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ORIGINAL RESEARCH ARTICLE

Investigation on Performance of Wearable Flexible On-Body Ultra-Wideband Antenna Based on Denim for Wireless Health Monitoring

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Abstract

Wireless health monitoring systems based on flexible wearable antennas are in high demand in recent times to facilitate communication among people and their health care providers. The major purpose of this research is to investigate the performance of a low-cost, fabric-based flexible wearable antenna design fabricated on denim for wireless health monitoring. The primary features of this antenna are its small size with overall dimensions of 30 mm × 35 mm × 1.2 mm, large impedance bandwidth of 114.6 %, high gain, and directivity of 4.63 dB and 4.86 dBi, respectively, at 9.82 GHz. The compact size, light weight, low cost, flexibility, simple fabrication, and easy integration within clothing are the key highlights of the ultra-wideband (UWB) antenna that make it a perfect choice as a human body-worn antenna for utilization in wireless body area network (WBAN) systems. The simulation and measurement results of the designed antenna are found to be in good agreement and confirm its superiority and fitness for WBAN applications to be operable for the ultra-wideband.

Keywords Ultra-wideband (UWB) · wireless body area network (WBAN) · wearable antenna · flexible antenna · gain · return loss · VSWR · wireless health monitoring

Introduction

In earlier research of wireless body area networks (WBAN), the main emphasis is on the usage of the sensor as a major component of WBAN systems which has constraints in self-identification capability and node placement detection, therefore, lacking efficiency and reliability for health monitoring. Sensor nodes not only have power constraints and hardware limitations but also not all the sensors are applicable or safe for the human body.[1] Therefore, there is a requirement to develop an accurate and reliable wireless health monitoring system based on an efficient, flexible, and compact antenna that can work without using additional sensors. The ultra-wideband (UWB) antenna operable in a frequency span of 3.1 GHz to 10.6 GHz is preferred because of the low radiation levels that are safe for human body tissues, considerably high data rates, enhanced communication range, enlarged channel capacity, resistance to jamming and remarkable performance with a small signal-to-noise ratio.

Although the Medical Implant Communication System (MICS), industrial, scientific, and medical (ISM), and terahertz frequency band are other competing bands for developing and executing WBAN systems, the merits of UWB antenna affirm its suitability for WBAN applications.[2] Three types of sensors, i.e., on-body (placed in direct contact with the body), in-body (that can be implanted inside the body), and off-body (placed in the vicinity of the body), are generally deployed in WBAN. In the current research, major emphasis will be on the latest WBAN on-body communication systems based on an on-body UWB wearable antenna used as an integral part of WBAN sensor node. The utility of this presented antenna has been justified by investigating the on-body effect of the human body on the performance characteristics of the antenna over the entire UWB range.

The design of the flexible antenna is discussed and comparatively analysed by using three different substrate materials, i.e., denim cotton, Teflon, and FR4 substrate material

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for the ISM band. FR4 provides better antenna performance efficiency in the context of resonating frequency. The denim textile substrate exhibits better performance in terms of bandwidth and resonance features, and the Teflon-based antenna was found to be suitable for high-speed communication systems. The on-body effect of the designed UWB antenna using AR 350 substrate material at different frequencies by utilizing an on-body propagation model in parallel and perpendicular orientations is studied and the latter is found to have a superior effect in the context of antenna gain and impedance characteristics.[3,4]

The fabrication techniques of two categories of flexible antennas, i.e., textile and non-textile antennas, are discussed by Corchia et al.[5] Fabrication techniques can rely on similar traditional IC manufacturing techniques or copper-clad laminates, and a solid ink printer or adhesive flexible copper foil and a laser-based cutting machine can be used for antenna fabrication. The testing and simulation result of a 60 GHz flexible antenna is demonstrated for millimeter-wave communication.[6] The designed UWB wearable antenna's characteristics and its impact, when worn on the body, have been numerically represented through an equivalent circuit model of antenna design and circuit theory analysis.[7] Ahmed et al.[8] demonstrated a specific absorption ratio (SAR) investigation of a wearable and flexible antenna making use of electromagnetic characteristics of the traditional metal plane as well as e-textile cell-based on electro-textile material as two types of conducting materials. Various fabrication techniques and testing of different flexible antenna designs based on Kapton polyimide material substrate applicable in the ISM band are explained.[9]

A compact button-shaped antenna design is presented, and SAR is analyzed. On-body and off-body characteristics of the implemented antenna which can be integrated within clothing are studied for WBAN communication applications.[10] Saeed et al.[11] highlight a flexible antenna with reconfigurability and resilience features utilizing an artificial magnetic conductor, slotted structure with a PIN diode. Antenna performance metrics and SAR gets improved with this design. Gao et al.[12] demonstrated an explorative study of aperture coupled geometry of WBAN antenna design for 2.45 GHz ISM band utility. The effect of the various feed line dimensions, curves, and bending in antenna geometry is studied. Wang et al.[13] highlights the suitability of the microstrip patch antenna for designing wearable antennas because of its low profile, simplicity in design and fabrication, low cost, and desirable radiation specifications such as high directivity.

Many altered designs and fabrication techniques of the triple-band and dual-band denim substrate-based textile antenna with large impedance bandwidth are presented. The simulation and fabrication results of the implemented antenna to be applicable in a variety of wireless applications in the fields of medical communication, military, etc., are demonstrated.[14,15] An inverted E-based antenna design and analysis is a wireless health monitoring system designed and implemented by utilizing body-worn antennas for continuous remote observation of health conditions of elderly persons or patients.[16] Design considerations and integrated fabrication techniques are discussed, including non-woven conductive fabric and e-textiles. A light-weight foam-based flexible hexagonal-shaped micro-strip patch antenna with high gain (9.14 dB) and slotted geometry is designed and analyzed.[17] The designed inexpensive, circularly polarized antenna is applicable for body area network applications presented for medical communications in the ISM band. Antenna performance is demonstrated by implementing an equivalent circuit model of the presented antenna.[18] Rao et al.[19] performed research and reviewed UWB antennas for their fabrication technologies and applications. Different broadband methods are investigated along with other approaches for bandwidth enhancement. Samal et al.[20] considered different optimization and fabrication procedures for the proposed novel design of compact textile antenna and discussed simulation results. Salleh et al.[21] presented a reconfigurable antenna that is circularly polarized. PIN diode-based reconfigurable switches are utilized for different GPS and Wi-Fi applications. Non-resonance and resonance techniques of substrate dielectric material characterization are discussed.[22] Non-resonant techniques to determine the magnitude of dielectric constant and dielectric characteristics deal with transmission/reflection procedures. Resonance methods are applied for dielectric permittivity and permeability characterization and are based on rectangular or circular waveguide-based resonant cavities and resonance-perturbation procedures. Liu et al.[23] discussed the application of electro textile material cells and their radiation properties. The impact of variation in e-textile materials and their properties such as woven density on antenna performance is also shown. The gain and bandwidth maximization method for UWB utility is discussed through a tapered slotted antenna with less cross-polarization.[24] A new small-sized ultra-wideband antenna is designed by utilizing stub expanding in the ground. This leads to enhancement of bandwidth by the creation of a resonant frequency at the smaller band.[25] The on-body and off-body effects and specific absorption rate are analysed for the designed fabric-based antenna is highlighted. The electromagnetic characteristics of the proposed antenna are evaluated to detect a tumour in the human body, particularly applicable for the detection of breast cancer.[26] A small-sized UWB antenna with hexagonal slot design geometry is implemented and analyzed for biomedical applications.[27]

The latest developments in the field of technologies related to textile-based body-worn antennas has been discussed. The effect of the various conducting materials used for antenna design and bending studies are also analyzed and explained.[28]The operation of designed and fabricated E-shaped polyester textile-based antenna is highlighted for WiMax utility, and the effect of bending cycles is explained for the antenna design.[29]

Based on extensive literature survey of comparable antenna designs, it has been observed that balancing the trade-offs between antenna performance, flexibility, cost, and size is still an underwhelming research focus. Therefore, to fill this identified gap, there is a requirement to design and implement an efficient UWB antenna with enhanced gain, compact size, low cost, and flexibility characteristics for WBAN applications such as wireless health monitoring systems. This research illustrates novelty in the design of the proposed ultra-wideband antenna based on minimization of surface wave losses, thereby increasing gain and impedance bandwidth by utilizing denim textile material with low relative permittivity $\varepsilon_r = 1.7$ as substrate. Minimization of electromagnetic deposition on the human body and bending losses effects because of body movements is achieved by reduction of the metal portion of the radiating patch of on the body-wearable antenna.

The dielectric characteristics of human body tissues, different body movements such as bending, and various on-body conditions such as wetness and humidity, are responsible for altering the antenna functionalities and characteristics. The conventional antennas based on a substrate with high relative permittivity material or rigid materials possess limitations in this regard. The low relative permittivity material denim substrate is preferably chosen for body-worn flexible antenna for wireless health monitoring because it achieves the desired radiation characteristics, enhanced bandwidth, and flexibility of antenna along with other features such as simple fabrication, low-cost, high flexibility, light-weight, mechanical robustness, can be easily placed on the human body or can be integrated onto clothing. The designed wearable antenna can also be placed inside the wearer's clothing in a hidden manner.

In the presented research work of antenna design and development, the major contributions are as follows:

- A flexible wearable UWB miniaturized antenna using denim textile substrate has been designed, simulated, and fabricated, and a parametric study has been performed.
- A correlative study of simulation and experimental results of the fabricated antenna in terms of performance specifications has been conducted.
- The comparative exploration of the presented fabricated antenna has been performed with comparable WBAN antennas discussed in the literature.

The paper is structured as follows. The “Introduction" section highlights the literature survey and related work and the main considerations of the research work. The antenna structural dimensions, description of substrate material, and fabrication techniques are framed in the “Fabric-Based Flexible Antenna Design Geometry" section. The next Section describes “simulation results and the parametric study”. The experimental setup and fabrication results are presented “Experimental Results and Discussion" section. “Conclusion" highlights the summary and future work.

Fabric-Based Flexible Antenna Design Geometry

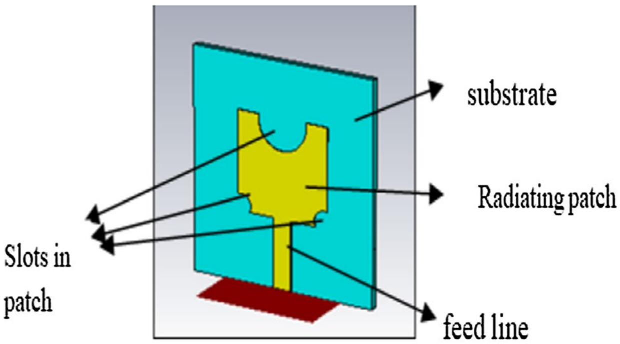
Antenna Structure

In the proposed rectangular microstrip patch antenna, basic geometry includes sandwiched denim substrate between upper conductor as a slotted radiating patch and lower conductor as partial ground. The designed antenna is fabricated on denim substrate with dimension 30 mm × 35 mm × 1 mm and relative permittivity and loss tangent 1.7 and 0.025, respectively. The ground plane and radiating patch are designed by using adhesive copper tape with a conductivity of 5.88×10^7 S/m and 0.1 mm thickness. For providing perfect 50 Ω impedance matching to the fabricated antenna, a microstrip feed line with dimensions 13.5 mm × 2.85 mm is used with a Sub-Miniature Version A (SMA) connector. The initial dimensions of the rectangular microstrip patch antenna are calculated from basic antenna design equations.[30] Figure 1 demonstrates a simulation model of the proposed antenna with design geometry of the radiating patch, substrate, and partial ground. Antenna design parameters with dimensions are shown in Table I.

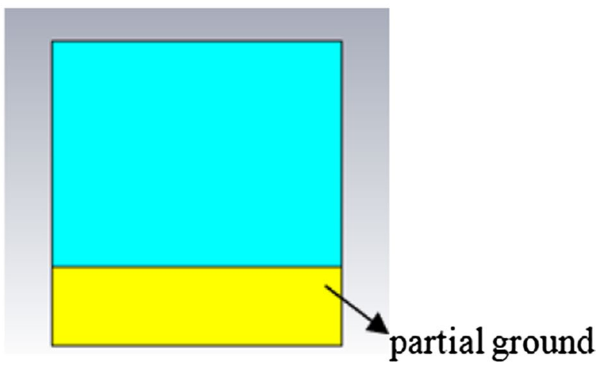
Optimization process and parametric study by varying various parameters specifications to get the final design geometry is performed using Computer Simulation Technology (CST) Microwave Studio as the antenna simulator software. The antenna’s performance with optimized geometry is enhanced by incorporating slots grooved from the radiating patch and partial ground, which is responsible for better impedance matching, bandwidth enhancement, negligible bending effect, low electromagnetic deposition, and reduced size due to removal of the metal portion.

Substrate Material Characteristics

Major design considerations for wearable, flexible antennas are the durability of wearable clothing and devices, robustness to harsh operating conditions, mechanical deformations, and impact of activities such as washing and ironing. The antenna RF characteristic variations due to bending and twisting in the proximity of the body is also a design issue that can possibly be solved by applying flexible antennas. The proposed flexible antenna design was preferably chosen



(a) Radiating patch geometry



(b) Partial ground structure

Fig. 1 CST Simulation model (a) Radiating patch geometry (b) Partial ground structure.

Table I Dimensions of the proposed antenna

Antenna design parameter	Dimensions
Overall size	30 mm×35 mm×1.2 mm
Substrate dimensions	30 mm×35 mm×1 mm
Patch dimensions	14.5 mm×15 mm
Ground dimensions	30 mm×8.5 mm
Feed dimensions	13.5 mm×2.85 mm

denim textile material as substrate as it minimizes surface wave losses and enhances bandwidth because of its low relative permittivity $\varepsilon_r = 1.7$. The denim substrate is a perfect choice for a body-worn flexible antenna for a wireless health monitoring system because it achieves the desirable characteristics that include a low-cost feature, high flexibility, light weight, mechanical robustness, and required radiation characteristics. Table II specifies the characteristics of substrate material used in the presented antenna.[2,14]

Table II Substrate material properties

Fabric substrate material	ε_r (Relative permittivity)	tan δ (Loss tangent)	h (Height of substrate in mm)
Denim	1.7	0.025	1

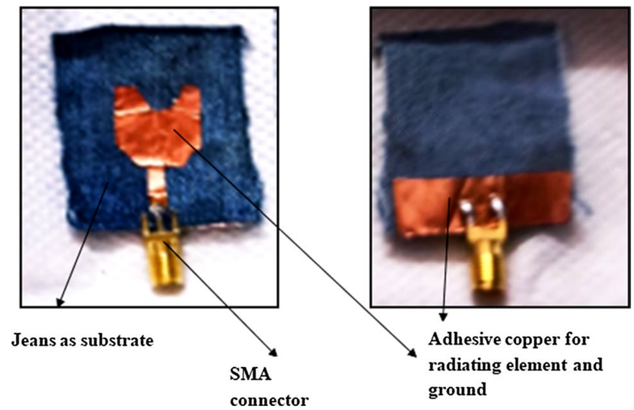


Fig. 2 Screenshots of the fabricated antenna.

Antenna Fabrication

Steps implemented for the designing and fabrication of a wearable, flexible antenna are as follows:

1. Selection of substrate material and other design considerations according to application requirements.
2. Defining the antenna geometry and dimensions.
3. Simulation using an EM simulator such as CST until desired performance characteristics are obtained.
4. Preparation of textile-based flexible substrate suitable for the application.
5. Fabrication of the antenna by cutting the self-adhesive conductive copper tape and substrate material (denim) and sticking copper tape on the substrate.
6. Connection of the SMA connector.

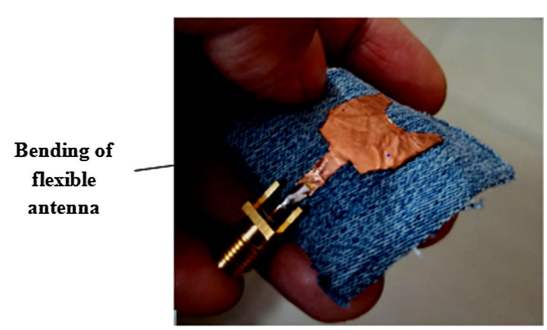


Fig. 3 Flexible denim-based wearable antenna.

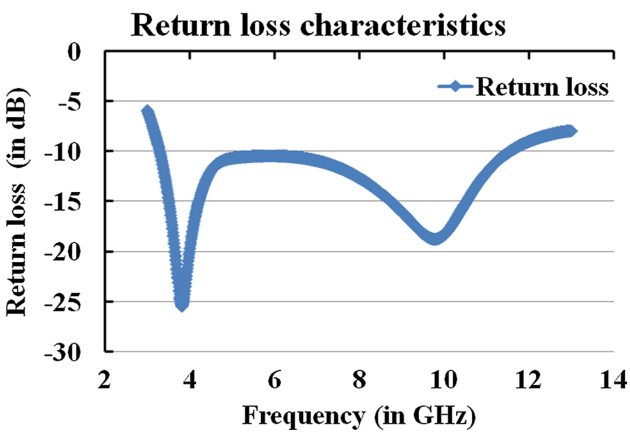


Fig. 4 Simulated return loss characteristics.

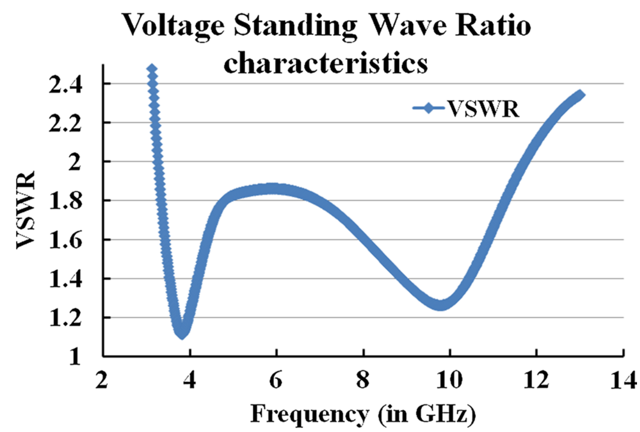
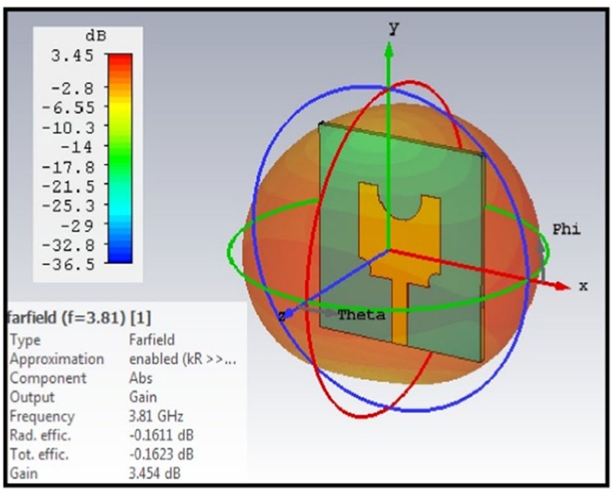
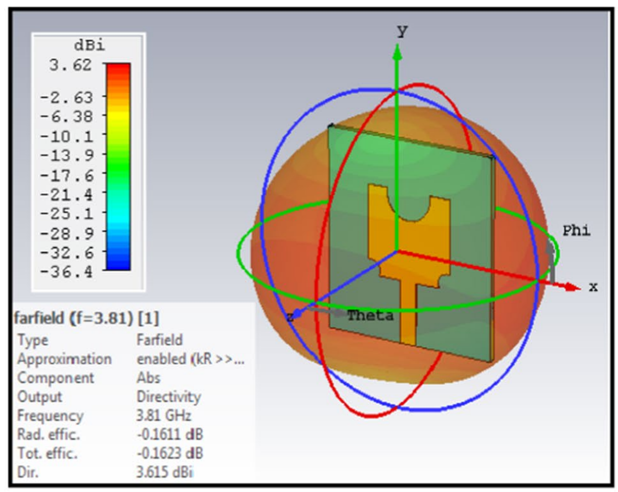


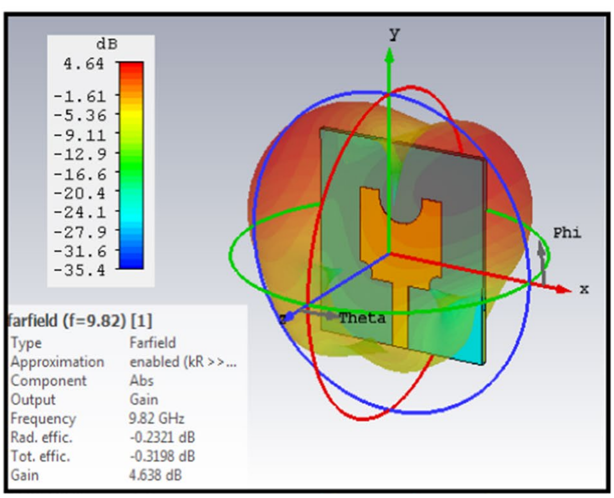
Fig. 5 Simulated VSWR characteristics.



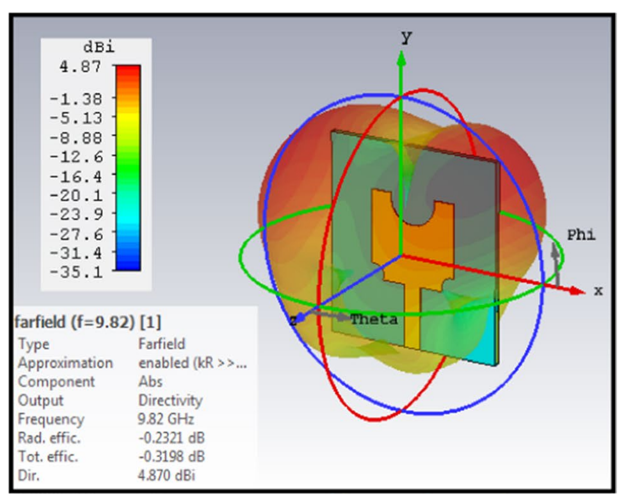
(a) Gain at 3.81 GHz



(b) Directivity at 3.81GHz

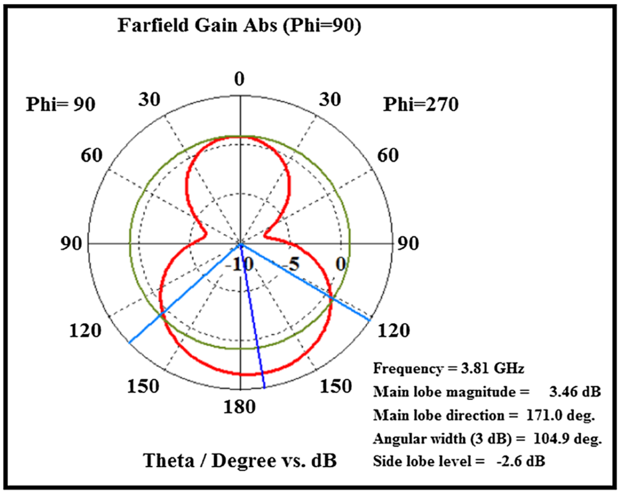


(c) Gain at 9.82GHz

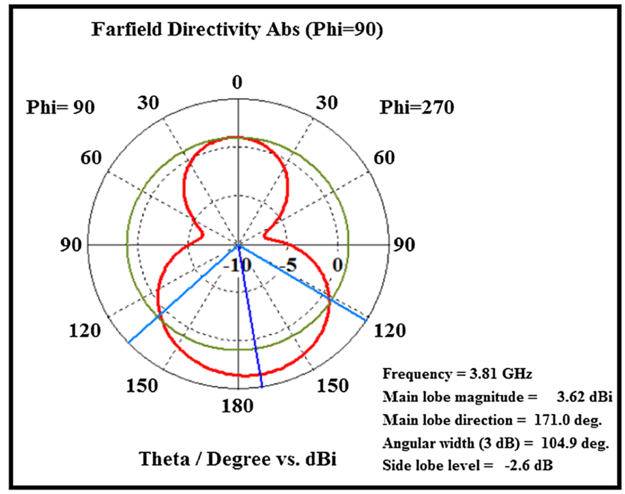


(d) Directivity at 9.82GHz

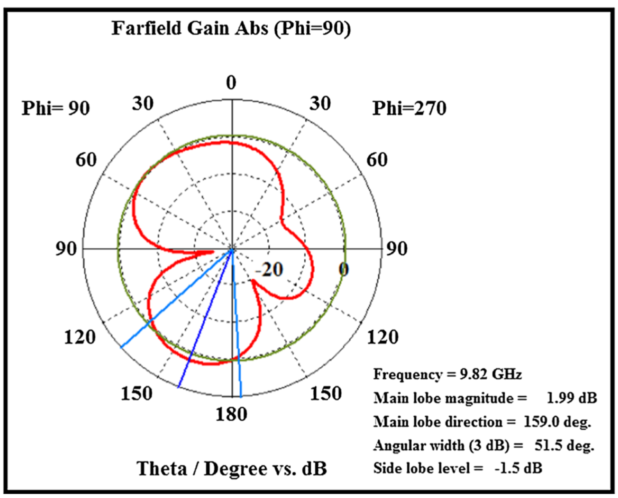
Fig. 6 Gain and directivity plot at resonant frequencies. (a) Gain at 3.81 GHz, (b) Directivity at 3.81 GHz, (c) Gain at 9.82 GHz, (d) Directivity at 9.82 GHz.



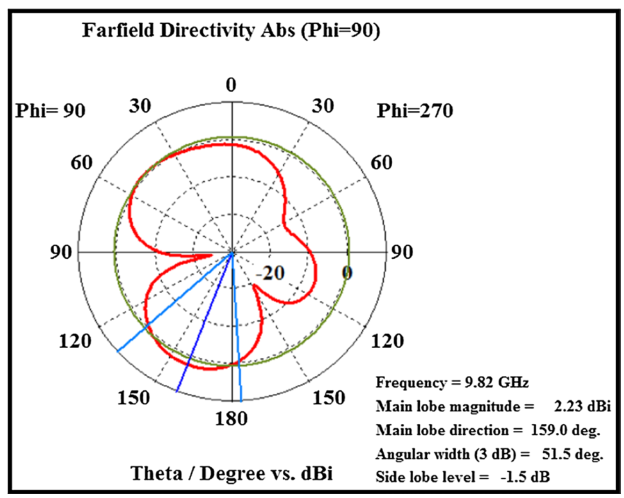
(a) Radiation pattern Gain at 3.81 GHz



(b) Radiation pattern Directivity at 3.81GHz



(c) Radiation pattern Gain at 9.82 GHz



(d) Radiation pattern Directivity at 9.82 GHz

Fig. 7 Radiation pattern characteristics at resonant frequencies. (a) Radiation pattern gain at 3.81 GHz, (b) Radiation pattern directivity at 3.81 GHz, (c) Radiation pattern gain at 9.82 GHz, (d) Radiation pattern directivity at 9.82 GHz.

7. Measurement and testing of antenna parameters through the VNA Anritsu MS2038 C and anechoic chamber.

In the presented work, textile denim fabric is chosen as a substrate to design and implement a textile-based flexible wearable UWB antenna, as demonstrated in Fig. 2. The highlighted antenna is designed, simulated, and optimized using CST simulation software using a frequency-domain solver. The copper foil fabrication technique is utilized for the design of the presented antenna wherein an adhesive copper tape of 0.1 mm thickness is adhered as the radiating patch element and partial ground plane structure on denim fabric substrate. This acts as a perfectly conducting material for antenna fabrication as a low-cost choice. To energize the fabricated antenna, a 50 Ω SMA connector is connected with a micro-strip feed line.

Figure 3 shows the presented flexible fabric-based wearable antenna, which is convenient for body-worn applications due to its conformability or resilience to be attached on non-planar bent or curved surfaces.

Simulation Results and Parametric Study

Simulation Results

The parametric study and simulation results of the designed antenna were completed using CST simulation software.

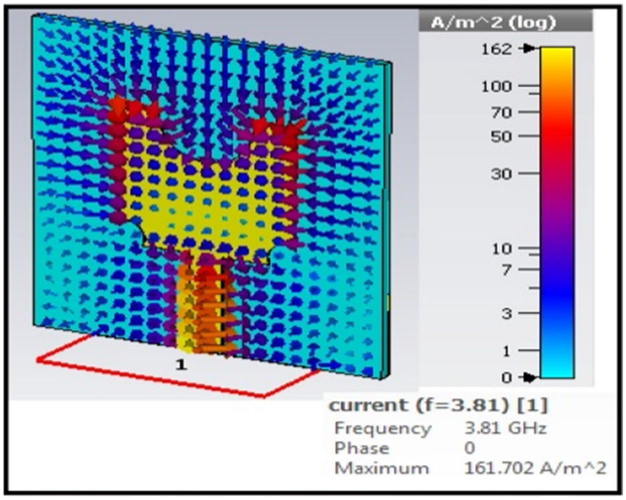


Fig. 8 Current density distribution at 3.81 GHz.

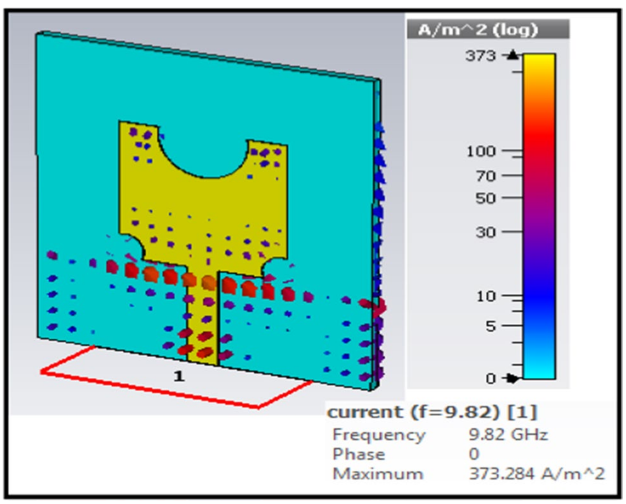


Fig. 9 Current density distribution at 9.82 GHz.

Return Loss and VSWR Specifications

Return loss or reflection coefficient or S_{11} and voltage standing wave ratio (VSWR) are the important antenna performance metrics used to analyze the power losses in the antenna. Ideally, in perfect conditions, no power should be reflected from the antenna, but in a practical scenario, due to imperfections, discontinuity, or impedance mismatching between the feed-line and radiating patch, some power is reflected by the antenna. Therefore, −10 dB is the minimum acceptable value for S_{11} and 2.0 is considered a suitable value of VSWR. Simulated S_{11} for the presented design is −25.403 dB and −18.732 dB at 3.81 GHz and 9.82 GHz, respectively, and VSWR values are observed to be 1.11 and 1.26 at 3.81 GHz and 9.82 GHz, respectively. Figures 4 and 5 demonstrate simulated S_{11} and VSWR characteristics, respectively.

Radiation Pattern Characteristics

The variation of radiation power as a function of the antenna's direction is presented by radiation patterns. The radiation pattern 3D plots are shown in Fig. 6 to illustrate the gain and directivity at 3.81 GHz and 9.82 GHz. The 2D polar plots of radiation patterns are illustrated in Fig. 7 at resonance frequency 3.81 GHz and 9.82 GHz. As depicted from Figs. 6 and 7, simulated gain and directivity at 3.81 GHz are 3.45 dB and 3.615 dBi, respectively. At 9.82 GHz, the gain and directivity of the proposed antenna are shown as 4.63 dB and 4.865 dBi, respectively.

Current Density Distribution Characteristics

The consequence of antenna notch and slots on impedance matching performance is explained by the current density distribution as demonstrated in Figs. 8 and 9 for 3.81 GHz and 9.82 GHz, respectively. The current density distribution illustrates the pattern of how the current flows on the radiating patch of the antenna. The maximum strength of the current is highlighted along the feed line, along the edge of the radiating patch, and the boundary of the partial ground of the antenna.

Surface Current Distribution Characteristics

To illustrate the impact of the slots on the designed antenna, the simulated surface current distributions at 3.81 GHz and 9.82 GHz at phases 0°, 90°, 180° and 270° are presented in Figs. 10a, b, c, d and 11a, b, c, d, respectively. We can see from these figures that the maximum surface current on the electric dipole is concentrated on the feed line, edges of slots, and truncated ground.

The variation in surface current concentration is also observed with varying phases. We can see from these figures that the maximum surface current on the electric dipole is concentrated on the feed line, edges of slots, and truncated ground. The variation in surface current concentration is also observed with varying phases. Table III summarizes the simulation outcomes of the presented antenna with regards to antenna performance parameters.

Parametric Study

The parametric study deals with performance exploration and optimization of the antenna by varying antenna parameters. It gives information regarding the impact of variation of antenna dimension parameters on the overall performance

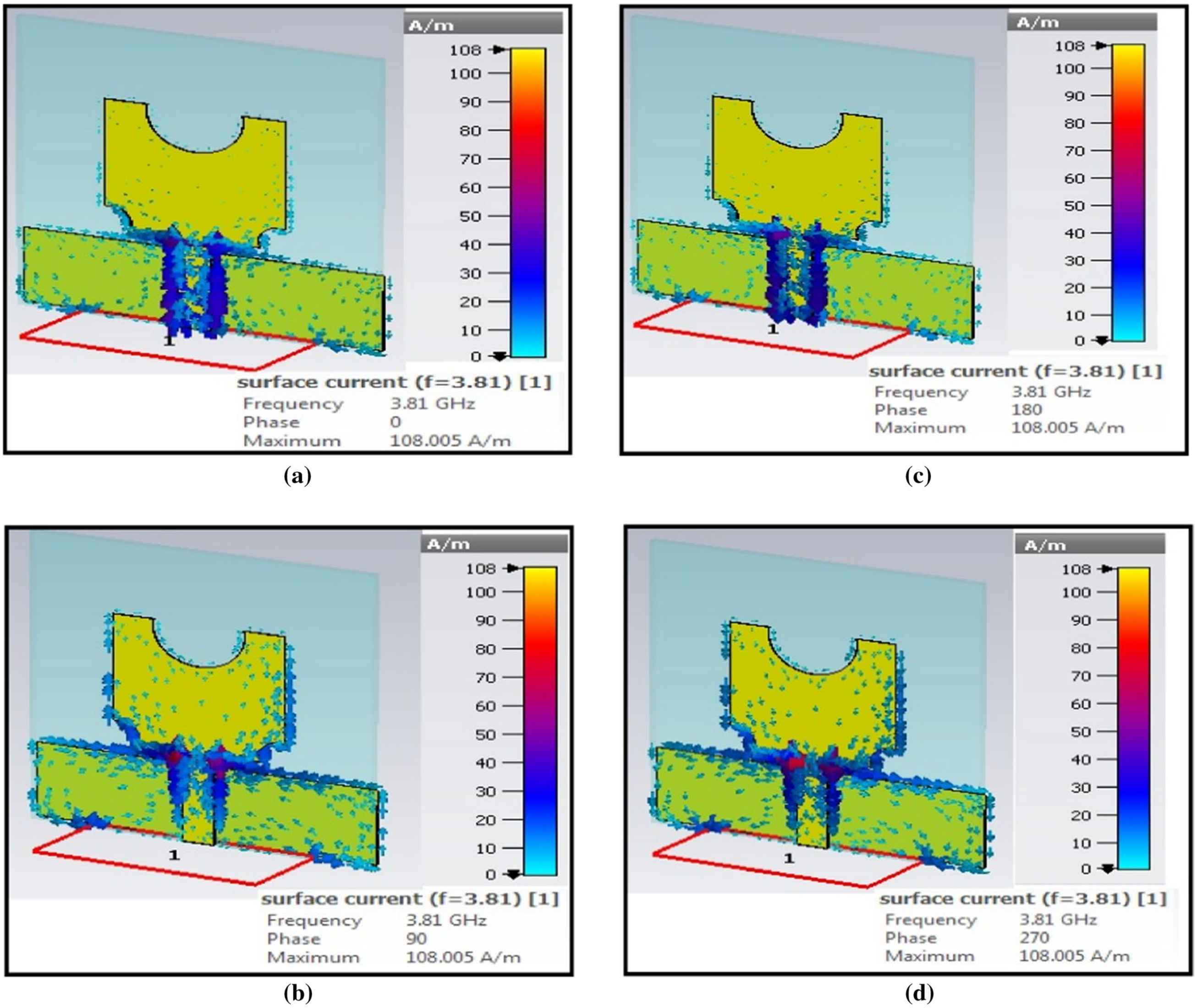


Fig. 10 Surface current distribution at 3.81 GHz at phase (a) 0°, (b) 90°, (c) 180°, (d) 270°.

of the antenna. In the presented work, antenna design is optimized through variation in antenna substrate height (h), length of the patch (l_p), width of the patch (w_p) and width of feed line (w_f), and their effect on return loss characteristics are demonstrated.

Different notch and slots are grooved from the patch and the partial ground is used with optimized values of h, l_p, w_p, and w_f to get optimum performance in the context of impedance matching and radiation characteristics. The effect of varying substrate height on return loss is demonstrated in Fig. 12. Significant improvement of S_{11} (−35 dB) is shown for $h = 0.8$ mm but ultra-wideband operation criteria are not met. Substrate height $h = 1$ mm, however, provides smaller S_{11} but covers the complete UWB spectrum. The length and width of the micro-strip antenna is a crucial parameter for antenna design that can be calculated by using basic design equations. As shown from Figs. 14 and 15, the optimum length and width of the patch of the designed antenna are observed to be 14.5 mm and 15 mm, so the antenna is fabricated with these parametric dimensions. The width of the micro-strip feed line signifies a key role in deciding the impedance matching. Figure 13 demonstrates the effect of variation of feed line width on reflection coefficient characteristics. A change in w_f from 2.85 to 2.5 mm shifts the resonant frequency from low to higher.

From Figs. 12, 13, 14, and 15, it has been investigated that the return loss and resonant frequencies of the antenna depend on antenna geometry parameters. The parameters $h = 1$ mm, $l_p = 14.5$ mm, $w_p = 15$ mm, and $w_f = 2.85$ mm are selected as optimum dimensions for UWB application

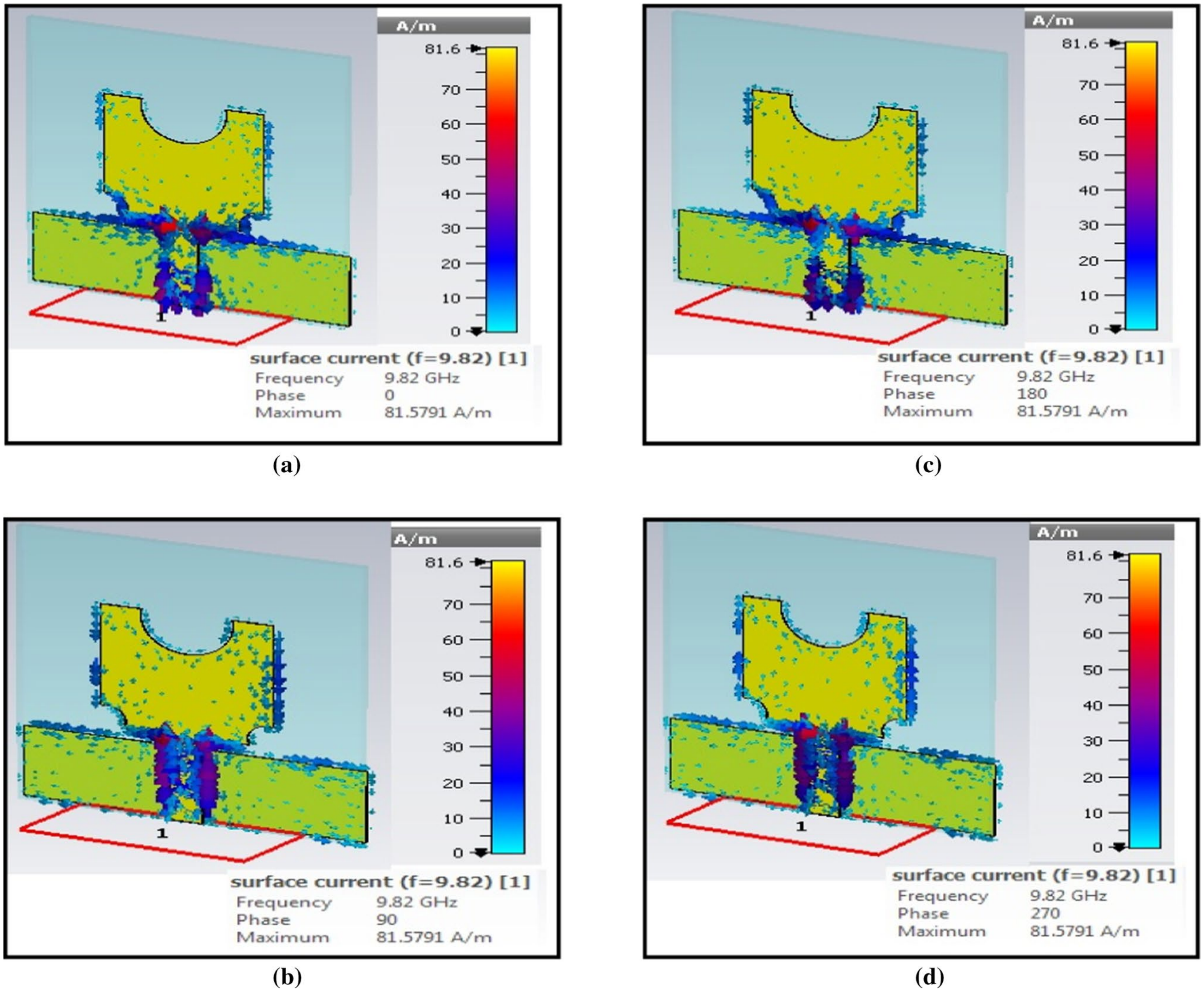


Fig. 11 Surface current distribution at 9.82 GHz at phase (a) 0°, (b) 90°, (c) 180°, (d) 270°.

Table III Simulation results of designed antenna performance

Antenna performance metrics	F1	F2
Resonant frequency (GHz)	F1=3.81	F2=9.82
Return loss S_{11} (dB)	−25.4	−18.73
VSWR	1.11	1.26
Gain (dB)	3.45	4.63
Directivity (dBi)	3.61	4.86
Efficiency (%)	95.6	95.2
Impedance bandwidth (GHz)	8.6	
Fractional bandwidth (%)	114.6%	

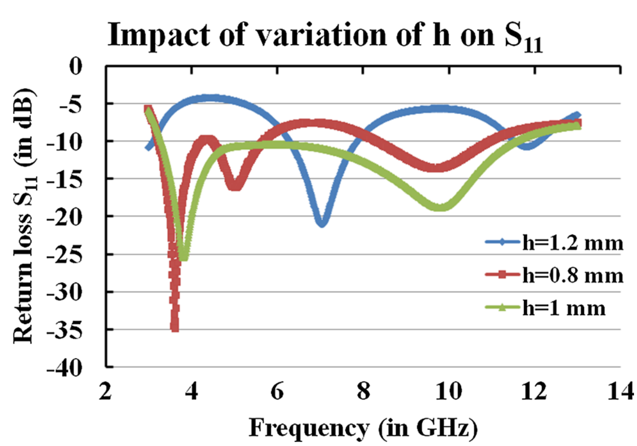


Fig. 12 Impact of variation of the height of the substrate.

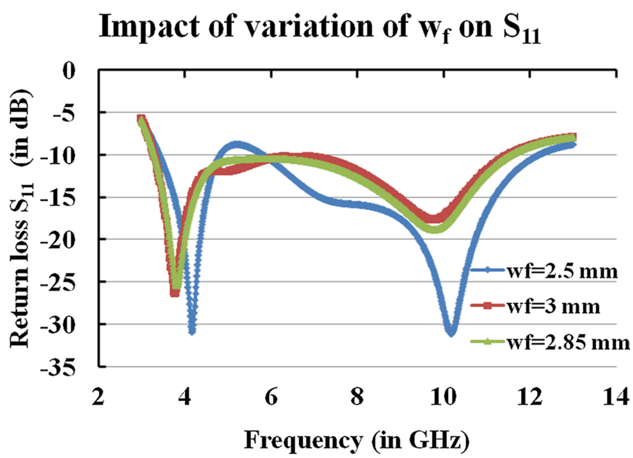


Fig. 13 Impact of variation of the width of the feed line.

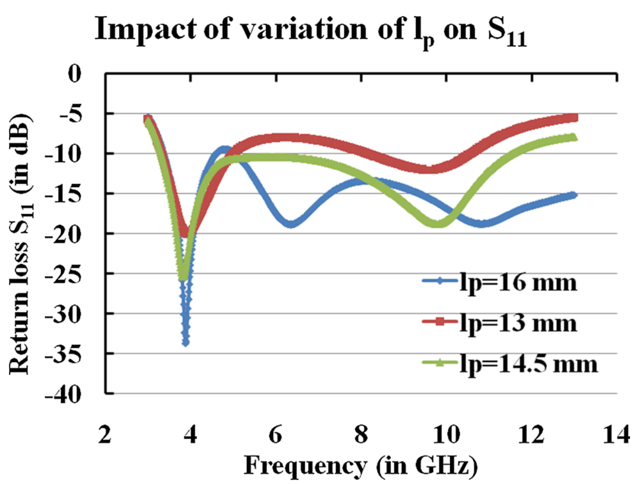


Fig. 14 Impact of variation of the length of the patch.

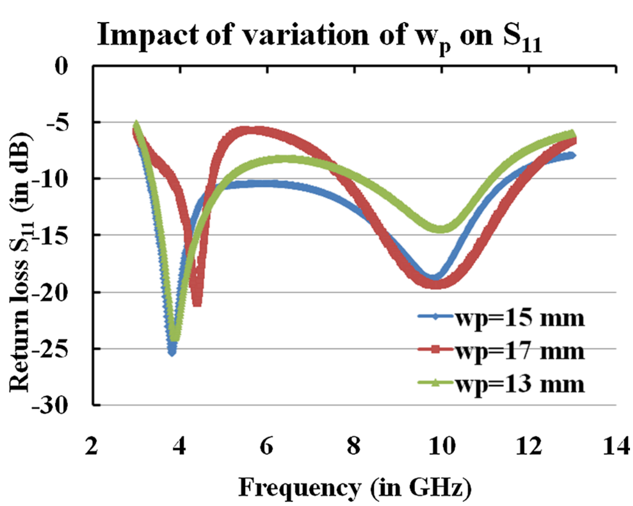


Fig. 15 Impact of variation of the width of the patch.

which provides broad impedance bandwidth (114.6%) from 3.2 to 11.8 GHz with dual-band resonant frequencies 3.81 GHz and 9.82 GHz.

Experimental Results and Discussion

Experimental Setup and Measurement

A testing environment of the fabricated antenna is presented in Fig. 16. Measurements of the fabricated antenna were carried out in an anechoic chamber to confirm the radiation pattern characteristics. The S_{11} parameter of the presented antenna were observed using a Vector Network Analyzer MS20XX series VNA (VNA Anritsu MS2038 C) with frequency coverage from 5 kHz to 20 GHz. Figure 17 represents the measurement of the proposed fabric-based flexible antenna through VNA. The antenna received power has been measured in an anechoic chamber by utilizing a test antenna. The testing setup through the anechoic chamber is demonstrated in Fig. 18. An anechoic chamber provides nil intervention in pulses propagated by a horn antenna which acts as a reference test antenna as it absorbs all the undesired reflections and propagated waves. A horn antenna was preferred as the reference antenna because of its large frequency range operation and high gain features.

Fig. 16 Testing environment of the proposed antenna.

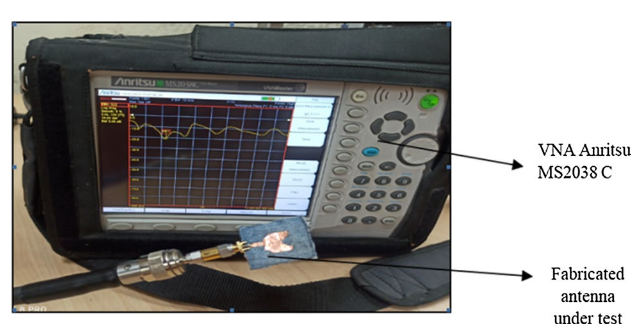


Fig. 17 Measurement of S_{11} through VNA.

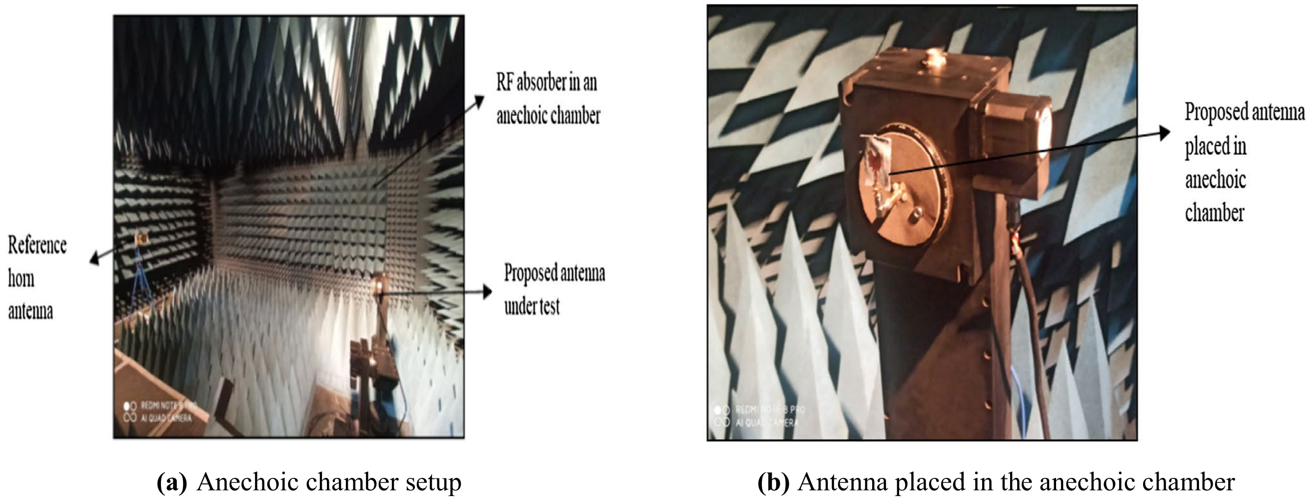


Fig. 18 Measurement setup. (a) Anechoic chamber setup (b) Antenna placed in the anechoic chamber.

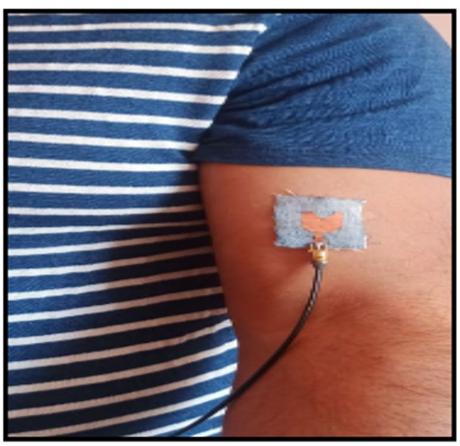


Fig. 19 On-body effect measurement.

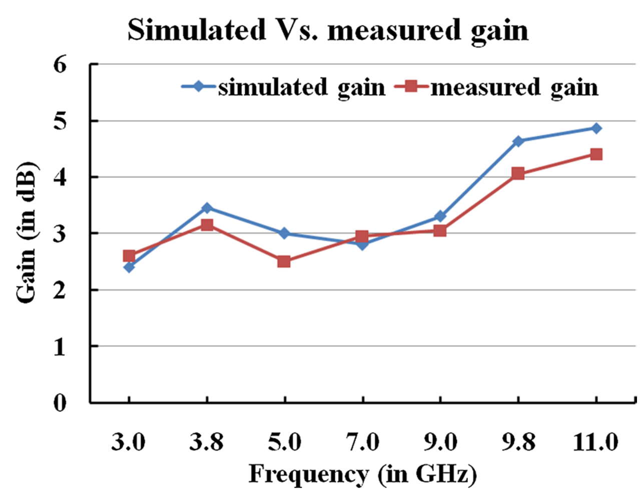


Fig. 21 Gain performance.

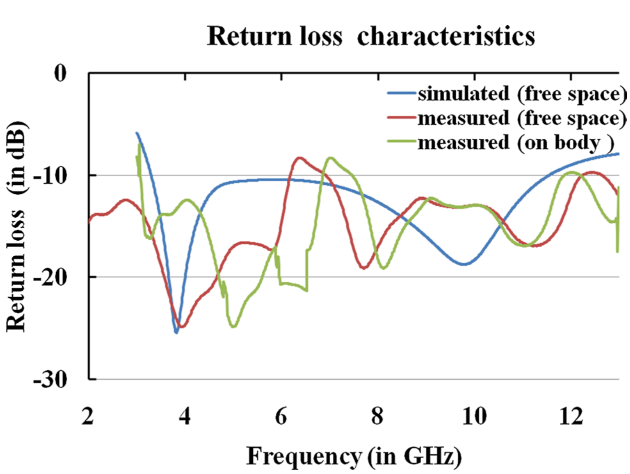


Fig. 20 Return loss performance.

Measurement Results

Free Space and On Body S_{11} Characteristics

The current research investigated and demonstrated the on-body effect of wearable UWB antenna design on S_{11} characteristics. The antenna was placed on the right arm of the body to illustrate on-body return loss effect of the wearable antenna, as shown in Fig. 19. Figure 20 represents simulated as well as measured S_{11} characteristics in the free-space condition and measured on-body wearable condition.

As demonstrated from Fig. 20, a slight variation was observed in S_{11} measured values under free-space conditions and for on-body conditions. The losses were incurred because of body movement effects such as bending and

Table IV Comparison of simulation with measurement results

Results	Resonating frequency (GHz)		Return loss S11 (dB)		Gain (dB)	
Simulation results (free space)	F1=3.81	F2=9.82	−25.4	−18.73	3.45	4.63
Measurement results (free space)	F1=3.82	F2=9.8	−24.1	−14.0	3.3	4.4
Accuracy	99.8%	99.8%	95.1%	75%	95.7%	95.1%

Table V Summary of comparison of antenna performance specifications of the presented antenna with the comparable WBAN textile antennas in literature

[Ref]	Antenna overall size	Substrate used	Resonant frequency (GHz)	S_{11} (dB)	Gain (dB)	Directivity (dBi)	Impedance bandwidth (GHz)
[2]	22.48 × 24.56 ×1.645 mm^3	Denim	4.28 8.58	−21.09 −34.84	2.45 4.11	3.72 5.50	3.5 to 10.5 (100%) UWB
[12]	60×60 mm^2	Felt	2.4	−35	4.27	Not reported	2.32 to 2.55
[13]	45×35 mm^2	Denim	3 7 9	−12 −18 −35	2.74 4.17 4.074	Not reported	4.2 to 10.6 (86.48%) UWB
[14]	86 × 90 ×1.06 mm^3	Denim	2.1366 4.756 11.49	−22.23 −38.10 −20.79	Not reported	3.3 4.2 5.19	4 to 6, 11 to 12 (87.4%, 89.6%)
[18]	30 ×20 ×0.7 mm^3	Denim	2.4	−33.15	2	Not reported	0.240 (15%) ISM
[20]	39×42×3.34 mm^3	Felt	3.5 8.3	−17 −15	Not reported	Not reported	3.6 to 4.3, 6.3 to 10.1
Proposed	30 ×35 ×1.2 mm^3	Denim (ε_r=1.7)	3.82 9.80	−26.41 −15	3.45 4.63	3.61 4.86	3.2 to 11.8 (114.6%) UWB

twisting and also due to the absorption of a fraction of radiated energy by body tissues. Also, a fair matching was attained between the simulated and evaluated reflection coefficients under free-space conditions with 95.1% and 75% accuracy for the presented fabricated antenna.

The simulated value of return loss for the antenna was observed to be −25.4 dB at 3.81 GHz and −18.73 dB at 9.82 GHz with an impedance bandwidth of 8.6 GHz. The fabrication results for the designed antenna demonstrates a little variation with simulation results in context to S_{11} and resonating frequency which shifts to the lower frequency band with the return loss values of −24.1 dB at 3.82 GHz, −16.9 dB at 5 GHz, and −14 dB at 9.82 GHz.

Gain Characteristics

Figure 21 represents the gain vs. frequency plot for the simulated antenna and fabricated antenna, which shows that the gain is almost comparable at the whole UWB frequency band. The highest simulated gain and measured gain are observed to be 4.63 dB and 4.4 dB at 9.82 GHz and 9.8 GHz, respectively. The positive values of the gain represent the antenna's directionality. It is also evident from Fig. 21 that there is good agreement between simulated gain and the gain obtained from testing the fabricated antenna. The simulated gain for the antenna was 3.45 dB at 3.81 GHz and 4.63 dB at 9.82 GHz. The measured gain was 3.3 dB at 3.82 GHz and 4.4 dB at 9.8 GHz. Accuracy values of 95.7% and 95.1% were achieved in measured gain with respect to simulated gain.

Table IV summarizes the comparison of simulated and fabricated results. The slight decrease in the measured impedance bandwidth and slight variation in simulated and experimental S_{11} value and gain is in consideration with the practical condition. In real practical cases, imperfections in impedance matching, adhesive copper tape surface, fabric material, and fabrication techniques due to the discontinuity between the feed line and radiating patch and soldering effect in the SMA connector causes power to be reflected back to the antenna. The limitations in the practical experimental scenario lead to a slight variation in the testing results and simulation results that were performed in ideal and perfect conditions.

Table V highlights the comparative analysis of the presented textile UWB antenna design with comparable antenna geometries for WBAN as described in references. The proposed antenna exhibits better antenna performance in context to radiation pattern characteristics, gain, and impedance bandwidth. Although, comparatively, size is not considerably compact but the proposed antenna balances the trade-off between antenna compactness and antenna's overall performance.

Conclusion

Design, simulation, and fabrication of denim fabric-based flexible wearable UWB antenna have been described in this paper. A parametric study is also performed to optimize the antenna geometry and to illustrate the effect of variation of dimensional parameters on the antenna's performance. The simulation results of the designed antenna shows close agreement with the experimental results of the fabricated antenna. The accuracy of 95.1% in the S_{11} value and accuracy of 95.7% in gain value of fabricated result to simulation results are observed. The highest simulated gain and directivity is depicted as 4.63 dB and 4.86 dBi and significant impedance bandwidth of 8.6 GHz ranging from 3.2 to 11.6 GHz (114.6%). The fabricated antenna has a compact size having dimensions of 30 mm × 35 mm × 1.2 mm, and the peak gain of the fabricated antenna is observed to be 4.4 dB.

The superior performance characteristics of the presented UWB antenna design in comparison to other related antennas mentioned in references, flexibility, compactness, low cost, light-weight, mechanical robustness are the features that confirm its suitability to be used as a wearable antenna for wireless health monitoring WBAN applications. As a future task, the antenna demonstrated in the current work can be tested for different antenna parameters for various body movements and positions that can be further utilized for different human body movement recognition and its classification.

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Conflict of interest The authors declare that they have no conflict of interest.

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