Defence Science Journal, Vol. 75, No. 1, January 2025, pp. 90-99, DOI : 10.14429/dsj.20106

Defence Locator Beacon: Integrating SHF Body-Wearable Antenna with Multifunctional Frequency Selective Surface

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ABSTRACT

The integration of a Super High Frequency (SHF) on-body antenna with Frequency Selective Surfaces (FSS) marks a significant advancement in defense beacon technology. This study presents a unique, wearable, apple-shaped SHF antenna incorporating a multifunctional FSS for use as a Defense Locator Beacon (DLB). Key features include high gain, highly directional radiation pattern, low Specific Absorption Rate (SAR), reduced Radar Cross Section (RCS), and compact dimensions. The antenna, made on denim fabric, operates across the entire SHF band. With a 9-cell FSS array on a semi-flexible RT Duroid substrate, the structure is both simulated and fabricated, showing enhanced performance: peak gain increased from 7.14 to 11.1 dBi, FBR from 3.58 dB to 19.87 dB, and RCS reduced from -25 to -50 dB. Link Budget Analysis confirms effective communication, with ranges of 67 m and 64 m for 100 Mbps and 200 Mbps. The proposed antenna ensures high-speed communication and accurate location identification for military personnel.

Keywords: Compact; Defence; Flexible; FSS; Link margin; RCS; SAR

NOMENCLATURE

ε_r	: Relative permittivity
f_L	: Lower frequency
$P_{backward}$	: Backward power
ΔT	: Change in temperature
$P_{forward}$	: Forward power
Σ	: Tissue's conductivity (S/m)
β	: Propagations Constant
φ_{fss}	: Reflection phase of FSS
E	: Electric field (V/m)
ρ	: Tissue's mass density (kg/m^3)

1. INTRODUCTION

In modern defence operations, the seamless exchange of information and precise location identification are pivotal for mission success and the safety of deployed personnel. High gain antennas stand as indispensable assets within the arsenal of military communication systems, facilitating rapid data transmission and accurate positioning across diverse operational environments. High-speed communication enables seamless integration of location information into command and control systems, allowing commanders to monitor the location of individual soldiers, units, or assets in real-time. This enhances situational awareness, enables more effective decision-making, and supports mission planning and execution by ensuring that personnel are properly positioned and deployed according to operational requirements[1-4]. In the dynamic and often challenging landscapes of Defence operations, these antennas ensure reliable connectivity, even amidst obstacles, interference, or GPS limitations. When integrated into wearable communication systems, high gain antennas empower soldiers with the ability to transmit and receive critical data swiftly; fostering enhanced situational awareness and informed decision-making on the battle-field[7-9].

Existing defence locator beacons utilise technologies such as GPS, satellite communication, and radio frequency transmissions to broadcast distress signals and facilitate search and rescue efforts. While these beacons have proven effective in many scenarios, they often face challenges such as large, bulky, susceptibility to jamming, and inadequate transmission range in certain environments. Despite their utility, current defence locator beacons suffer from several limitations that hinder their effectiveness in demanding military operations. The proposed next-generation defence locator beacon addresses these challenges through innovative design features and advanced technologies.

The linch pin of location identification lays in the excellent quality of gain and highly directional radiation patterns. The main objective of DLB is to send a distress signal. Integration of SHF on-body wearable antenna, augmented with FSS presented here is a groundbreaking advancement in defence beacon technology. The result is a substantially enhanced gain and highly directional radiation signatures, rendering the defence personnel more resilient to location surveillance. Long range communication reliability is paramount in mission scenarios

Received : 16 April 2024, Revised : 11 July 2024
Accepted : 12 August 2024, Online published : 10 January 2025

and is conferred by the Link Margin Analysis presented here. The set-up involves the incorporation of 3×3 array. Antenna is fabricated on denim which is completely flexible material and FSS is fabricated on RT-Duroid that is again a semi-flexible material. A very low value of SAR ensures soldier's safety. All these qualities make the proposed next-generation defence locator beacon perfect for seamless integration into existing military infrastructure, including communication networks, satellite systems, and search and rescue protocols.

2. LITERATURE REVIEW

To comprehend to the multifunctional capabilities of the antenna proposed in this paper, it is compared with some similar work done in previous literatures. Table 3 displays some important attributes and depicts how the proposed design is better than the rest.

The work done in the literature suffices some attributes but not all. The studies are more or less showing similar work done with non-flexible material using FSS to enhance gain[3-5]. The values are good however, not body-wearable. The designs have used semi-flexible materials and does not ensure human safety as SARs are not calculated[4,6]. Work done has computed RCS of 10 dB, that is again far less than the 25 dB achieved by the proposed design[10]. Work display good values of SAR however the gain achieved are very less[11-12]. All the above literature does not show link budget analysis hence cannot be said to have accurate and high speed data rate needed for defence or military location identification systems.

It is evident that the proposed design is a mixed study that covers all the necessary aspects that are essential in successful application and demonstration of a Defence Locator Beacon. Such collaborative work is not to be seen in literature till date. This makes the design inevitably novel and highly beneficial for the said applications.

The synergy of these elements in a single design represents a significant advancement in the field. This novel approach not only pushes the boundaries of antenna design but also offers substantial practical benefits for Defence Locator Beacon applications. The comprehensive nature of this work, combining multiple optimisations that are typically addressed separately, makes it a unique and valuable contribution to the field.

3. ANTENNA FORMATION AND CHARACTERISTICS

This section delivers the formation of proposed antenna. The geometric configuration of the proposed architecture is shown in Fig. 1(a) displaying the front and back view of the proposed antenna. The antenna is designed on denim fabric

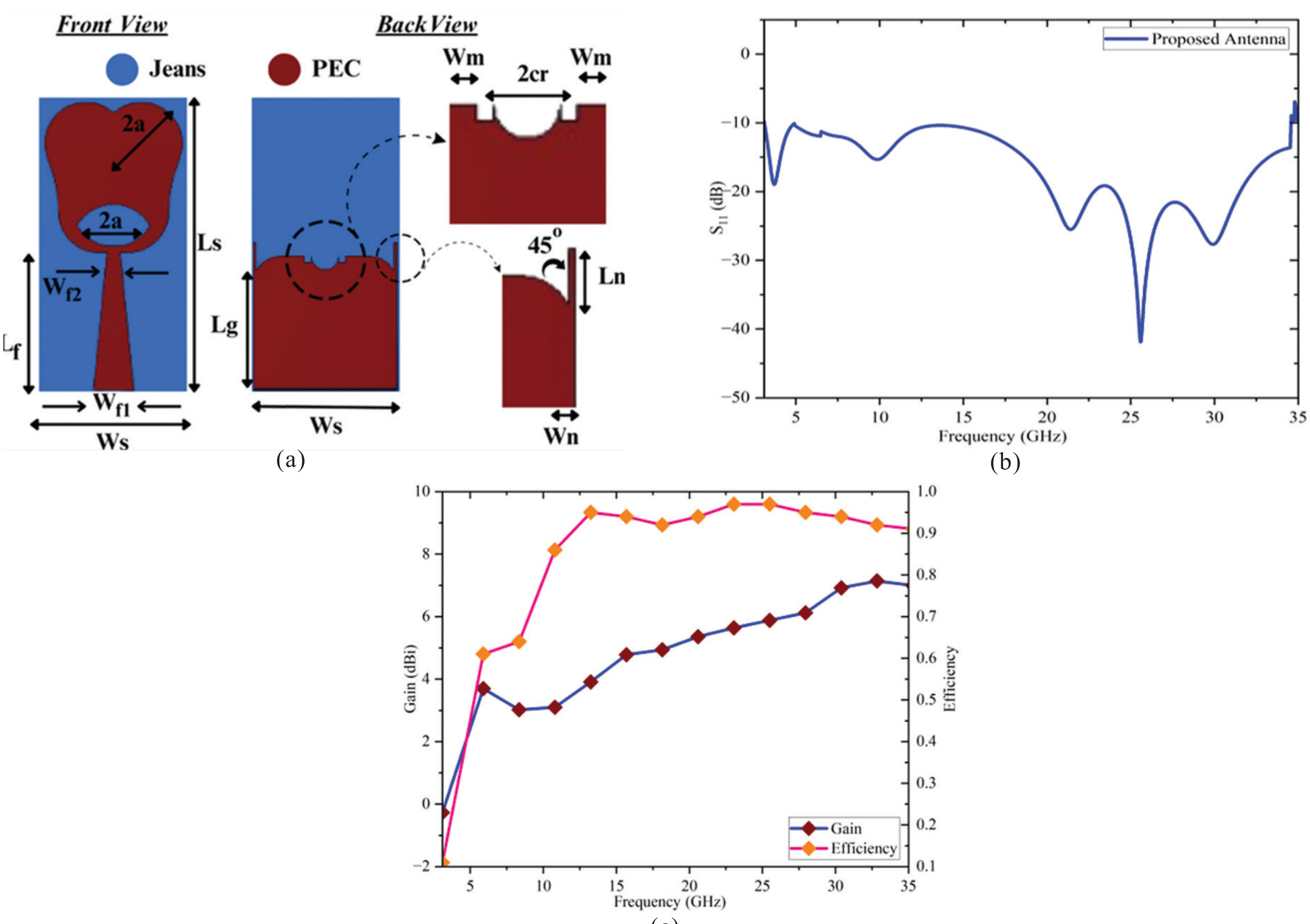
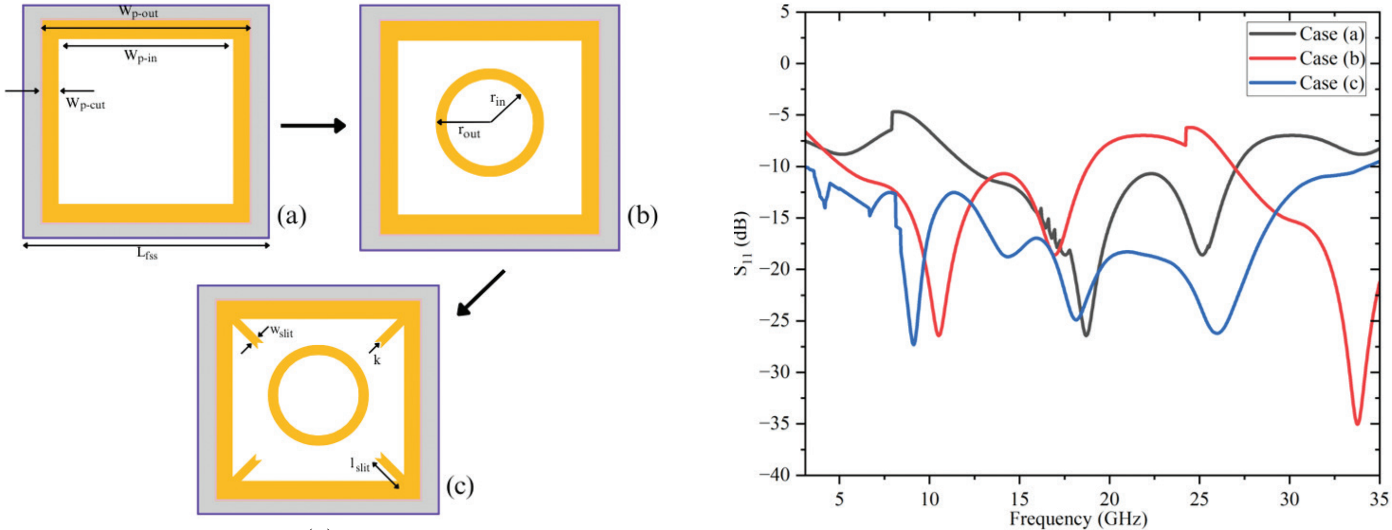


Figure 1. (a) Proposed Apple-Shaped Antenna (a) S_{11} (b) Gain (Left Y); and (c) Efficiency (Right Y) v/s Frequency.



(a) (b)

Figure 2. (a) Stepwise formation of unit cell; and (b) S_{11} characteristics.

Table 1. Designed parameters of antenna and FSS

Designed parameters of antenna			Designed parameters of FSS		
Elements	**Description**	**Values (mm)**	**Elements**	**Description**	**Values (mm)**
L_s	Substrate length	21.5	L	Array length	45
W_s	Substrate width	10.5	L_{fss}	Unit length	15
a	Patch radius	3	$W_{p\text{-}in}$	Inner square length	12.3
W_{f1}/ W_{f2}	Feedline width	3,1	$W_{p\text{-}out}$	Outer square length	14
L_f	Feedline length	10.15	$W_{p\text{-}cut}$	Border width	1.7
L_g	Ground length	9.75	r_{in}	Inner circle radius	3
L_n	Notch length	2	r_{out}	Outer circle radius	4
W_n	Notch width	0.25	l_{slit}	Notch length	8.5
W_m	Square-slit width	0.5	w_{slit}	Notch width	0.5
cr	Circular slit radius	1	k	Cut	0.1

with relative permittivity of 1.65, loss tangent of 0.0009 and thickness 1 mm. The various parameters optimized are given in Table 1. The complete design consists of an apple-shaped patch with tapered feed and a leaf-shaped slot. The defected ground structure is used to obtain the maximum bandwidth and is achieved with circular and rectangular slits and notches introduced on the partial bent ground. Better notch characteristics help in effectively filtering out unwanted signals and interference from other communication systems, ensuring cleaner and more reliable signal reception and transmission[10-11]. This architecture furnished a huge bandwidth of 3.1 GHz till 34.5 GHz.

3.1 Reflection Coefficient Characteristics

The reflection coefficient S_{11} remain below -10 dB for the given range as shown in Fig. 1(b).

3.2 Gain and Efficiency Characteristics

Figure 1(c) plots the gain and efficiency graph for the entire frequency range. It is clear that the antenna acquires the highest gain of 7.14 dBi at 32GHz. Efficiency acquired is 96 % although at higher frequencies, the efficiency is reduced and that is to happen due to mismatch losses. It can be seen that gain at 3.1GHz is negative, hence a reduced efficiency of 11 %. FSS structures can enhance radiation characteristics by controlling the propagation of electromagnetic waves, leading to improved antenna performance in terms of signal strength and coverage area[3-4]. The advantage of incorporating FSS is discussed in details through all performance characteristics

3.3 FSS Formation

Unit cell is formed initially. It is printed on the 0.254 mm wide RT Duroid 5880 (Lossy) that has a permittivity of 2.2, and loss tangent of 0.0009.

The step-by-step making of a unit cell is shown in Fig. 2(a). The unit cell (L) dimension of FSS can be calculated approximately from Eqn. (1)[4]

$$L_{fss} = \frac{c}{4f_L\sqrt{(\varepsilon_r + 1)/2}} \quad (1)$$

In Fig. 2a(a), the square patch of side length14mm is constructed and another square with side of 12.3 mm is separated leaving the patch with bordered square of width 1.7

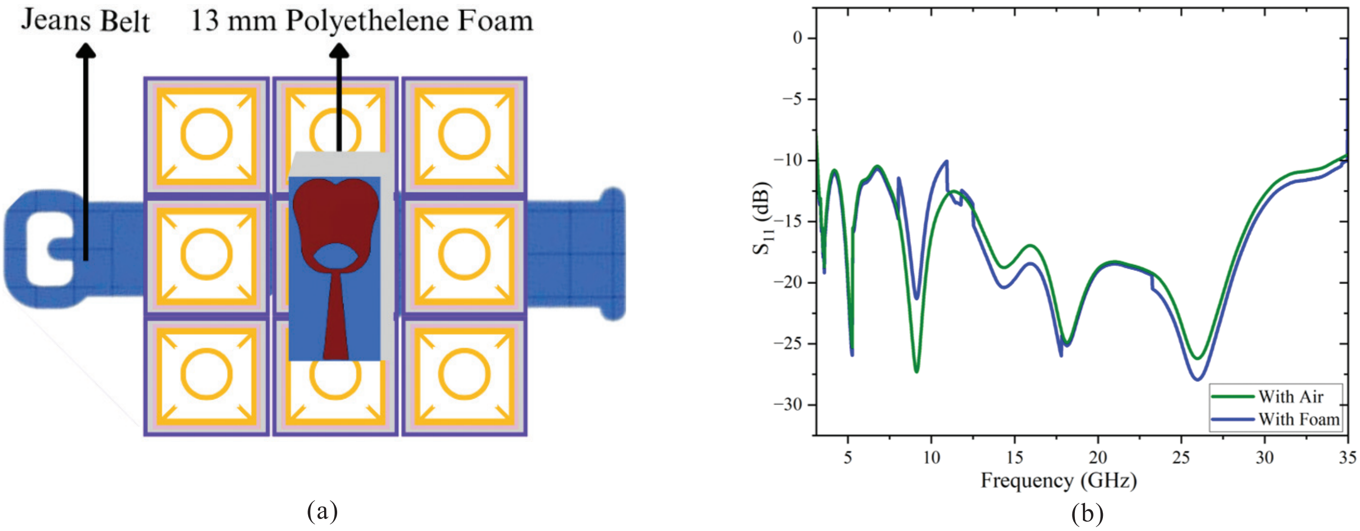


Figure 3. (a) Complete set-up; and (b) S_{11} Comparison of air and foam filled structure.

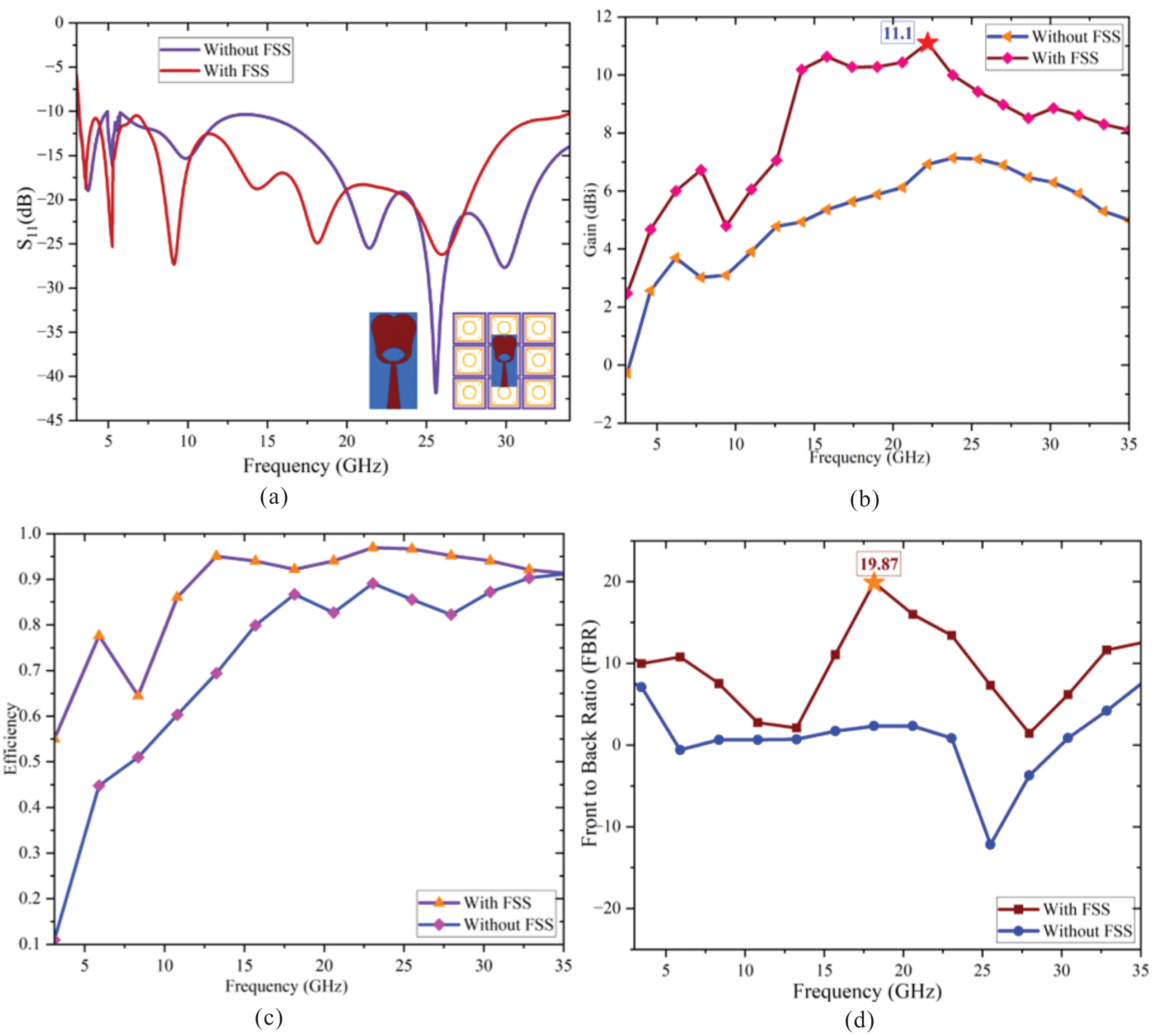


Figure 4. (a) S_{11}; (b) Gain; (c) Efficiency v/s Frequency; and (d) Analysis of FBR with and without FSS.

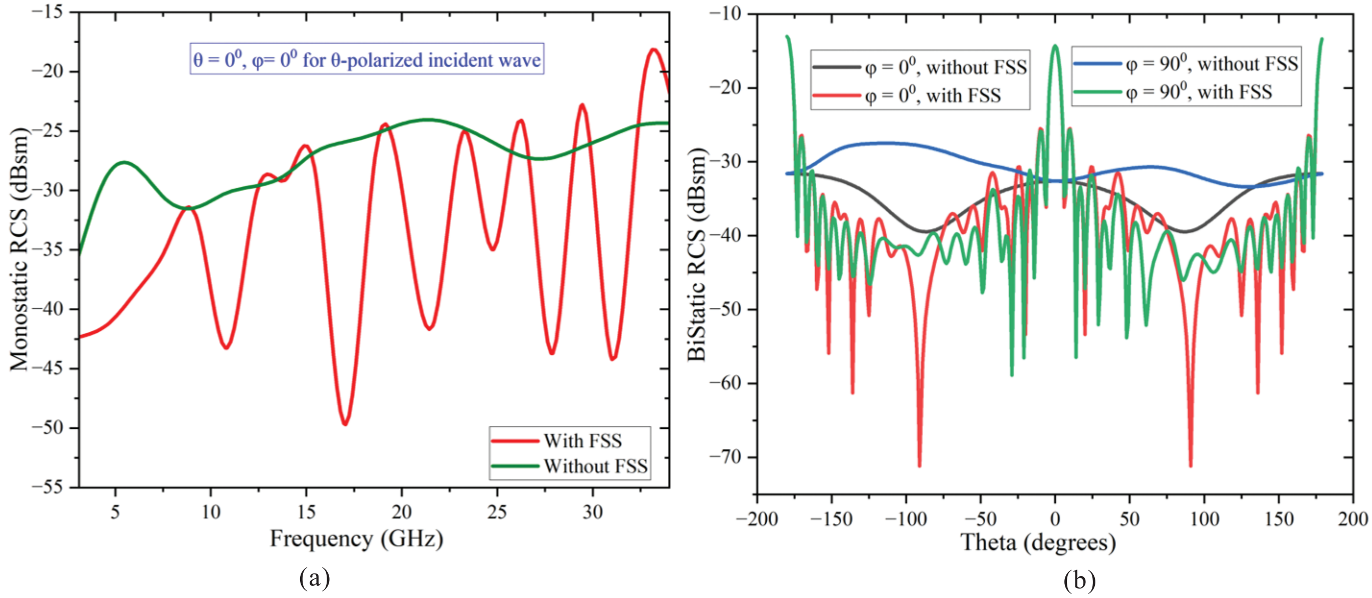


Figure 5. (a) Monostatic RCS for θ-polarized incident wave; and (b) Bi-Static RCS for complete bandwidth.

mm. This provides the frequency bandwidth from 5.2 till 18.3 GHz. In Fig. 2a(b), a cylinder of outer and inner radius of 4 mm and 3 mm respectively is added to the patch. This results in the improvement in the frequency range from 4.7 till 23 GHz. Finally, in Fig. 2a(c), notches on 4 sides of square patch of 0.5 mm width and 8.5 mm length are added diagonally, due to which the bandwidth comes out from 3.1 till 34 GHz. By suppressing specific frequency bands, notch filters improve the overall signal-to-noise ratio[10-12]. The design parameters of FSS are given in Table 1. Reflection Coefficient characteristics for each of progression is shown in Fig. 2(b).

The FSS is a periodic structure inclusive of numerous unit cells in certain array form[5]. The proposed 9 unit cells are periodically added in 3×3 matrixes and the array is constructed with dimensions 45×45 mm^2 as shown in Fig. 3(a). The designed FSS deliver the required performance in terms of finer frequency resolution, sharper resonance peaks, and more intricate transmission/reflection characteristics.

4. ANTENNA-FSS PLACEMENT

When an antenna radiates electromagnetic waves, these waves propagate outward in all directions. However, when an FSS is placed behind the antenna, a portion of these waves will be reflected towards the antenna due to the presence of the FSS which ultimately enhances gain and that works if the electromagnetic waves radiated by antenna and those by FSS are in phase, hence satisfying following Eqn. (2)[6]

$$\varphi_{fss}-2\beta d=2n\pi;\ n=\cdots -2, -1, 0, 1, 2..$$

where, 'd' is distance between the FSS and antenna. Taking the center frequency 10.34 GHz, where there is zero phase reflection, the optimum distance d=12.85≈13mm (0.14 λ_0) was evaluated.

The antenna is intended to be worn on wrist of a defence personnel, realistically the gap is filled with a polyethylene foam (dielectric constant of 2.26, loss tangent of 0.00031, and density of 2.2lb) [7]. The width of foam is same as the distance. Fig. 3(a) depicts the final look of the set up. As the air is now replaced with foam, it is necessary to see the implications of the replacement in terms of S_{11} as shown in Fig. 3(b). The analysis confirms minimal impact of using polyethylene foam and no disturbance to impedance bandwidth.

5. PERFORMANCE ATTRIBUTES

Performance attributes prove that antenna is capable of doing the assigned duties especially commandeering a distress signal. This section compartmentalises the improvements and implications of FSS implementation to justify the said application to be used as DLB.

5.1 Electromagnetic Characteristics

S_{11} attributes are shown in Fig. 4(a) for antenna without and with FSS. It can be seen that bandwidth of antenna remain unaffected with the involvement of FSS.

5.2 Gain and Efficiency Characteristics

The main intention of FSS implementation is to achieve enhanced gain that is crucial for identifying locations of soldier whenever a distress signal is sent at an accurate level as it can transmit and receive signals over longer distances[8]. Figure 4(b) shows the improved gain over the entire frequency range. The negative gain at the lowest frequency is now improved to a positive value as expected from implementing FSS. The peak gain achieved was enhanced from 7.14 dBi to 11.1 dBi (at 23 GHz). Figure 4(c) shows the efficiency with FSS addition. Antenna has become more efficient now and hence can pick weaker signals and reject interference from other directions, leading to more reliable communication among the soldiers and command center[10-11]

5.3 Front to Back Ratio (FBR)

It refers to the power ratio between the maximum radiation intensity in the front beam direction versus the back direction of the antenna. A higher FBR value indicates the antenna is more directional and focuses more energy towards the front. This improves the signal quality in the intended direction which is an essential need for recognizing the locations of defence personnel. It is calculated using the Eqn. (3)[9]

$$FBR\ (dB) = 10\ \log 10\ (\frac{P_{forward}}{P_{backward}}) \qquad (3)$$

Figure 4(d) shows the comparative analysis of FBR with and without FSS. The peak value achieved was from 3.58 to 19.87 dB (at 18 GHz).

6. RCS REDUCTION ANALYSIS

By controlling the scattering of electromagnetic waves, FSS minimises the delectability of antennas to radars, making them valuable components in defence applications where low observability is essential. Radar Cross Section (RCS) is a measure of how detectable an object is by radar. Larger RCS means the object will reflect more radar signals to the radar receiver, making it easier to detect. A smaller RCS means the object is harder to detect. Monostatic RCS is the typical radar configuration used in most military applications - the transmitter and receiver are co-located. FSS can be engineered to absorb or scatter incoming radar waves, thereby reducing the RCS[13]. The monostatic RCS results of the designed antenna with and without FSS is displayed in Fig. 5(a) under θ – polarised incident plane wave with magnitude of 1 V/m. Bi-static RCS over the entire frequency range for incident angle $\varphi=0^0$ and $\varphi=90^0$ is displayed in Fig. 5(b).

The results display excellent reduction in RCS over the entire frequency range. Peak Mono-RCS reduction achieved is from -25 dB till 50 dB around 17 GHz, average reduction of -25dB is seen across. This ensures the stealth capabilities of the proposed antenna. Bi-Static RCS can be seen for two values of φ, and dip of 25 to 30 dB is seen at $-100< \theta<100$.

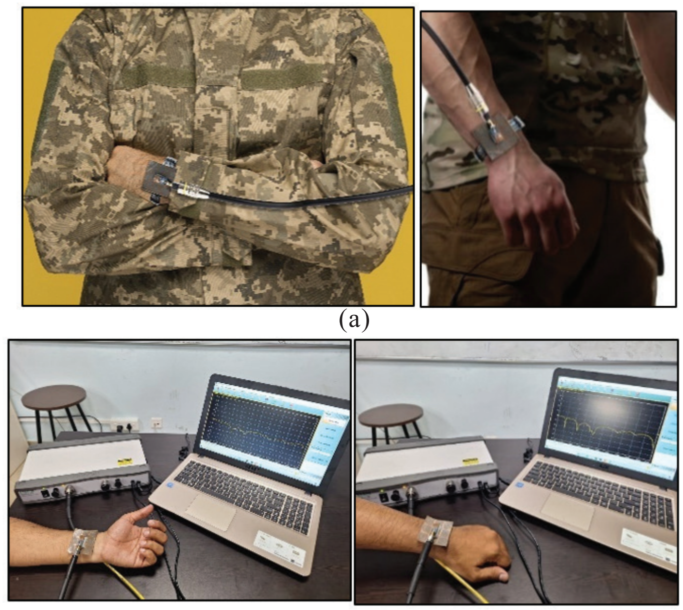
7. ON-BODY ANALYSIS

The designed wearable antenna system should allow military personnel to maintain continuous communication capabilities while on the move. Whether deployed on foot, in vehicles, or in urban environments, it should ensure that soldiers can maintain reliable connectivity without being encumbered by traditional fixed antennas or bulky communication equipment[14]. It is therefore paramount to understand the behavior of proposed antenna when it is worn on the wrist of the soldier. The antenna designed here ensures that kind of safety as it possess a very low SAR value well under the pre-mentioned standards of 1.6 W/kg for 1 g and 2 W/Kg for 10g of tissue.

It is calculated using Eqn. (4)[15]

$$\mathrm{SAR} = \sigma|\mathrm{E}|^2/\rho \qquad (4)$$

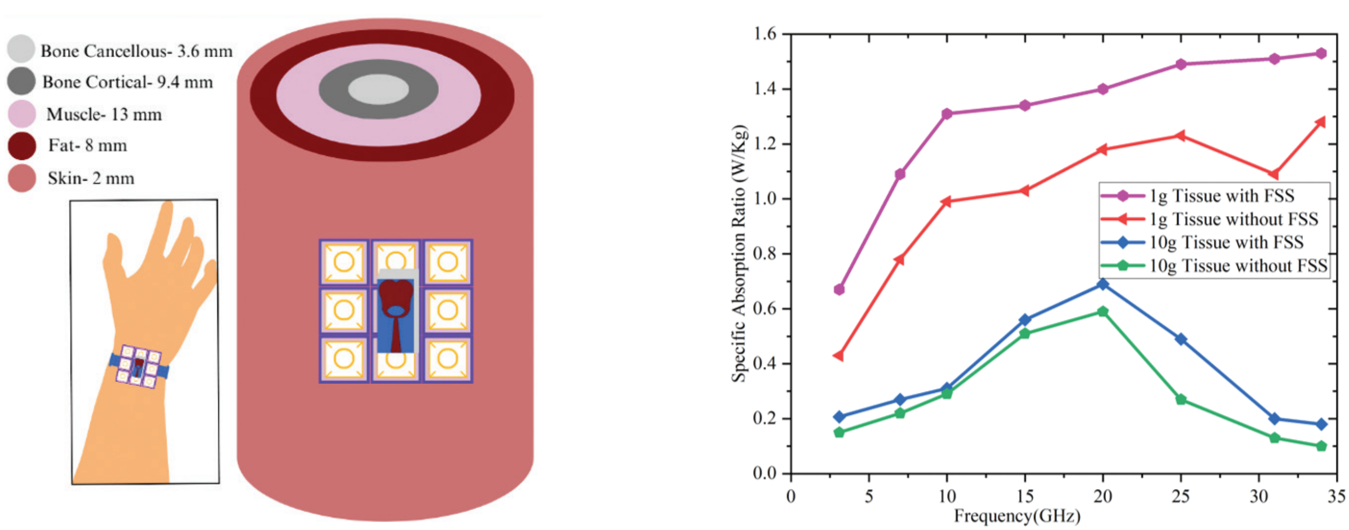
The simulation and values are determined using CST 5-layer phantom model as shown in Fig. 6(a). Figure 6(b) displays the correlation of SAR with and without FSS.



(a)

(b)

Figure 7. (a) Complete assembly–fabricated; and (b) Measurement set-up with VNA.



(a) (b)

Figure 6. (a) Phantom model of tissue of wrist with antenna; and (b) SAR v/s Frequency for 1 g and 10 g tissues with and without FSS.

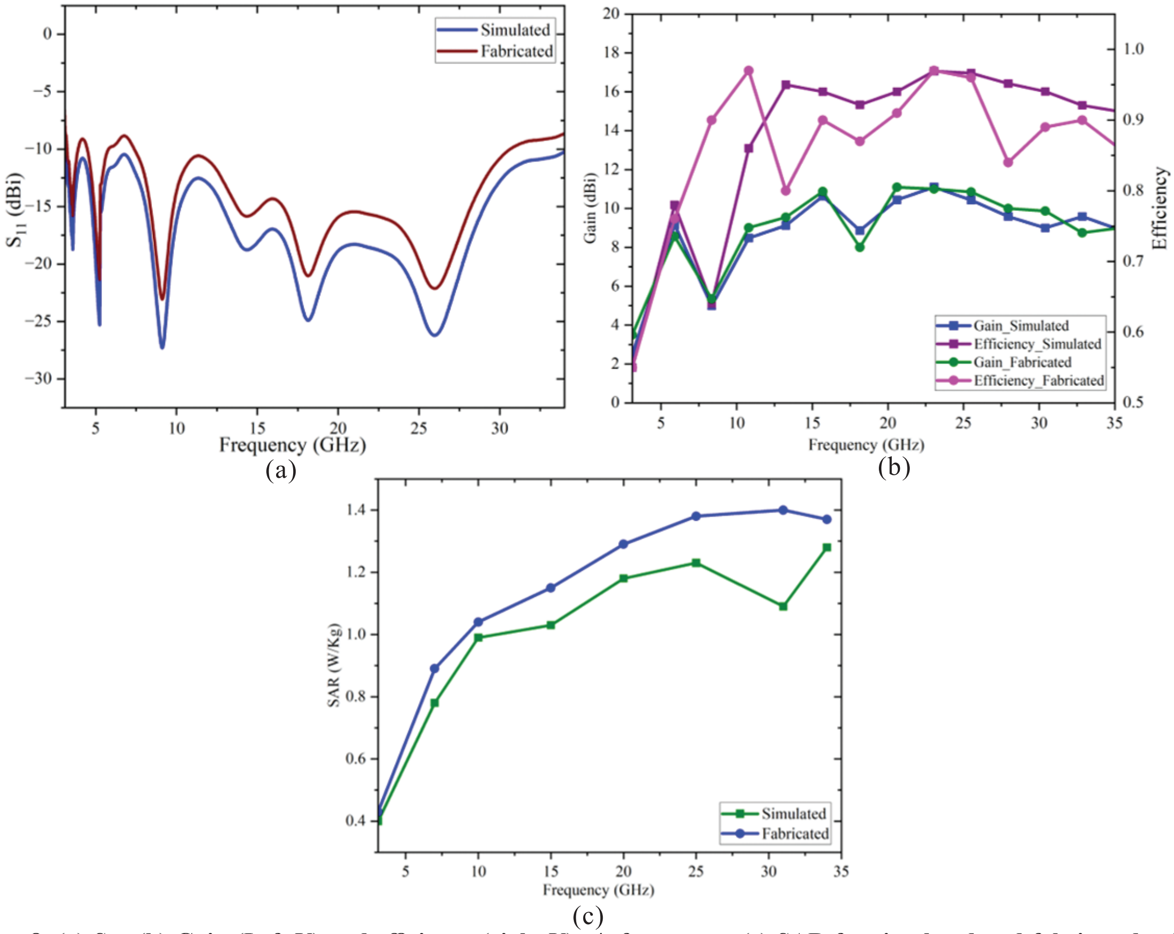


Figure 8. (a) S_{11}; (b) Gain (Left Y) and efficiency (right Y) v/s frequency; (c) SAR for simulated and fabricated values.

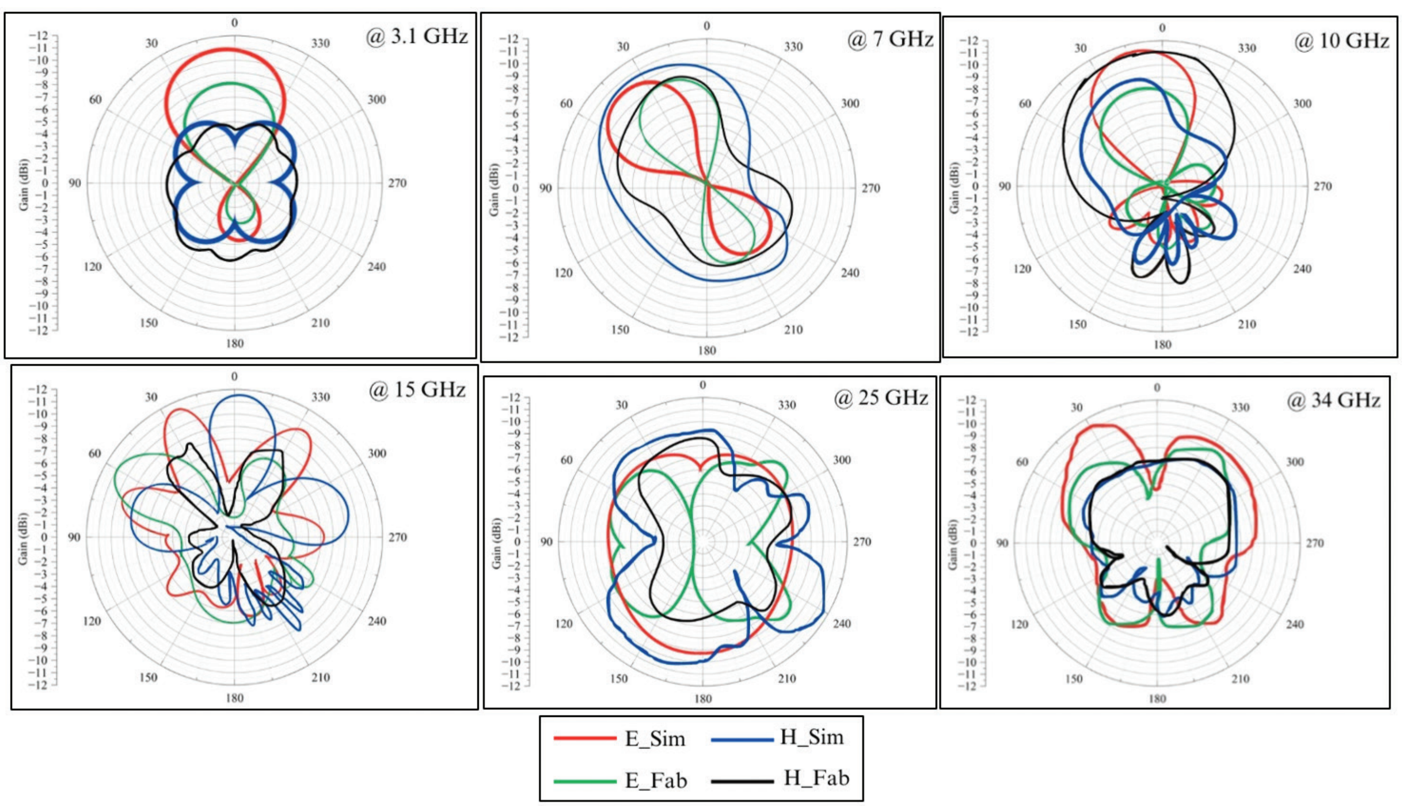


Figure 9. Radiation pattern of simulated and fabricated antenna – for 3.1, 7, 10, 15, 25 and 34 GHz.

It is clear that the antenna itself has a very low value of SAR and implementing FSS reduces it further. The peak SAR was found to be 1.51 W/kg and 1.4 W/kg for 1g tissue and 0.69 W/Kg and 0.59 W/Kg for 10 g tissue without and with implementation of FSS respectively.

8. PROTOTYPE MANUFACTURING

Antenna is fabricated on denim and multifunctional FSS is etched on RT Duroid 5880. Figure 7(a) shows the set up. For user comfort, a denim band of 0.5 mm thickness is attached at the back of FSS to work as a proper wrist band. VNA is connected to the set-up as shown in Fig. 7(a).

8.1 Electromagnetic Characteristics

Simulated and fabricated results of S_{11} can be seen in Fig. 8(a).

8.2 Gain and Efficiency Characteristics

Figure 8(b-Left-Y) shows the comparison of simulated and fabricated antenna gain. It can be seen that the highest gain acquired was 11 dBi at 23.05 GHz. The gain values are in good agreement. Similarly, when the efficiency was calculated as shown in Figure 8(b-Right-Y) along the frequency range and compared with the simulated ones, the values are analogous to each other.

8.3 On-Body Characteristics

The SAR values for the antenna itself were very low and implementation of FSS supported those measurements. The SAR was measured practically as well using Temperature Method with Eqn. (5)[8]

$$SAR=c(\Delta T/\Delta t) \quad (5)$$

where, ‘c’ is the heat capacity of a human skin and that value is 3391. Figure 8(d) displays the measured and simulated values

(a) (b)

Figure 10. Antenna set up working as transmitter on human wrist and receiver at a distance of 300 cm.

Table 2. Link margin at various frequencies

Frequency(GHz)	**5.5**		**10**		**25**		**34**	
FSS	**Without**	**With**	**Without**	**With**	**Without**	**With**	**Without**	**With**
Transmitter gain	0.947	1.41	4.19	4.64	5.89	6.29	7.04	7.85
Receiver gain	1.79	2.14	4.73	4.95	5.7	5.96	7.26	7.57
Data rate (B_r) (Mbps)	100/200	100/200	100/200	100/200	100/200	100/200	100/200	100/200
LM at 300 cm	**61.8/58.8**	**67.4/64.3**	**57.9/54.9**	**61/59.9**	**57.4/54.1**	**65.1/62.1**	**57.3/54.2**	**59.3/56.3**

Table 3. Related Works in terms of various attributes

Reference	**Dimensions**	**Frequency range**	**Material used**	**Peak gain**	**RCS (dB)**	**Link margin**	**SAR**
[1]	30x35	3.1-15	FR4	7.6	NP	NP	NP
[2]	16x22	3.1-18.6	FR4	9.4	NP	NP	NP
[3]	40x30	2.39-19.94	Rogers 6002	9.5	NP	NP	NP
[4]	30x40	2.27-5.55	FR4	7.3	NP	NP	NP
[5]	29x35	24.5-25.7	FR4	9	NP	NP	NP
[6]	50x50	2.2-12.7	FR4	11.5	NP	NP	NP
[7]	35x30	3.16-15	FR4	10.9	NP	NP	NP
[10]	24x29	2.92-7.36	FR4	8.87	10	NP	NP
[11]	9.4x11.3	4.72-6.19	polydimethylsiloxane	8.54	NP	NP	Yes
[12]	42x43	1.5-6	Flannel	3.35	NP	NP	Yes
Proposed	**10.5x21**	**3.1-34.5**	**Denim**	**11.1**	**Implemented and demonstrated**		

of SAR and it is evident that the antenna prototype is safe for human use.

8.4 Radiation Characteristics

2-D polar plots for simulated and measured radiation patterns of the designed antenna set-up for various frequencies are shown in Fig. 9 for 3.1 GHz, 7 GHz, 10 GHz, 15 GHz, 25 GHz and 34 GHz.

9. LINK MARGIN ANALYSIS

In military operations, real-time sharing of tactical information between different units, such as ground forces, aircraft, and naval vessels, is vital for situational awareness and coordination. Our goal is to ensure the DLB has strong strength of signal to provide the location of the soldier to the command center and back. In high-speed communication, maintaining a reliable link is essential to prevent data loss or interruption. Link budget analysis helps in evaluating link reliability by accounting for factors like fading, multipath propagation, and atmospheric conditions.

To comprehend to the link budget analysis, two identical antennas working as transmitter (T_x) and Receiver (R_x) respectively are placed at the wrist of human and at a distance of 300 cm respectively. The set up and practical approaches are depicted in Fig. 10. An ideal PSK modulation scheme is assumed, with a BER of 10^{-4} at an SNR of 9.64 dB for high data rates of 100Mb/s and 200 Mb/s. Link margin is calculated using following Eqn. (6)

$$LM=Ap(dB)-Rp(dB) \tag{6}$$

The results achieved are displayed in Table 2.

The improvement in communication strength can be seen as the FSS is implemented in Table 2. The LM improved from 61 m to 67 m for 100 Mbps and 59 m to 64 m for 200 Mbps. With the values acquired, it is undisputable to state the fact that the proposed antenna set up is entirely capable to work as a DLB for wide range distance and provide subtle and reliable high-speed communication.

10. CONCLUSION

The designed structure stands out as a cutting-edge solution tailored for Defence Locator Beacon applications. Its impressive gain signifies its ability to amplify signals efficiently and is pivotal for maintaining connectivity and locating defence personnel swiftly and accurately. Moreover, the antenna's exceptional reduction in RCS and FBR enhances stealth capabilities, signal integrity, reducing interference, enabling defence operations to maintain covert profiles. The antenna's compliance with SAR standards underscores its commitment to safety. Furthermore, the antenna's impressive Link margin facilitates high-speed data transfer which is instrumental in transmitting critical information swiftly and accurately. In summation, the multifaceted capabilities of this antenna make it an indispensable asset for defence and military endeavors, offering unparalleled performance in locating and safeguarding defence personnel through the Defence Locator Beacon technology, thereby bolstering national security and operational effectiveness.

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doi: 10.1007/s11277-023-10644-5

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In the current study, she has conceptualised and carried out the methodology and manuscript preparation.

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Mr Saurabh Shukla is a Scientist ‘F’ at DRDO Delhi. His areas of research include: Design and development of various broadband electronically scanned antenna arrays for electronic warfare jammers.
In this study, he contributed in the search for requirements of wearable antenna in defence applications and helped with gaps and scope for improvement in location identification in defence and military systems.