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REGULAR ARTICLE

Groove-Slotted Textile Antenna for Enhanced Wearable Healthcare Applications

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This study proposed a novel Microstrip Patch Antenna designed on a flexible textile substrate for wearable applications. The compact antenna, measuring $0.28\lambda_0 \times 0.28\lambda_0$, achieved triple-band operation at 3.5 GHz, 8.52 GHz, and 10.9 GHz. The first band, the S-band, supports wireless body area networks (WBANs) for real-time health monitoring. The second band, in the X-band, enables high-resolution imaging and sensing for non-invasive diagnostics. The third band, in the upper X-band, supports medical and space research, offering precise movement detection for rehabilitation monitoring. The antenna's small size, wide impedance bandwidth, and multi-band operation ensure reliable data transmission and body-conformal compatibility. It adheres to the IEEE 802.15.6 standard for WBANs and supports applications like WLAN, WiMAX, and short-range communications. The design features a groove-shaped slot for improved impedance matching and bandwidth, along with truncated edges and a partially grounded plane for performance optimization. With a peak gain of 10.1 dBi, it provides efficient radiation in wearable scenarios. Constructed on a flexible Bakhram substrate, the antenna conforms to the human body, addressing challenges like signal attenuation and deformation. Its low specific absorption rate (SAR) ensures safety, making it suitable for healthcare monitoring, fitness tracking, and wearable communication systems.

Keywords: WBAN, WLAN, WiMAX, Bakhram substrate, IEEE 802.15.6, SAR, Body-centric application.

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1. INTRODUCTION

Textile antennas are known for their lightweight, flexible, and conformal nature, making them suitable for wearable applications like healthcare monitoring, fitness tracking, and military systems. Their ability to function under bending, stretching, and skin contact ensures their effectiveness for on-body communication. However, challenges such as performance stability, low SAR, and environmental durability remain, necessitating further advancements in this domain. Recent studies have focused on innovative materials and designs to improve their reliability and efficiency. Jeans cotton textile materials are widely utilized due to their flexibility, durability, and suitability for wearable applications [1]. A wideband, low-profile antenna was developed for wearable biomedical devices, exhibiting compactness and enhanced performance [2]. A textile-based meta-patch antenna with a seven-stage CWVM (Cockcroft-Walton Voltage Multiplier) rectifier improved gain, bandwidth, and efficiency for energy harvesting. A 2×2 rectenna array was fabricated on felt material and tested under free space, on-body, and Wi-Fi conditions, ensuring consistent performance for IoT and healthcare applications [3]. A circular patch antenna, featuring star and arc-shaped slots on semi-flexible Rogers RT/duroid 5870 with a partial ground, achieved omnidirectional radiation [4]. Research has explored various substrate materials for wearable antennas, including jeans, Polydimethylsiloxane (PDMS), denim, cotton, felt, and foam, due to their flexibility and suitability for wearable systems [5, 6]. Walsh-Hadamard coding techniques were found to be efficient and robust in ensuring orthogonality [7].

A low-profile antenna, fabricated on a thin Rogers 3003 Compact antennas with radiators featuring square and hexagonal rings allowed dual-band operation and frequency tunability, making them versatile for multiple applications [8]. Substrate, demonstrated stable performance in both flat and bent configurations, showcasing its practicality for wearable devices [9]. An advanced hexa-band metamaterial using tunable split-ring resonators exhibited high performance across the S, C, X, and Ku bands. This design utilized tunable metal strips for precise frequency customization, highlighting its potential for wireless communication and sensing applications [10]. A dual-band portable antenna fabricated on poly-cotton textile incorporated slot-loading techniques to excite higher-order modes, offering flexibility and conformability for wearable devices [11]. Antennas with square slotted structures and horizontal/vertical lines further enhanced their adaptability for wearable communication [12]. A compact triple-band antenna using hexagonal ring patches interconnected by a modified plus-shaped feedline resonated at 2.4 GHz, 3.5 GHz, and 5.5 GHz, supporting Bluetooth, WLAN, WiMAX, and 5G applications [13]. A four-port triband MIMO antenna, incorporating a G-shaped loop radiating patch with trimmed edges, achieved high gain

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and isolation for 5G mmWave systems [14]. A Y-shaped monopole antenna with an open-ring resonator provided efficient operation [15]. A transparent, flexible X-band antenna employed a dumbbell-shaped metasurface arranged in a checkerboard pattern for effective polarization conversion [16]. The dielectric constant of the jeans material (used as a textile substrate) was measured using the ring resonator method.

This on-body communication system, operating at 5.3 GHz, is ideal for Wi-Fi and medical applications [18], self-isolation MIMO (Multiple Input and Multiple output) method used for UWB(Ultra-Wide Band) [19]. While these advancements are noteworthy, several research gaps persist. Most wearable antennas face challenges related to environmental and mechanical conditions, including moisture, temperature fluctuations, and repeated deformations. Achieving a balance between compact size, wideband operation, and low SAR levels remains difficult.

Additionally, scalable and cost-effective fabrication methods are essential for industrial production but are not yet fully developed. Addressing these gaps requires ongoing innovation in materials, designs, and manufacturing approaches. This study introduces an antenna design operating at 2.5 GHz, making it suitable for Wi-Fi and medical applications. Its low-profile, wideband structure includes slots to improve operational bandwidth, achieving a reflection coefficient (S11) of –30.4 dB. This antenna is versatile for various wireless applications, particularly in healthcare. Moreover, the study underscores the importance of cost-effective and scalable manufacturing techniques to enable large-scale production, ensuring the practicality and industrial viability of wearable antennas.

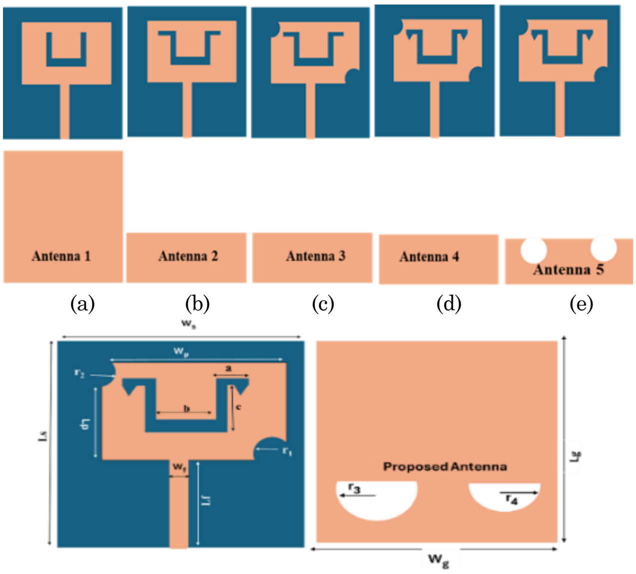
2. PROPOSED ANTENNA DESIGN

Figure 1 illustrates the geometry and dimensional specifications of the proposed compact wideband wearable antenna. The antenna's overall physical volume is $0.28\lambda_0 \times 0.28\lambda_0$ mm^3, where λ_0 represents the free space wavelength. Fabricated on Bakhram substrate with a dielectric constant (ε_r) of 1.96. The antenna consists of a patch with a small rectangular extension and two additional rectangular slots. The proposed antenna is designed and simulated using Ansys 2021 R2 HFSS software. The optimized antenna design parameters are tabulated in Table 1.

Table 1 – Principal parameters of different layers used for the simulation

Parameter	Value (mm)	Parameter	Value (mm)
W_s	35	r_2	1.5
L_s	35	r_3	3.5
W_f	3	r_4	2.5
L_f	18	a	4.5
W_g	12.5	b	11
L_g	35	c	7.5
r_1	1.5	d	15
L_p	18	W_p	27

The design evolution of the proposed compact Groove shaped slot Textile wearable antenna is depicted in Fig. 1. Initially, a solid rectangular patch with a U-shaped slot full ground plane for basic resonance is designed, as depicted in Fig. 1(a) (considered as reference antenna). To match the impedance of 50 ohms, U-slot is further extended in the patch. Further, the full ground plane of the proposed design is altered as partial ground plane as shown in Fig. 1(b), to enhance the reflection coefficient.



(f)

Fig. 1 – Design evolution of all steps(a-e), whereas the proposed structure (*f*) is proposed Textile wearable design.

As depicted in Fig. 1(c), incorporated symmetrical circular corner truncations having dimensions r_1 = 1.5 mm and r_2 = 1.5 mm to improve radiation performance. And two triangular slots engraved on the patch to enhance the impedance bandwidth as depicted in Figs. 1(d). The final design adds circular slots on the ground plane and fine-tunes the geometry, ensuring compactness and optimal performance under wearable conditions. The progression demonstrates systematic improvements in bandwidth, efficiency, and overall stability 1(e). Whereas Fig. 1(f) partial ground plane to improve antenna performance. Further modified partial ground plane to full ground plane with two unsymmetrical semicircular slots on ground The progression demonstrates systematic improvements in bandwidth, efficiency, and overall stability illustrates in Fig. 1(f) is proposed antenna. The full ground plane design offers several advantages for wearable antennas. It provides better isolation from the human body, reducing SAR, improving radiation efficiency, and ensuring stable resonance even under bending conditions. Additionally, it directs radiation away from the body, enhancing safety and overall performance [17]. The proposed antenna achieved results, and the comparative analysis of all design steps is further discussed in Fig 2.

3. RESULTS AND DISCUSSION

The performance of the proposed antenna was evaluated based on its reflection coefficient, radiation pattern, and gain, demonstrating its suitability for wearable biomedical applications. Initially, the solid rectangular patch with a U-shaped slot and a full ground plane, as shown in Fig. 1(a). resonated at 3.3 GHz. Replacing the full ground plane with a partial ground, as depicted in Fig. 1(b). improved the return loss to 22.8 dB but resulted in a narrow bandwidth of 0.13 GHz. Adding symmetrical circular cuts with a radius of 0.5 mm at the patch corners, as shown in Fig. 1(c). shifted the resonant frequency from 3.14 GHz to 4.3 GHz. Further modifications, such as engraving groove-shaped slots on the patch, as shown in Fig. 1(d). enabled dual-band operation at 3.63 GHz with a bandwidth of 0.91 GHz (3.08-3.99 GHz) and 6.1 GHz with a bandwidth of 1.16 GHz (5.75-6.91 GHz).

Incorporating symmetrical circular slots with a radius of 3.1 mm on the ground plane, as shown in Fig. 1(e). achieved triple-band operation at 2.82 GHz, 8.52 GHz, and 10.9 GHz, with impedance bandwidths of 0.74 GHz, 1.55 GHz, and 1.00 GHz, respectively. The first band, centered at 2.82 GHz in the S-band, is suitable for WBANs and low-power communication systems, enabling real-time health monitoring in wearable biomedical devices. The second band, centered at 8.52 GHz in the X-band, supports high-resolution imaging and sensing for non-invasive diagnostics and health monitoring. The third band, centered at 10.9 GHz in the upper X-band, is ideal for advanced medical and space research, offering precise movement detection and tracking, particularly for rehabilitation monitoring.

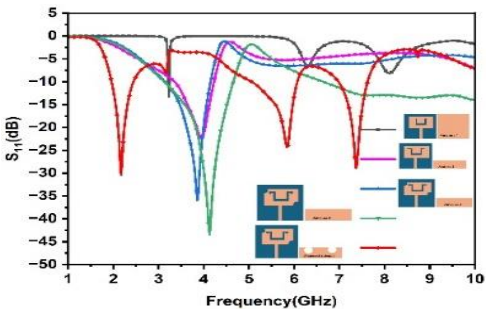


Fig. 2 – Reflection co-efficient (S_{11}) at different design evolution steps

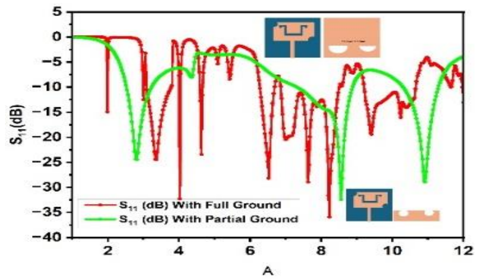


Fig. 3 – Reflection co-efficient (S_{11}) at partial ground and full ground design evolution steps

The final antenna design, shown in Fig. 1(f). includes a full ground plane with two unsymmetrical semicircular slots of radii r_3 = 3.5 mm and r_4 = 2.5 m. This modification enhances the antenna's performance for wearable applications, enabling efficient operation at multiple frequencies: 3.5 GHz, 6.29 GHz, 8.5 GHz, 10.9 GHz, 15.57 GHz, 18.47 GHz, 20.07 GHz, and 23.11 GHz, as shown in Fig. 3. In comparison, a partial ground plane offers compactness and flexibility but increases electromagnetic coupling with the body, leading to higher SAR, detuning, and reduced radiation efficiency, which makes it less suitable for wearable applications. The adoption of a full ground plane addresses these challenges, ensuring reliable, efficient performance across multiple frequency bands, making the design ideal for wearable biomedical applications.

According to the data observed, the antenna design has achieved Peak gain is 10.1 dBi at a frequency of 2.5 GHz, as shown in Fig. 3. In Fig. 5. Illustrates 2D far field radiation pattern at resonating frequency of Show in Fig 8. The fabricated prototype antenna, using a bakharam textile substrate, demonstrated effective performance at 3.5 GHz, confirming its suitability for Wi-Fi and medical applications. 2.5GHz for φ = 0° and φ = 180° orientations. The proposed antenna demonstrates maximum radiation power in the broadside direction.

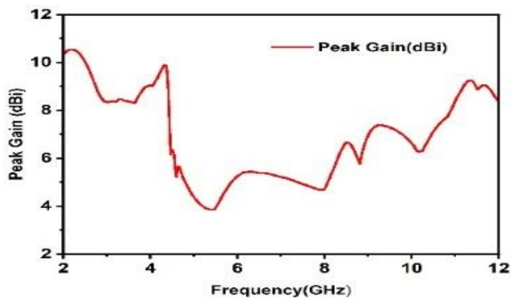


Fig. 4 – Peak Gain at 3.5 GHz

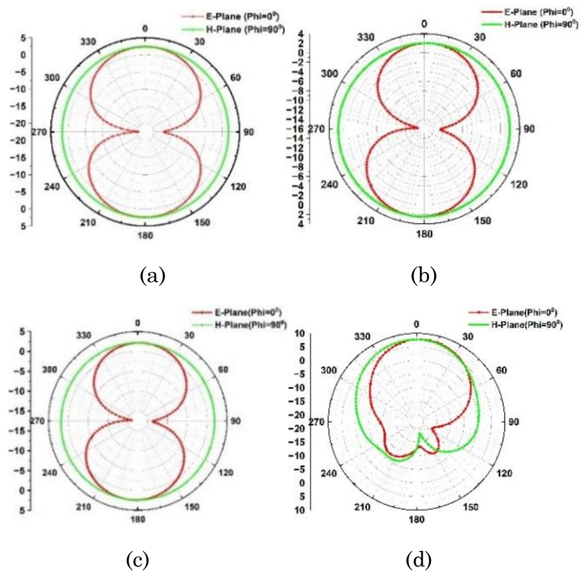


Fig. 5 – 2D far field radiation pattern (a) at 3.5 GHz,(b) at 8.52 GHz (c) at 10.9 GHz and (d) 2D far field at Full ground plane

Furthermore, the directional radiation pattern ensures effective signal transmission, making it suitable for wearable biomedical applications. Figure 6 shows the surface current distribution of the proposed antenna at 3.5 GHz. Strong current density is observed around the Grooved – shaped slot and feedline, ensuring effective resonance. The symmetrical circular slots on the ground improve current flow, enhancing the antenna's overall performance.

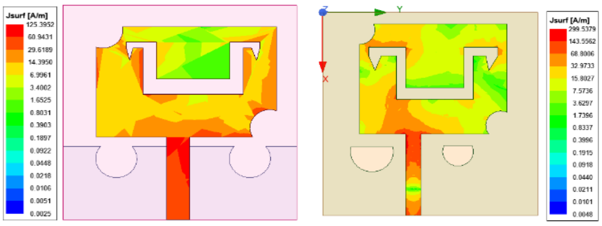
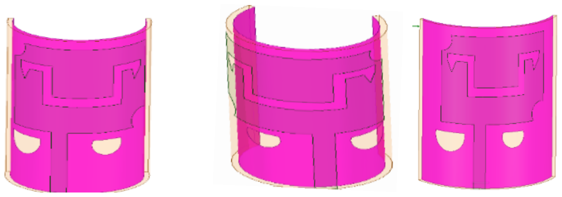


Fig. 6 – Surface current distribution with partial ground at 3.5 GHz

The proposed antenna was tested in both bending Fig. 7 and flat Fig. 2 conditions for wearable biomedical use. The conformal design worked well under bending, with bands at 2.82 GHz for health monitoring, 8.52 GHz for diagnostics, and 10.9 GHz for motion tracking. The flat design gave better results in static conditions but could not adapt to body movements. The conformal antenna's flexibility makes it ideal for wearable healthcare systems. Bending analysis at 3.5 GHz, 6.29 GHz, 8.5 GHz, and 10.9 GHz Fig. 7 showed stable performance with minimal changes in reflection and radiation, confirming the full ground plane design's reliability for wearable applications.



(a) Θ = 0⁰ (b) Θ = 45⁰ (c) Θ = 60⁰

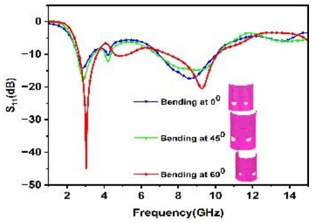


Fig. 7 – Antenna Bending Analysis at different angles and |S11|

Fig. 8 – Fbricated prototypeantenna top and bottom view

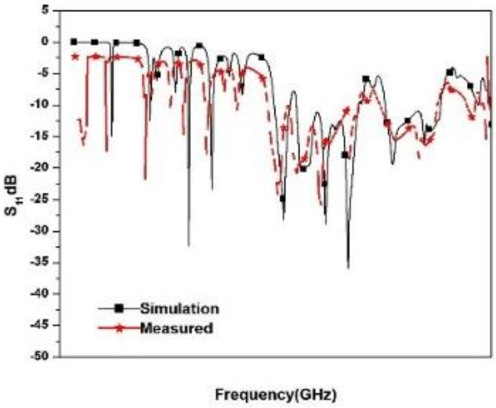


Fig. 9 – Simulated vs. Measured S11(dB)

The comparative performance analysis of the proposed antenna design, as shown in Table II, includes key parameters such as reflection coefficient, gain, and bandwidth. The results demonstrate that the proposed design is compact, provides a wide bandwidth, and achieves high gain, making it particularly suitable for wearable applications operating at 3.1 GHz.

Table 2 – Comparative analysis with other conventional antennas

Ref. No	Substrate	Dimensions (mm²)	Band Width (GHz)	Operating Frequency (GHz)	Peak Gain (dBi)	Reflection Co-efficient (S11)	Confor-mal	SAR (W/Kg)
[1]	RT/Duroid 5880	$0.47\lambda_0 \times 0.47\lambda_0$	0.32	2.45	3.69	– 69.1	Yes	–
[3]	RT/Duroid 5870	$0.38\lambda_0 \times 0.25\lambda_0$	1.2/0.94	2.45/5.2	2.5/4.63	–	Yes	–
[4]	Jeans	tt × $0.25\lambda_0$	0.25/1.4	2.4/5.8	1.1/3.9	– 30	Yes	0.15/0.89
[8]	Rogers 3003	$1.12\lambda_0 \times 0.28\lambda_0$	0.68/0.86	28/38	6.11/7.15	– 20.11	-	0.9, 0.7/ 1.14, 1360
[12]	FR_4 Epoxy	$0.29\lambda_0 \times 0.31\lambda_0$	0.23/0.88/0.23	2.4/3.5/5.5	3.51/4.91/5.23	– 26/– 46/–48	-	–
[15]	PDMS	$0.55\lambda_0 \times 0.55\lambda_0$	2.8	15.2	11	– 34.5	Yes	–
Proposed work	Bakhram	$0.28\lambda_0 \times 0.28\lambda_0$	0.74/1.55/1	3.5/8.5/10.5	10.1	– 30.4	Yes	–

4. CONCLUSION

The proposed antenna features a compact, conformal design with triple-band operation at 3.5 GHz, 8.52 GHz, and 10.9 GHz, providing wide impedance bandwidths of 0.74 GHz, 1.55 GHz, and 1.00 GHz, respectively. These frequency bands are well-suited for WBANs, high-resolution imaging, and advanced medical diagnostics. With low SAR values, the antenna ensures safe on-body operation, while its stable performance, flexibility, and reliable data transmission make it ideal for wearable biomedical applications. The measured results of the fabricated prototype align well with the simulated results. A comparative performance analysis with traditional antennas is presented in Table 2.

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Портативна антена з пазами та прорізами для медичних застосувань

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У цьому дослідженні запропоновано нову мікросмужкову патч-антену, розроблену на гнучкій текстильній підкладці для портативних пристроїв. Компактна антена, з розмірами $0{,}28\lambda_0 \times 0{,}28\lambda_0$, працює у трьох діапазонах: 3,5 ГГц, 8,52 ГГц та 10,9 ГГц. Перший діапазон, S-діапазон, підтримує бездротові мережі на тілі (WBAN) для моніторингу показників здоров’я в режимі реального часу. Другий діапазон, у X-діапазоні, забезпечує отримання зображень та зондування з високою роздільною здатністю для неінвазивної діагностики. Третій діапазон, у верхньому X-діапазоні, підтримує медичні та космічні дослідження, пропонуючи точне виявлення руху для моніторингу реабілітації. Невеликий розмір антени, широка смуга пропускання імпедансу та багатодіапазонна робота забезпечують надійну передачу даних та сумісність з тілом. Вона відповідає стандарту IEEE 802.15.6 для WBAN та підтримує такі програми, як WLAN, WiMAX та зв’язок на короткій відстані. Конструкція має пазоподібний паз для покращеного узгодження імпедансу та смуги пропускання, а також усічені краї та частково заземлену площину для оптимізації продуктивності. З піковим коефіцієнтом підсилення 10,1 дБі вона забезпечує ефективне випромінювання в умовах носіння. Побудована на гнучкій підкладці Бахрама, антена адаптується до форми людського тіла, вирішуючи такі проблеми, як ослаблення сигналу та деформація. Її низький питомий коефіцієнт поглинання (SAR) забезпечує безпеку, що робить її придатною для моніторингу здоров'я, відстеження фізичної форми та систем носіння зв’язку.

Ключові слова: WBAN, WLAN, WiMAX, Підкладка Бахрама, IEEE 802.15.6, SAR.