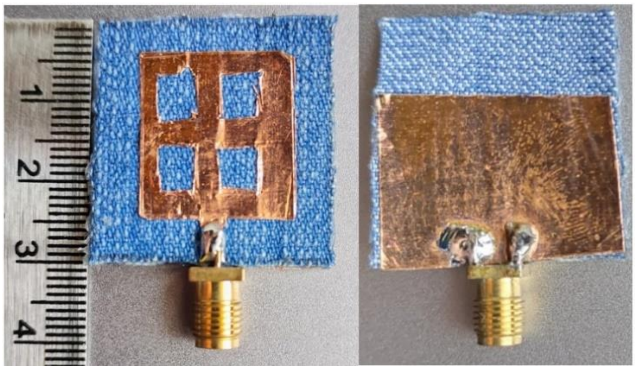


Fig. 2 Design steps of the proposed model



(a)



(b)

Fig. 3(a) The antenna model with parameters, and (b) prototype.

Textile antennas represent an innovative fusion of traditional antenna technology with fabric-based materials. These antennas are designed to seamlessly integrate into clothing or textile substrates, offering a range of benefits stemming from their flexibility, lightweight nature, and potential for unobtrusive integration into everyday garments. One significant advantage lies in using adhesive conductive films for fabricating these antennas. This method streamlines the production process by allowing the direct application of conductive materials onto the textile surface. Adhesive conductive films offer flexibility, allowing the antenna to conform to the textile's shape without compromising comfort. This flexibility is essential in garments, ensuring the antenna doesn't hinder movement or cause discomfort during wear.

Adhesive films simplify the integration process, enabling precise placement of conductive elements onto the fabric. This makes designing antennas that blend seamlessly into clothing easier, maintaining aesthetic appeal. These films typically have a minimal thickness and weight, ensuring the overall textile antenna remains lightweight. This characteristic is crucial in wearable technology, providing the antenna doesn't add unnecessary bulk or weight to the garment. Fabrication with adhesive conductive films can be scalable and cost-effective for mass production. The process lends itself well to automation, potentially reducing manufacturing costs compared to other methods. The use of adhesive films allows for precise customization of antenna designs.

Manufacturers can create various shapes and sizes of antennas to suit specific applications or design requirements. Overall, employing adhesive conductive films for fabricating textile antennas enhances their functionality, durability, and comfort while opening doors for innovative designs in wearable technology. The proposed antenna's prototype model is depicted in Figure 3. Figure 3a represents the final model with dimensions, and Figure 3b illustrates the fabricated model. Copper and silver are both excellent conductors of electricity, but they differ in conductivity and flexibility. Silver is the most conductive metal known to humans. It has the highest electrical conductivity of any metal, making it an exceptional material for conducting electricity. Copper also has high electrical conductivity and is the second most conductive metal after silver. While it's slightly less conductive than silver, it's still highly efficient for electrical conduction.

However, copper is more flexible than silver. In terms of flexibility, copper is generally more flexible than silver. Copper is known for its malleability and ductility, which can be easily bent, shaped, and formed without breaking. This flexibility makes copper a preferred choice for various applications that require the material to be shaped into intricate designs without losing its structural integrity. On the other hand, while silver is also somewhat malleable and ductile, it tends to be less flexible than copper. Silver is a softer metal than copper, but it can become brittle when repeatedly bent or subjected to mechanical stress, making it less ideal for applications where flexibility is a primary concern. For applications where flexibility is crucial, copper is often preferred due to its superior flexibility and ability to withstand bending and shaping without breaking or becoming brittle compared to silver. Hence, the copper film fabricated model is best suited for on-body applications.

3. Results and Discussions

3.1. Reflection Coefficient (S11)

The reflection coefficient is used in microwave engineering and Radio Frequency (RF) systems, particularly in characterizing devices like antennas, amplifiers, and other components in RF circuits. S11 refers explicitly to the reflection coefficient at Port 1 of a two-port network or device, commonly represented in a scattering parameter (S-parameter) matrix. As shown in Figure 4. The propounded model operates at 3.75, 5.7 and 7 GHz on body and ISM band applications. Both the simulations and measurements are decent matches with each other.

3.2. Radiation Patterns

The radiation pattern refers to the directional dependence of the strength of the emitted or received electromagnetic fields. These patterns are often analyzed in two principal planes: the Electric field plane (E-plane) and the Magnetic field plane (H-plane). The proposed antennas' simulated radiation patterns at 3.75, 5.7 and 7 GHz applications are illustrated in Figure 5.

3.3. Gain and Efficiency

The gain and efficiency of an antenna are essential parameters that characterize its performance in transmitting or receiving electromagnetic signals. Both gain and efficiency are critical in determining the overall performance of an antenna system. High gain is desirable for long-range communication or reception in a specific direction. In contrast, high efficiency ensures minimal power losses within the antenna system, leading to better overall system performance.

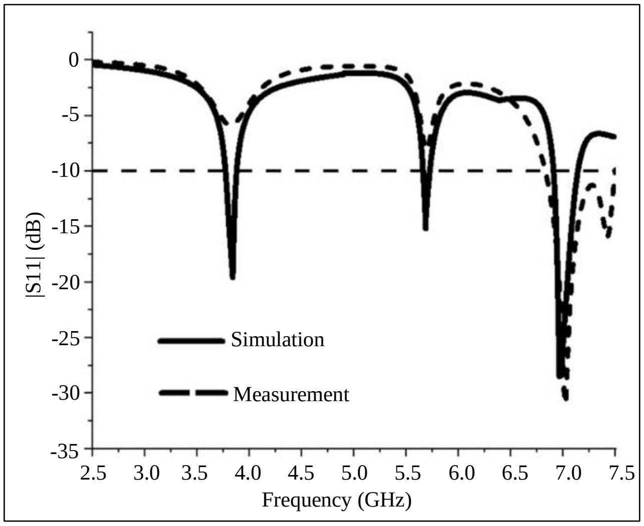
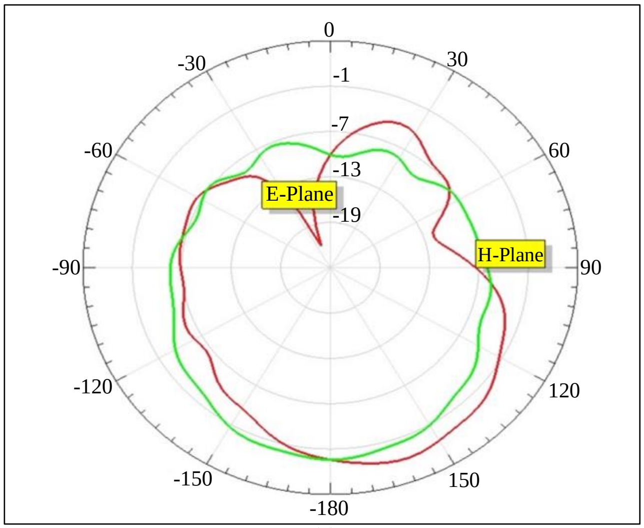
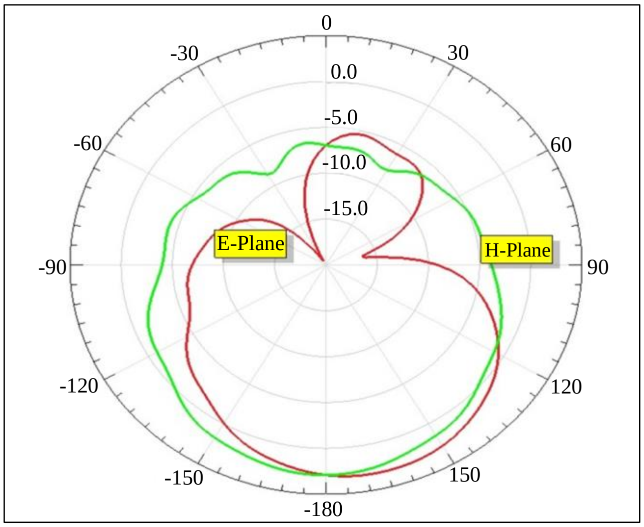


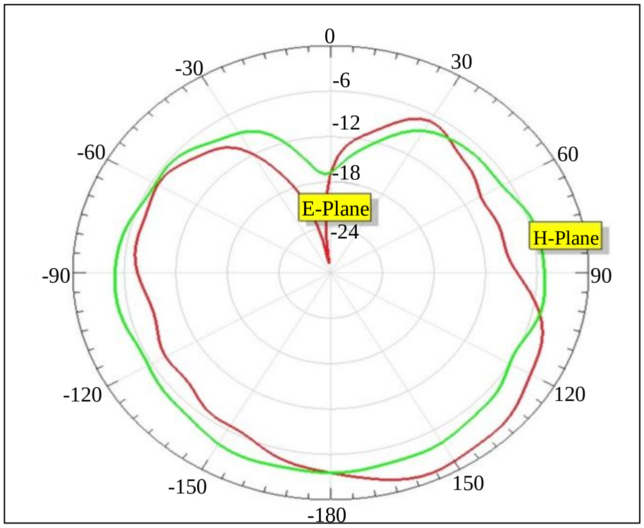
Fig. 4 The simulated and measured S11 plot



(a)



(b)



(c)

Fig. 5 The radiation patterns of the proposed antenna at (a) 3.75, (b) 5.7, and (c) 7 GHz frequencies.

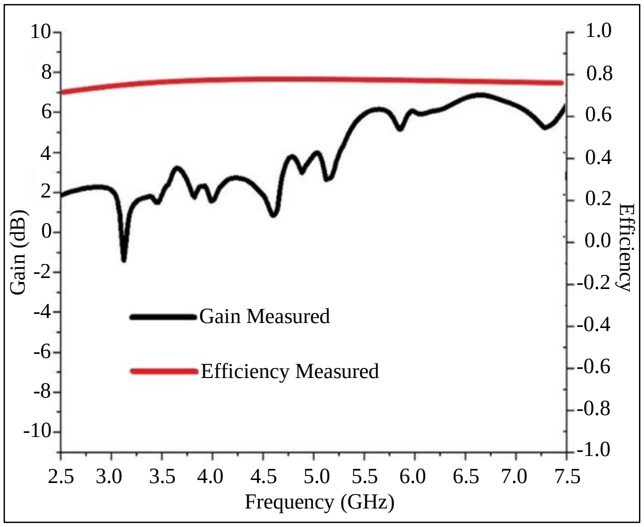


Fig. 6 The gain and efficiency plot

As illustrated in Figure 6. The gain of the proposed antenna is between 3.2-6.5 dB, and the efficiency falls around 80%.

4. Bending and SAR Analysis

4.1. Bending Analysis

This research investigates the operational performance of textile antennas when subjected to bending in both horizontal and vertical dimensions. As these antennas are integrated into clothing, they experience bending in various directions due to the heterogeneous nature of the human body. To assess this behaviour, real-time readings are conducted by conforming the propounded textenna onto a curved structure with a radius denoted as Rc, as depicted in Figure 7.

This study delves into two distinct bending characteristics, categorized as follows: (1) vertical perspective turning, involving bending concerning length, and (2) the horizontal perspective involves whirling, accompanied by a bending motion in relation to width.

When the textenna undergoes twisting along its lengthwise plane, it creates vertical bending scenarios. The subsequent section assesses the vertical flexibility response of the proposed polyester antennas, subjecting them to vertical twisting across a range of bending angles from 0 to 45 degrees, with increments of 15 degrees.

When the antenna is curved along its width level, it gives rise to horizontal bending scenarios. The subsequent section examines the horizontal flexibility response of the proposed polyester antenna by subjecting it to horizontal twisting across a spectrum of bending angles from 0 to 45 degrees. In both scenarios, as given in the Tables 1 and 2, the antenna functions well with a marginal change in the operating frequencies. However, they still fall under the ranges of WBAN and ISM bands.

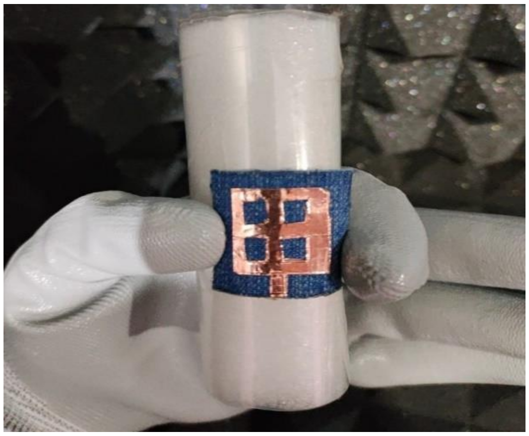


Fig. 7 Illustration of conformability of the proposed antenna

Table 1. X-axis bending concerning resonating frequencies

S. No.	Bending Angle (degrees)	Resonating Frequencies (GHz)
1	15	3.79, 5.72 and 7.1
2	30	3.82, 5.83 and 7.19
3	45	3.69, 5.6 and 6.9

Table 2. Y-axis bending concerning resonating frequencies

S. No.	Bending Angle (degrees)	Resonating Frequencies (GHz)
1	15	3.66, 5.61 and 6.91
2	30	3.61, 5.57 and 6.85
3	45	3.78, 5.77 and 7.7

4.2. SAR Analysis

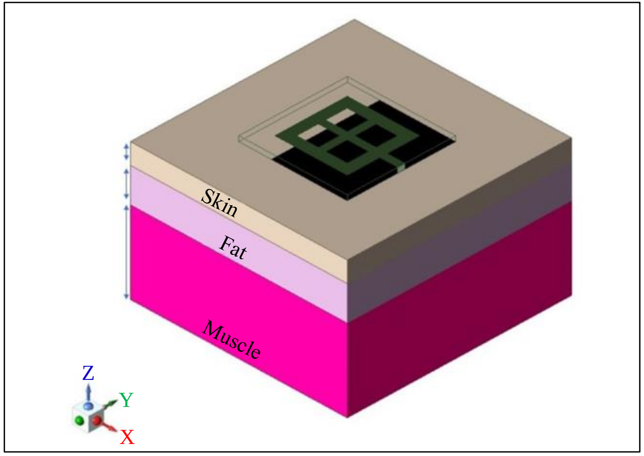


Fig. 8 The antenna on a human phantom model

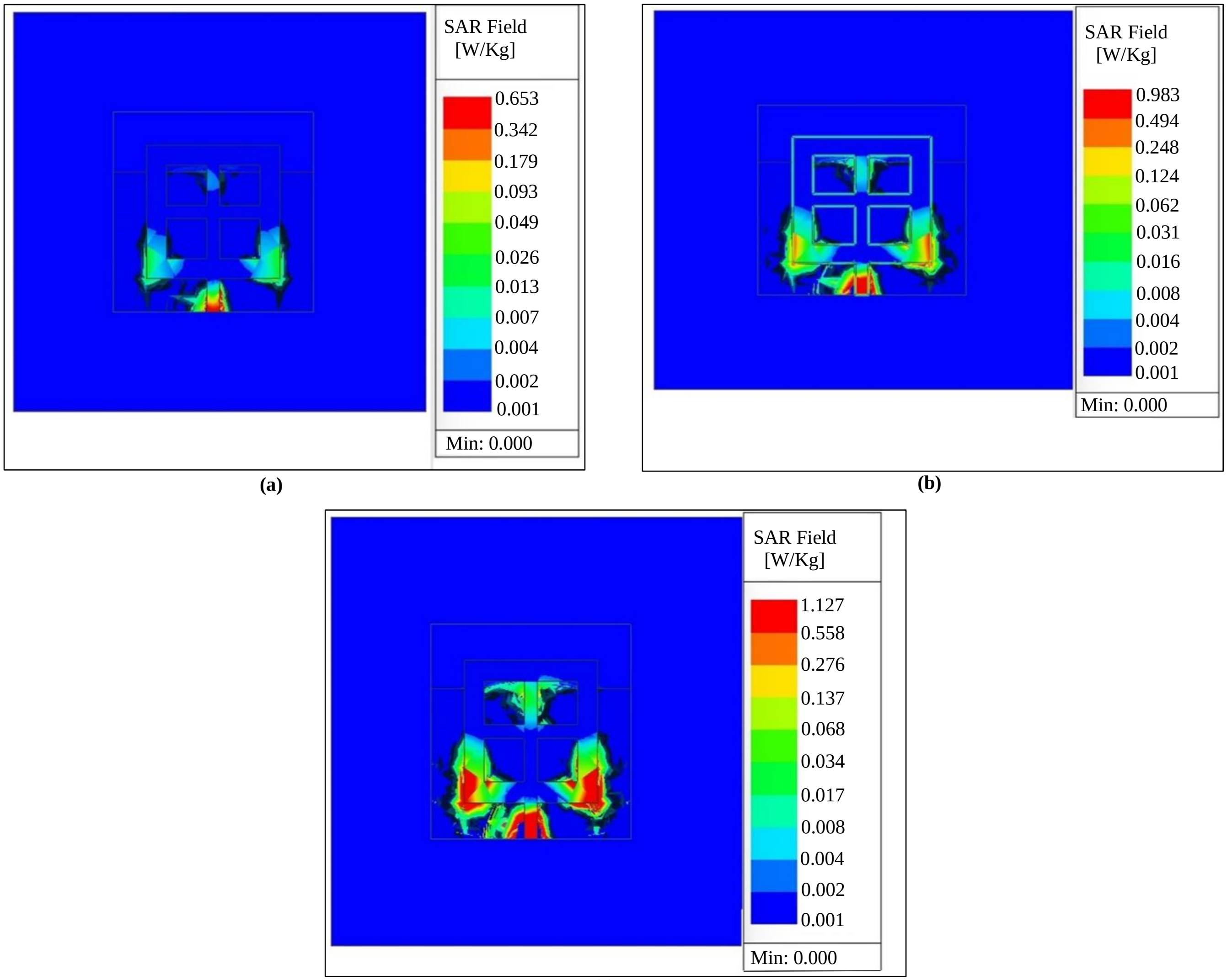
Textile antennas represent a significant advancement in wearable technology and applications centred around the human body, showcasing impressive qualities like flexibility, resilience, and wearability. Nevertheless, the interaction between the human body and electromagnetic waves necessitates careful consideration of specific absorption rates due to potential health implications.

To ensure these antennas' safe and dependable operation, conducting SAR analysis using a realistic human body model becomes imperative. This research used a sophisticated three-layered body phantasm prototype incorporating body tissues, as depicted in Figure 8. This specialized phantom model facilitates SAR calculations at various points across the body where textile antennas are present.

The unique three-layer phantom model comprises a 2mm skin layer, an 8mm fat layer, and a 23mm muscle layer. Through this comprehensive analysis, we can precisely determine SAR values at specific locations on the body impacted by the presence of textile antennas. This research provides invaluable insights into ensuring the safety and reliability of textile antennas in wearable applications.

Understanding the potential risks associated with textile antennas is crucial in guiding their design and optimizing performance. Utilizing a 3-level human phantom model for SAR assessment offers invaluable insights into the exposure and potential hazards linked with these antennas.

Specific Absorption Rate (SAR) evaluation using this model yields critical information. Regulatory standards typically limit maximum SAR values to 2 W/kg for accepted public exposure in the head and trunk regions. These values vary across the phantom's layers based on the antenna's frequency and power levels. Analyzing SAR values enables fine-tuning textile antenna designs, ensuring compliance with safety guidelines without compromising functionality.



(a) **(b)**

(c)

Fig. 9 The SAR analysis at 3.75, 5.7 and 7 GHz on body and ISM band applications

In this study, the proposed textenna was positioned exactly on the 3-layer body phantom, and SAR standards were meticulously analyzed, as depicted in Figure 8. Results shown in Figure 9 affirm that at frequencies of 3.75, 5.7 and 7 GHz on the body and ISM band applications, the maximum SAR recorded at 1 gram of tissue stands at 1.127, 0.983 and 0.653 W/kg, respectively. This comprehensive analysis assures the safety of employing the proposed antenna on the human body, meeting safety standards effectively. Such analysis ensures compliance and aids in optimizing textile antenna designs, striking the delicate balance between safety and performance for wearable applications.

5. Conclusion

This study introduces a jean-based antenna designed for wearable wireless communications at 3.75, 5.7 and 7 GHz frequencies on body and ISM band applications. Constructed using conductive copper film, this antenna's fabrication method facilitates large-scale production, offering a compact design ideal for seamless integration into human clothing. Emphasizing its purpose for wearable communication, rigorous testing involved assessments across various bending positions, ensuring adaptability and functionality.

Direct evaluations on body tissue confirmed the antenna's reliable operation when integrated into the human body, affirming its practicality for wearable communication systems. SAR analysis at 3.75, 5.7 and 7 GHz frequencies revealed maximum SAR limits of 1.127, 0.983 and 0.653 W/kg, respectively. These results, combined with functional and on-body assessments, firmly support the suitability of the propounded antenna design for safe on-body wireless communication at these frequencies.

In summary, the comprehensive analyses conducted, encompassing functional assessments, SAR evaluations, and on-body testing, collectively endorse the applicability and safety of the developed polyester textile antenna for robust and secure on-body communication at 3.75, 5.7 and 7 GHz frequencies. This research lays a solid foundation for advancing wearable communication technology while ensuring user safety and performance reliability.

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