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A flexible dual-H shape monopole antenna with dual H shape EBG for WBAN

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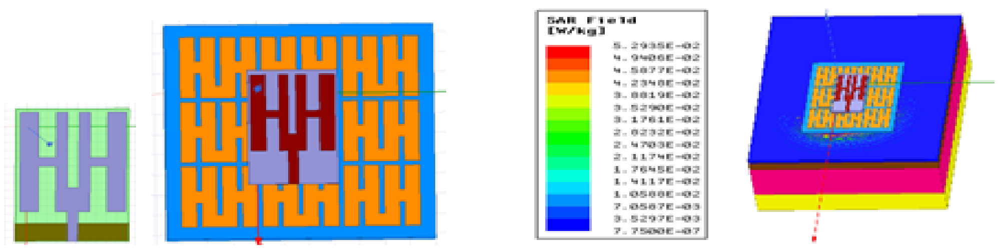
Article

ABSTRACT



This paper introduces compact novel dual H-shaped antenna that incorporates an innovative dual H-shaped electromagnetic bandgap structure (EBG), designed for 2.4 GHz applications within the Industrial, Scientific, and Medical (ISM) band, particularly for wearable technologies. The design features a, flexible, robust antenna tailored to come across the requirements of wearable applications. Both dual H-shaped antenna and the 3x3 dual H-shaped EBG array are simulated using Ansys HFSS (High Frequency Structure Simulator). The simulation results are justified by experimental measurements. The efficacy of the EBG structure in mitigating surface waves and lowering the specific absorption rate (SAR) is demonstrated through simulations with a four-layer human body model, showing measured SAR values are well within the regulatory limits. Furthermore, the antenna's performance was assessed under bending and on-body conditions.

Keywords: Flexible monopole antenna, Electromagnetic band gap structure, integrated design, specific absorption rate

INTRODUCTION

In recent times, Wireless Body Area Networks (WBANs) are advancing quickly and attracting the researchers due to their potential applications in healthcare monitoring and sports training.[1] Wearable antenna technology is primarily utilized for these applications. These wearable antennas must be conformal to adapt to different body parts, which requires the use of flexible materials. Their design should ensure minimal performance degradation when get in touch with the human body. Many studies have investigated that the textile fabric, including denim fabric, works as a potential substrates for antennas and metamaterials in these applications.[2] The demand for flexible on-body antennas is increasing, driven by substantial needs in health checkup scenarios. Now days the key factors for wearable devices include their performance in challenging robust environments[3] a compact and low-profile design,[4] flexibility,[5] enhanced bandwidth and minimal Specific Absorption Rate (SAR) values to fulfill market requirements.

A wide bandwidth in textile antennas is essential, as it reduces sensitivity to detuning caused by adverse environmental factors. SAR measures, when exposed to an electromagnetic field how much energy the human body absorbs. This absorbed power can potentially pose health risks, making SAR evaluation crucial. It is essential that SAR levels remain well below the accepted safety limits. To protect the public from excessive exposure to electromagnetic fields, various organizations, such as IEEE, ICNIRP, and the FCC, have set limits on radiation emitted by these electronic devices. In line with the recommendations from the FCC and ICNIRP, the Specific Absorption Rate need to be below 2 W/kg averaged over 10 grams of tissue and under 1.6 W/kg averaged over 1 gram of tissue.[6,7,8] Over time, various authors in the literature have proposed numerous techniques aimed at minimizing SAR. One approach involves the integration of artificial magnetic conductors, identified as EBG structures and high-impedance surfaces (HIS), to serves as backing shield for the wearable antennae. This design helps minimize surface waves, thereby reducing radiation directed toward the human body and leading to significant improvements in SAR reduction.[9] In body wearable applications the presence of vias can impact user comfort so it is appealing to utilize a uniplanar EBG structure without vias.[10]

In the past, numerous authors have reported on different types of EBG structures. The work by S. Velan et.al.[11] describes a dual-band antenna at a 2.4 GHz, with a fractal design, supported by a 3 x 3

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array of square-shaped EBG structures, with a unit cell size of 50 mm x 50 mm, to get SAR reduction. Ashyap et.al.[12] reported a compact wearable textile antenna aimed for medical applications operates at 2.4 GHz and measures 46 mm x 46 mm. This antenna utilizes a flexible jeans material as its substrate and is backed by a 2 x 2 array of EBG structures claims gain improvement and SAR reduction. B.S. Abirami et.al.[13] have reported a printed Yagi-Uda antenna with flexible substrate, operating at a 2.4 GHz, is supported by an EBG structure for on-body communication, employing a 3x3 EBG array to inhibit EM wave propagation. In the report by S. Kim et.al.[14], the author presents a monopole antenna constructed by using paper substrate and inkjet printed electromagnetic bandgap array. The work by H.R. Raad et.al.[15] presents a printed M-shaped monopole antenna backed by a Jerusalem Cross artificial magnetic conductor at 2.45 GHz, the integration of the Jerusalem Cross artificial magnetic conductor reduces electromagnetic interference. In the report by S. Yan et.al.[16] the author presents a dual-band antenna operating for 2.4 GHz and 5 GHz, incorporated with EBG, with dimensions of 100 x 100 x 4.5 mm^3 and a unit cell array of 4 x 4. The study highlights that this textile antenna achieves a high Front-to-Back Ratio (FBR) and a low SAR value across a wide bandwidth. S. Zhu et.al.[17] have reported an antenna incorporated with EBG of shape double concentric square, featuring EBG unit cells that operate at 2.4 GHz and 5 GHz as a dual band with overall dimensions of 120 x 120 x 4.3 mm^3. The study investigates a reduction in radiation penetration into the body. In the work by P. Sambandam et.al.[18], the author presents EBG of fork shape is incorporated with a compact monopole antenna for wearable applications, utilizing a 2x1 EBG array, which results in a SAR value of 0.695 W/kg. In the work by G.P. Gao et.al.,[19] the author presents a antenna having circular ring slot patch integrated with 3x3 array of rectangular EBG with dimensions of 81 mm x 81 mm x 4 mm, along with its equivalent circuit model. The author claims that this antenna, which has a low SAR, is suitable for wearable applications. In the reports by Pandey et.al.,[20,21] the author uses DGS (defected ground structure) to enhance bandwidth of antenna. The DGS is in which the ground plane of a microstrip circuit is modified by introducing defects like etched patterns such as holes, slots, patches in the ground plane to control the electromagnetic waves on the surface to achieve specific filtering or resonance effects. Electromagnetic band gap structures are based on periodic arrangements of conducting or dielectric materials in the form of patches, rings or geometric shapes arranged in lattice like structure to suppress surface waves.

Table 1: Implemented antenna structure and EBG structure with number of EBG unit cells.

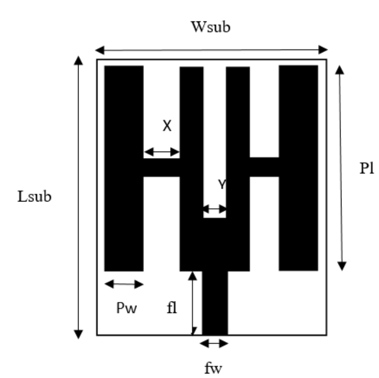
Ref. No.	Antenna Structures	EBG Structure	No of unit cells
[12]	Inverted E shaped microstrip antenna	Four T shapes in stripline pattern	2 x 2 array of EBG
[14]	Microstrip linear monopole antenna	Single ring resonators	4 x 3 array of EBG
[15]	M shaped monopole antenna	JC AMC	3 x 3 array of JC AMC
[18]	Beveled Y shaped monopole antenna	Fork slotted structure	2 x 1 array of EBG
Proposed	Dual H shaped monopole antenna	Dual H shaped EBG	3 x 3 EBG array

Table 1 shows the different structures of antenna and EBG implemented. The proposed antenna structure as dual H shaped with Dual H shaped EBG is novel one.

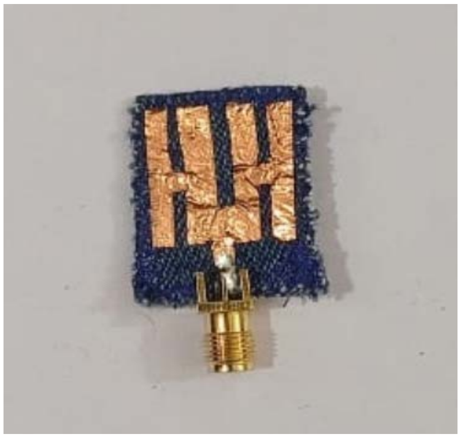
This paper introduces a flexible monopole wearable antenna that integrates with a compact uniplanar EBG structure, specifically designed for wearable applications in the ISM band of 2.4 GHZ, measuring 57 x 57 x 3 mm^3. This design achieves greater size reduction compared to earlier studies without compromising performance. The aim of EBG structure integration with antenna is to create phase reflection and suppress surface waves, leading to a significant reduction in SAR. Section II details the design and characterization of the flexible monopole antenna and EBG structure. The section III focuses on analyzing the antenna's performance on the EBG plane. Section IV represents the effect of bending on antenna incorporated with EBG. Finally, Section V evaluates the antenna-body interaction, considering the reflection coefficient (S11), the effects of structural bending, and the specific absorption rate.

FLEXIBLE MONOPOLE ANTENNA DESIGN

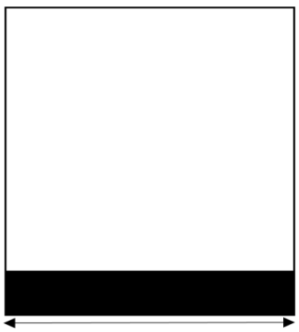
The proposed novel dual H shaped flexible monopole wearable antenna resonating at 2.4 GHz is aimed by using Ansys HFSS. The patch of proposed antenna is constructed from copper tape which act as conductive element while wearable low cost jeans fabric with εr=1.78 and a 0.085 loss tangent having thickness 0.8 mm with resistivity 431 Ωm as a substrate [22]. The length of substrate is Lsub = 34mm and width Wsub = 23mm. The antenna is powered by microstrip feed line. Using a microstrip feed line keeps the design compact and well-integrated with the antenna structure. This approach minimizes losses and enhances performance, making it ideal for wearable applications where size and efficiency are crucial. For dual H shape patch copper tape is used with the thickness of 0.17mm having conductivity 5.8X107 S/m. The overall dimensions of dual H shape patch are as patch length Pl = 25 mm, width Pw = 3.8 mm, X = 3.42 mm, Y = 2.28 mm, feed line length fl = 7.6 mm and width fw = 1.6 mm and ground plane length gw = 23 mm, width gl = 4.48 mm. The proposed model of antenna fabricated with these specifications. Figure 1 displays the proposed antenna model, showcasing its specifications from both the top and bottom views.



(a) Top View of Dual H shape antenna



(b) Top View of fabricated Dual H shape antenna



(c) Bottom View of Dual H shape antenna

(d) Bottom View of fabricated Dual H shape antenna

Figure 1. Dual H shaped monopole antenna configuration (a) Top View of Dual H shape antenna, (b) Top View of fabricated Dual H shape antenna, (c) Bottom View of fabricated Dual H shape antenna (d) Bottom View of fabricated Dual H shape antenna

Figure 2 illustrates the simulated and measured S_{11} reflection coefficients for the fabricated antenna. The figure indicates that, in the absence of the EBG structure, the simulated antenna resonates at a frequency of 2.4 GHz, exhibiting an S_{11} value of -24.28 dB. This reflects a strong impedance match at that frequency, indicating efficient energy radiation. Conversely, the fabricated antenna shown in figure 3 resonates at 2.42 GHz, with an S_{11} of -21.57 dB. Although there is a slight shift in resonance frequency, both the simulated and measured results demonstrate a close match in performance characteristics. The close alignment of these results underscores the reliability of the simulation models used and validates the effectiveness of the antenna design.

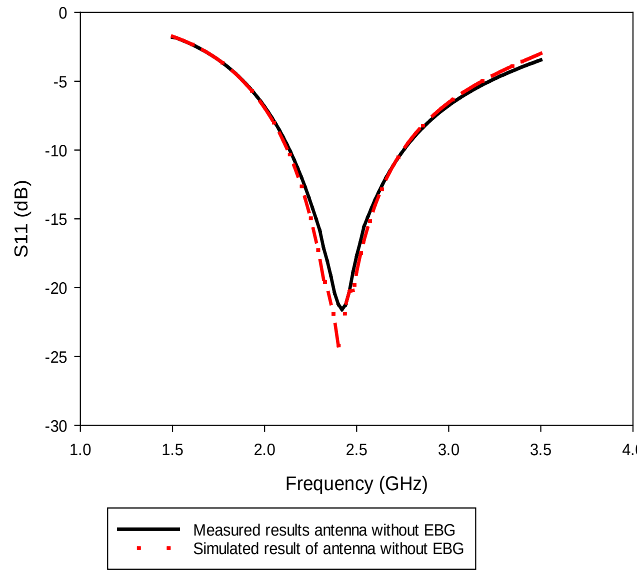


Figure 2. Comparison of measured and simulated reflection coefficient S11 of proposed antenna

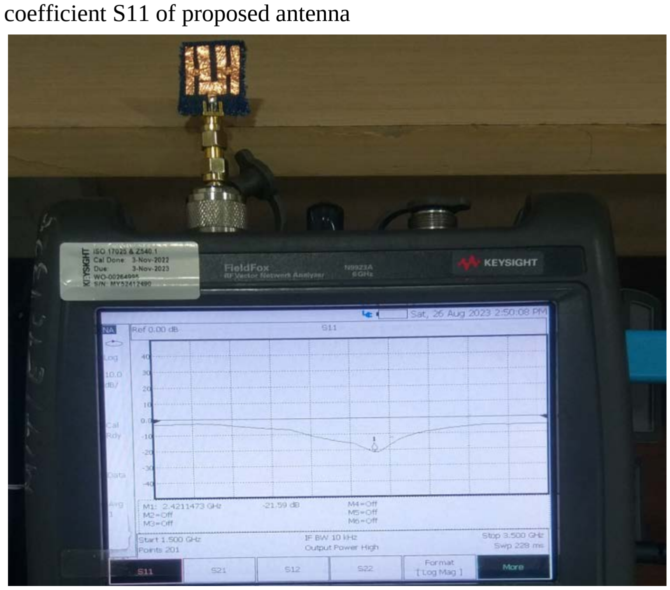
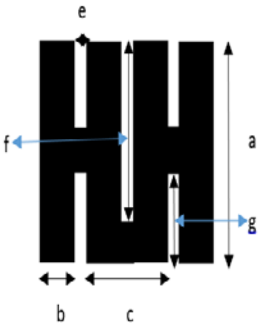
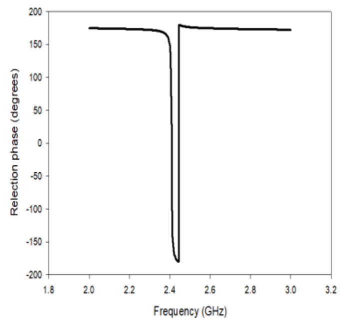


Figure 3. Fabricated antenna measurement on VNA

PROPOSED EBG DESIGN

This section outlines the EBG unit cell design. The jeans fabric used for antenna substrate with same specifications is used for EBG substrate. The EBG unit cell designed is novel Dual H shape to achieve desired reflection phase with various dimensions as shown in figure 4 (a) unit cell length a = 19 mm, b = 3.8 mm, c = 9 mm, d = 7.8 mm, e = 1.2 mm, f = 15.6 mm, g = 3.9 mm. These dimesions helped to get the desired operating frequency by the equations.[23] To determine the phase of the reflection coefficient , the EBG unitcell structure is analyzed using master slave boudaries on the sides of the unit cell, with a wave port impedance introduced at the top. This proposed EBG unit cell structure reflects normally incident electromagnetic waves with a zero-degree phase at a specific frequency 2.4 GHz. as shown in figure 4 (b). In this way the EBG performance at the operating frequency is validated, and EBG act as artificial magnetic conductor, with increasing frequency EBG surface reflection phase varies from -180 degrees to +180 degrees.





(a) EBG unit cell (b) Phase Response

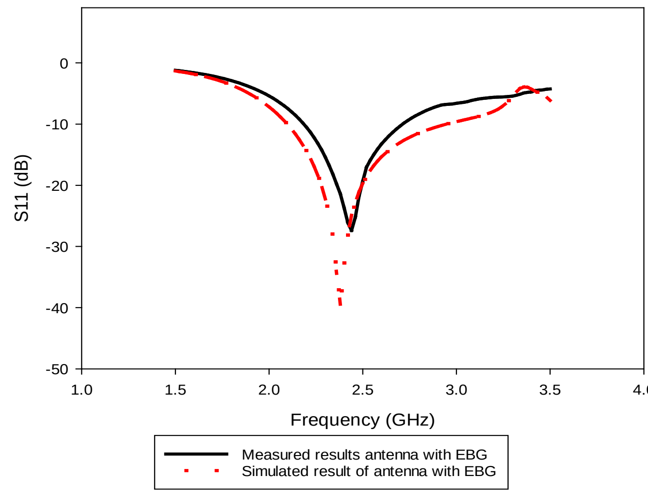
Figure 4. EBG a) Proposed EBG unit cell b) Its Phase Response

ANTENNA INTEGRATED WITH EBG

The designed dual H shape antenna is positioned above the EBG array as illustared in figure 5 (a). To prevent short circuit due to any mismatch and electrical contact the gap of 1mm is kept between antenna and EBG array so there is no direct connectivity between antenna and EBG structure. The feed is attached to only antennas patch not EBG structure as shown in Figure 5(b). Figure 5(c) presents the simulated and measured reflection coefficients of the antenna with a 3x3 EBG array in free space From this figure 5 (c), the simulated antenna integrated with EBG resonates at frequency 2.4 GHz with S_{11} as -39 dB and fabricated antenna integrated with EBG resonates at frequency 2.42 GHz with S_{11} as -24.28 dB. The results indicate a slight shift in resonance frequency when the antenna is combined with the EBG structure. This variation may be attributed to factors not accounted in the simulations, such as soldering tolerances and SMA connectors.

(a) Antenna incorporated with EBG array

(b) Side view



(c) Simulated and measured results of antenna with EBG

Figure 5. (a) Antenna incorporated with EBG array (b) Side view (c) Simulated and measured results of antenna with EBG

Figure 6 illustrates the comparison of simulated and fabricated result of antenna without EBG and with EBG. Figure 7 exhibits the radiation patterns of the antenna, both simulated and measured, with and without the EBG structure in the E-plane and H-plane, it depicts back lobe is reduced when antenna incorporated with EBG.

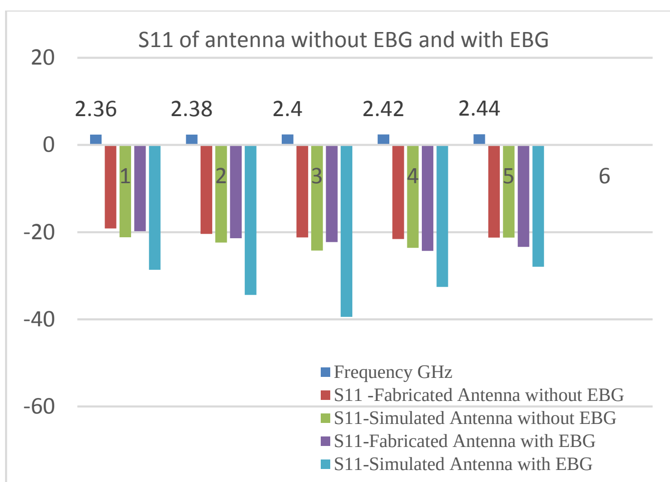
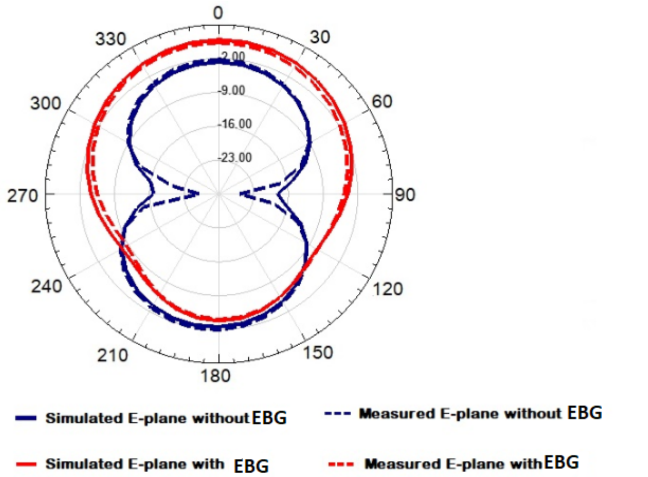
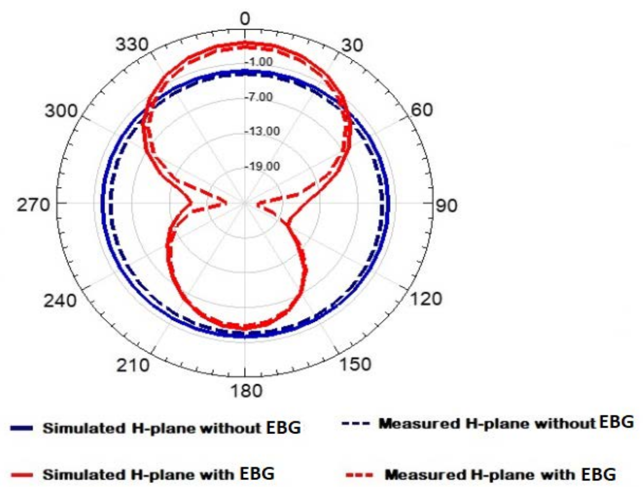


Figure 6 comparison of simulated and measured result of antenna without EBG and with EBG



(a) E plane



(b) H plane

Figure 7. (a) Simulated and measured radiation patterns of antenna with EBG in (a) E plane and (b) H plane.

BENDING ANALYSIS

To look in to the effect of antenna bending, when worn on body parts like the arm and leg, three foam cylinders of different diameters are fabricated. Figure 8. shows fabricated cylindres with diameters as 80 mm, 100 mm, 120 mm with the proposed antenna wraped on it. The investigation of S_{11} reflection coefficient characteristics of antenna integrated with EBG in free space with those on different bending diameters in both X and Y directionis shown in figure 8.[24] The return loss (S_{11}) characteristics plotted in figure 9 shows that when the diameter of cylinder is changed the resonant freuency of proposed antenna and its operting frequency band are slightly shifted which will be considered as negligible because the antenna preserves its frequency of operation with sustained bandwidth provided by reflection coefficient S_{11}.

ANTENNA INTEGRATED WITH PROPOSED EBG SAR ANALYSIS

Radio waves emitted by wireless devices can be absorbed by the surrounding environment, including humans. The penetration of these radio waves into human tissues can be evaluated using the Specific Absorption Rate (SAR). The SAR levels of the proposed

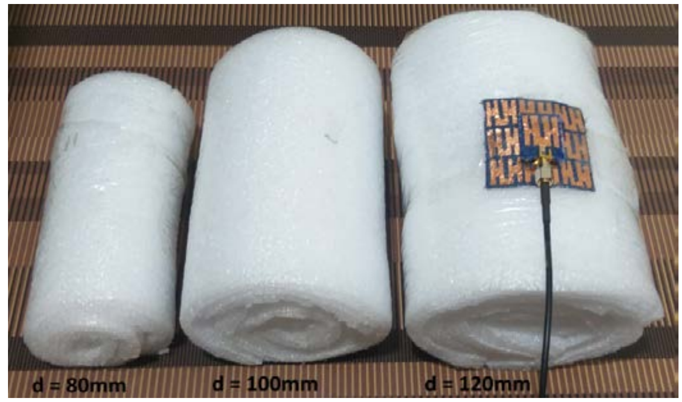
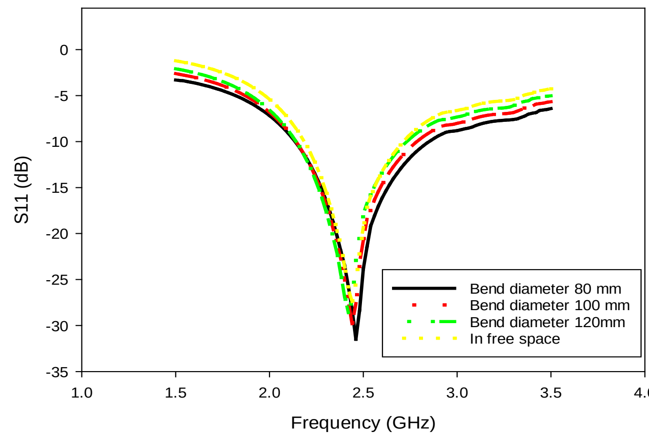
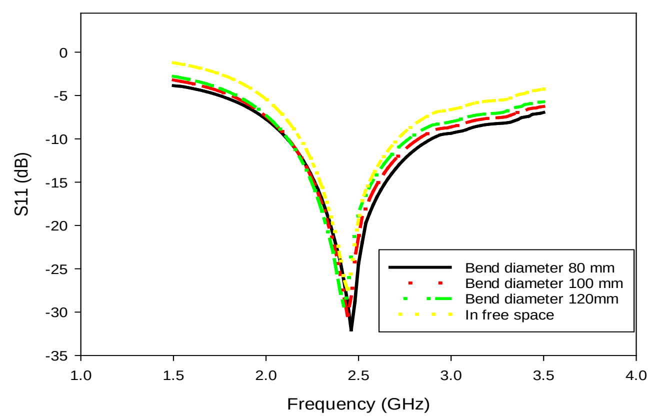


Figure 8. Fabricated foam cylinders with varying diameters



(a) X- direction



(b) Y- direction

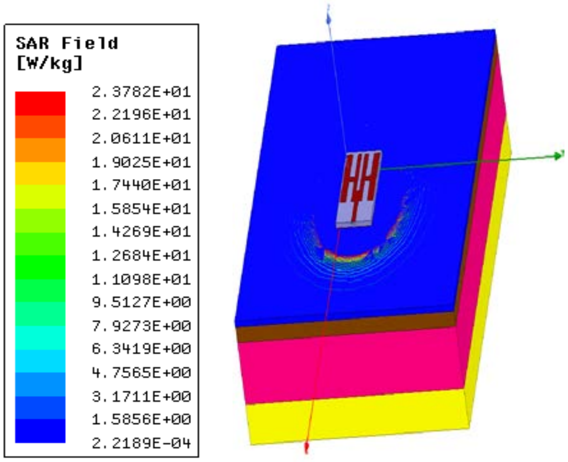
Figure 9. S11 plots in free space are compared for bending at different diameters in (a) the X direction and (b) the Y direction.

antenna placed with EBG structure and without EBG, must be assessed during the design phase to ensure compliance with safety limits using a four layer rectangular human model. The human model comprises four layers: first one is skin, second fat, third muscle and fourth one is bone. Table 1 provides the detailed information on the permittivity, conductivity, thickness and density of each layer [2526]. The SAR calculations are performed according to the IEEE C95.1 standard, which sets guidelines for assessing exposure to electromagnetic fields using Ansys HFSS.

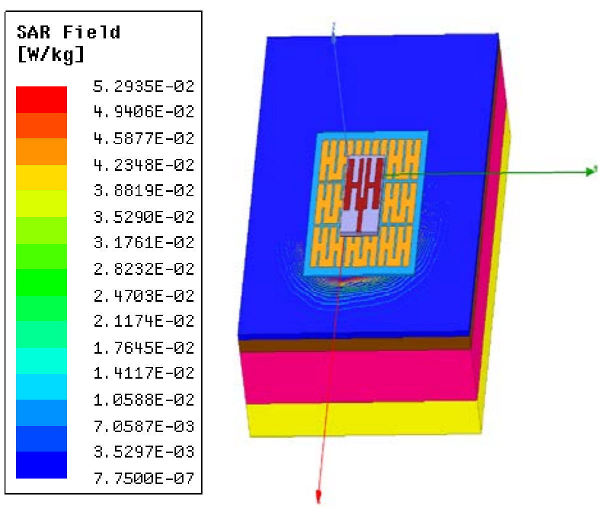
The SAR values attained in the human body model with only proposed antenna, averaged over 1 g of tissue, are presented in Figure 10(a) as 23 W/kg. Figure 10(b) displays the SAR value in the human body model when the antenna is integrated with the EBG, averaged over 1 g of tissue, as 0.0529 W/kg at 2.45 GHz, which falls well within the FCC specifications of 1.6 W/kg. When comparing the SAR values of the antenna alone and the antenna with EBG, it is observed that the incorporation of the EBG structure results in a drastic reduction of the SAR value.

Table 2 : Human tissue properties at a 2.45 GHz

Layer	Skin	Fat	Muscle	Bone
Thickness	2 **mm**	5 **mm**	20 **mm**	13 **mm**
Permittivity (εr)	37.95	5.27	52.67	18.49
Conductivity	1.49 **(S/m)**	0.11 **(S/m)**	1.77 **(S/m)**	0.82 **(S/m)**
Density	1001 **(Kg/m3)**	900 **(Kg/m3)**	1006 **(Kg/m3)**	1008 **(Kg/m3)**



(a) Without EBG



(b) With EBG

Figure 10. Simulated SAR for an input power of 1 mW in a four-layer human body model: (a) without EBG and (b) with EBG.

The S_{11} comparison of the antenna with the EBG in free space and on the body is pointed in Figure 11; it indicates the results found to be in close agreement. Table 2 illustrates that the proposed antenna incorporated with EBG structure features a compact design and maintains SAR level within acceptable limits when compared to other existing structures.

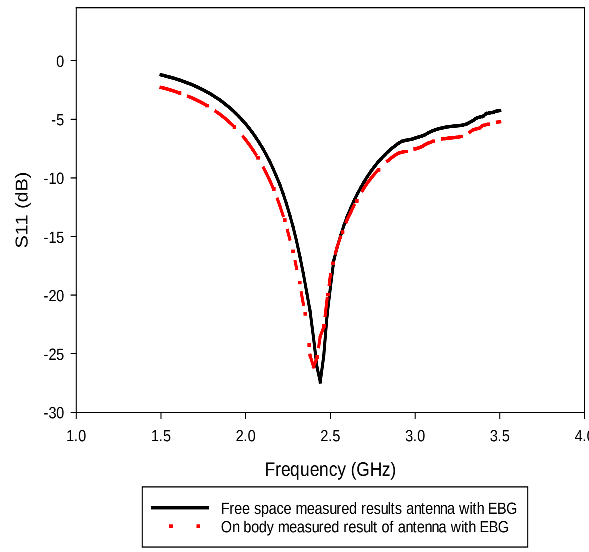


Figure 11. S11 of antenna with EBG in free space and on body

Table 3: Comparison of existing flexible wearable antennae with proposed antenna

Ref.	Dimensions (mm^3)	Unit cells array	Substrate	SAR in (W/kg)
[11]	150x150x4	3x3	Jeans	0.079 over1g
[16]	100x100x4.5	4x4	Felt	0.0464 over 10 g
[17]	120X120X4.3	3X3	Felt	0.079 Over 1g
[19]	81x81x4	3x3	Felt	0.554 Over 1g
[23]	62x42x4	2x2	Rogers RO3003	0.79 Over 1g
Proposed design	57x57x3	3x3	Jeans	0.0529 Over 1g

Conclusion

This work involves design, simulations, creation and key experimental measurements of a dual H-shaped patch antenna and a dual H-shaped EBG structure. The antenna design is performed using HFSS, and the proposed dual H shaped EBG structure is incorporated with antenna. This paper experimentally demonstrates and confirms that the proposed dual H-shaped antenna, integrated with a dual H-shaped EBG, is suitable for WBAN applications in sports tracking and health monitoring.

Experimental measurements for the antenna, both with and without the EBG, closely align with the designed values. The measured S11 results demonstrate that the antenna with Electromagnetic Bandgap (EBG) design achieves effective impedance matching at a 2.4 GHz in ISM band. In addition to on-body measurements, bending analysis has been conducted, and the results were observed to be stable. SAR analysis was performed using a rectangular human body model consist of four layers to assess the prototype's suitability for wearable applications. The incorporation of EBG structures led to a significant reduction in SAR value, Decreasing from 23 W/kg to 0.0529 W/kg.

CONFLICT OF INTEREST STATEMENT

Authors do not have any known factor that might have influenced the work reported in this article.

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