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# Investigation of SAR Reduction and Bending Effect Using a Flexible Antenna with EBG Structure for 2.45 GHz Wearable Applications

**Sonal Jatkar*, Nilesh Kasat**

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**Abstract**: This paper presents, an analysis of Co-Planar Waveguide fed textile antennas operating at 2.45 GHz frequency with an Electromagnetic Band-Gap array for WBAN applications. Denim substrate, characterized by its dielectric constant of 1.6 and thickness of 1mm which is stacked together to get height of 3mm. Simulation using HFSS provides a return loss of -52 dB at 2.45 GHz. Size of antenna after incorporating 2*2 array in EBG structure is 61*61*3 $mm^3$. It results in increase gain from 2.36 dB to 4 dB without EBG and with EBG respectively. Stochastic frameworks employing polynomial chaos principles expansions is used to model antenna dimensions. The study aimed to investigate how bending affects antenna performance, employing two bending scenarios: one in the H plane and the other in the E plane. Also, for WBAN applications, SAR value is simulated on human body phantom using HFSS simulator and is obtained to 41.04 W/Kg without EBG and 0.522 W/Kg with EBG.

***Index Terms***- Stochastic model, Textile Antenna, EBG, WBAN, SAR

## 1. Introduction

The rising emphasis on making electronics smaller has sparked a greater need for gadgets that can be conveniently worn on the body. Wearable and flexible electronics are now widely recognized in modern society, as the fusion of textiles and electronic components has greatly improved daily life. Looking ahead, electronic systems will seamlessly interact with clothing, enabling textile antennas to support communication tailored to individual human needs. Ongoing progress in electronic devices, including advancements in wearable technology, has resulted in a wide range of portable and body-worn devices such as activity trackers, smartwatches, health monitoring systems, medical surveillance, smart glasses, helmets, and smart clothing, smart entertainment, diagnostics, Satellite applications etc. [1-3].

Within these applications, wearable antennas, especially those intended for body-area networks, play a crucial role. Designing antennas and communication systems for the human body presents numerous challenges not encountered in traditional systems. These antennas are crafted to be flexible, often utilizing textile materials in their design [4-6]. However, conventional antenna systems often fail to deliver satisfactory performance due to inherent limitations, whereas textile-based antennas have shown promising results in addressing these challenges and achieving improved functionality in wearable systems. In the realm of wearable applications, antennas must adhere to specific criteria. Firstly, their size should be compact, they should be lightweight and flexible [7, 8]. The substrate material is crucial, as research in materials indicates that materials with low dielectric constants can minimize surface wave loss by expanding antenna bandwidth. Additionally, these materials offer flexibility to antennas, enabling integration with clothing for wearable applications on the human body. When subjected to deformation such as bending, antennas may fail to function at the intended frequency, leading to performance deterioration. This is because these material properties alter the dimensions of the antenna, resulting in frequency detuning and decreased antenna functionality [9, 10]. When an antenna comes into contact with the human body, it can cause a change in the dielectric constant. The human body generally behaves like a material with losses, absorbing electromagnetic waves because of the characteristics of biological tissue. This interaction impacts various performance parameters. The level of energy absorption is evaluated through the Specific Absorption Rate (SAR) metric. According to FCC regulations, SAR should not surpass 1.65 W/kg per gram and 2W/kg per 10 grams for IEC standards [11–14]. The proposed design successfully meets these requirements.

This work introduces C-shaped radiating patches designed for WLAN applications. The dielectric material substrate for these antennas is fabricated from denim fabric. There is growing concern about frequency detuning in antenna performance caused by structural changes, especially in flexible devices such as textile antennas. To address this concern, this paper introduces a 2.45GHz textile antenna with CPW feeding as a solution

*Sipna College of Engineering, SIES Graduate School of Technology, Navi Mumbai, India.
E-mail: sonalj@sies.edu.in
Ph. D. Supervisor, Sipna College of Engineering, Amravati, Maharashtra.
E-mail: nnkasat@sipnaengg.ac.in

to mitigate frequency detuning problems. The antenna's efficacy is assessed while subjected to two bending scenarios: E-plane and H-plane configurations. Furthermore, the SAR, designed with safety in mind, satisfies all criteria to mitigate the potential The effects of radiation on the human body.

In accordance with the suggested design, the antenna is constructed and undergoes testing using a vector network analyzer. The subsequent sections provide a detailed overview of the manuscript's organization. Section 2 provides details on the initial structure's design, with dimensions.

Section 3 is about bending assessment performed to verify the behavior of an antenna. Section 4 extensively compares simulated and measured results for the proposed structures. The final section, Section 5, encapsulates the conclusion of the study.

## 2. Antenna and Ebg-Fss Design 1

### *2.1 Antenna Design*

The rectangular CPW-fed antenna's geometry is determined through the use of mathematical formulas given in equation (1) and equation (2)

$$Width = \frac{c}{2f_0\sqrt{\frac{\varepsilon_R + 1}{2}}}; \quad (1)$$

$$\varepsilon_{eff} = \frac{\varepsilon_R + 1}{2} + \frac{\varepsilon_R - 1}{2}\left[\frac{1}{\sqrt{1 + 12\frac{h}{w}}}\right]$$

$$Length = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} - 0.824h\left(\frac{(\varepsilon_{eff}+0.3)(\frac{w}{h}+0.264)}{(\varepsilon_{eff}-0.258)(\frac{w}{h}+0.8)}\right) \quad (2)$$

### *2.2 Square loop EBG-FSS Design*

The arrangement of an electromagnetic band gap frequency selective surface can be established for a particular frequency, using the formula provided in equation (3).

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (3)$$

Increasing capacitance and inductance values results in a lower frequency and a subsequent reduction in bandwidth. While raising inductance is possible, it requires using a thick substrate, making the system electrically large. A more efficient alternative is to utilize a Frequency Selective Surface (FSS) structure. This method employs an equivalent model based on a series LC circuit, allowing the determination of the desired frequency through equation (4).

$$f = \frac{1}{2\pi\sqrt{(L+L_S)C_S}} \quad (4)$$

Therefore, utilizing a frequency selective surface (FSS) is essential instead of employing a patch with capacitive surface characteristics.

In this approach, a square loop array with dimensions of 2x2 is generated and confirmed through simulations employing the High-Frequency Structure Simulator (HFSS), for simulation of EBG structure.

The formula denoted as equation (5) which depicts an LC series circuit, is employed for the computation of the capacitance ($C_s$) value.

$$C_s = \frac{W\,\varepsilon_0(1+\varepsilon_r)}{\pi} cosh^{-1}\left(\frac{W+g}{g}\right) \quad (5)$$

The equation (6) for inductance (Ls) is defined in terms of EBG unit-cell width, represented by $W_n$, where the inductance is influenced by the presence of looped metallic conductors.

$$L_S = \ell n \frac{\mu_0}{4\pi} l_n \left\{1 + \frac{32h^2}{w_n^2}\left[1 + \sqrt{1 + \left(\frac{\pi w_n^2}{8h^2}\right)}\right]\right\} \quad (6)$$

$$L = \mu_0 h \quad (7)$$

In equation (7), μ signifies the permeability, while h denotes the substrate's height.

A compact wearable textile antenna is proposed, incorporating a C-slot for size reduction. The antenna design involves a conducting patch with a specified width ($W_{patch}$) and length ($L_{patch}$) along with two gaps introduced into the substrate of a coplanar waveguide (CPW) antenna. The substrate is of length ($L_{sub}$) and width ($W_{sub}$) and, is supported by two rectangular patches ($L_{ground}$ and $W_{ground}$) located beside the radiating elements.

Denim material is chosen as the dielectric substrate, characterized by a dielectric constant of 1.6 and tanδ of 0.07. Textiles, particularly denim, are preferred for their wearability, washability, affordability, flexibility, and low maintenance requirements, making them widely used in this context.

The antenna fed with CPW and the EBG array of 2*2 are first independently designed and subsequently combined with foam of thickness 10 mm acting as a separator. The spacing between the components is carefully adjusted to optimize the integrated system's S11 performance.

Fig. 1 depicts the entire configuration in its configured state, while Fig. 2 illustrates the EBG structure

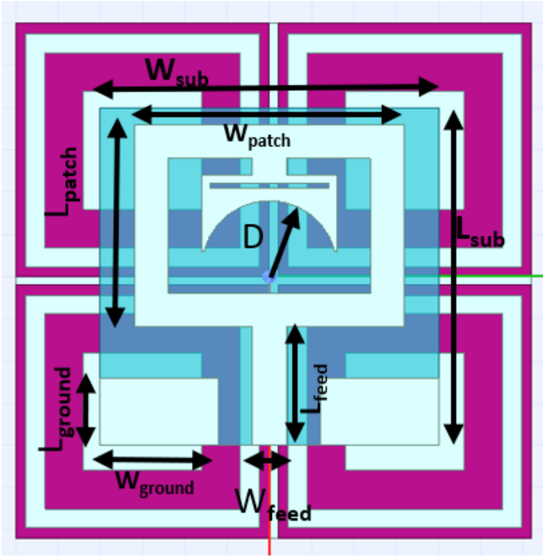



**Fig.1.** CPW-fed antenna design

$W_{sub}$=40mm $L_{sub}$=40mm $W_{patch}$=32mm $L_{patch}$=24mm Gap=1.5mm D=16.9mm $L_{ground}$=12mm $W_{ground}$=17mm $W_{feed}$=3mm $L_f$=14mm

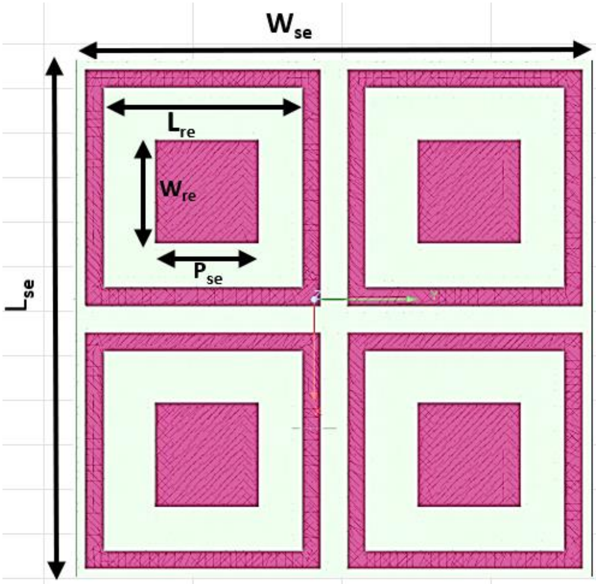



**Fig.2.** EBG Array Structure

Optimized dimensions of Unit EBG Cell:

$W_{se}$=61mm $L_{se}$=61mm $L_{re}$=23.1mm $P_{se}$=14mm $W_{re}$=14mm

*2.3 Modelling Patch Dimensions*

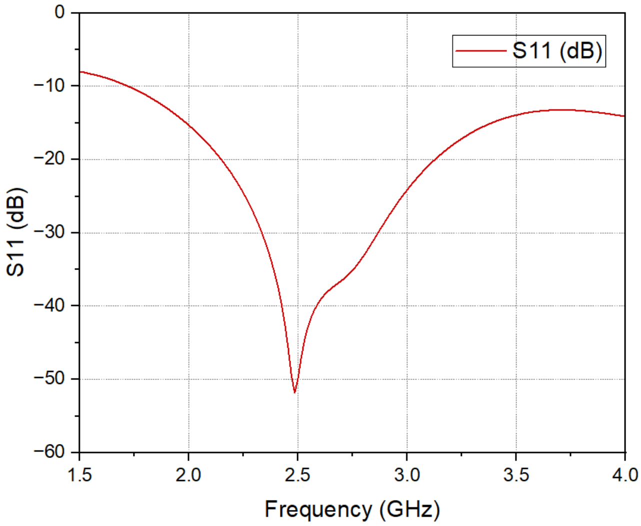
In the process of incorporating geometric tolerances into the design, a corner analysis is initially conducted to identify the primary design parameters in a particular antenna geometry. Incorporating stochastic processes into machine learning models enhances precision, enabling the creation of more precise and refined outcomes. and robust algorithms for antenna design, optimization, and signal processing in wearable applications. By leveraging machine learning techniques alongside stochastic modeling, engineers can create wearable antenna systems that are better able to adapt to real-world variability and provide reliable performance in diverse operating conditions. Specifically discussing the dual-polarized textile patch antenna operating at 2.45 GHz, the length (L) and width (W) dimensions, are treated as stochastic variables. The patch length (L) adheres to a Gaussian distribution mean of 45.39 mm and a std. deviation ($\sigma_L$) of 0.13 mm. The correlation between the length and width is found to be -0.009, indicating that these random variables are essentially uncorrelated.

After measuring the patch length (L), it has been found that a minimum of 75% of the textile antenna prototypes have a real component of their input impedance falling between 47.5 and 52.5, along with an imaginary component below 2.5. This ensures effective matching with a 50-ohm system.

## III. RETURN LOSS, BENDING AND SAR ANALYSIS

*3.1 S11 plot*

The observed outcome indicates return loss of -52dB at 2.45GHz, as depicted in Fig. 3a. Fig. 3b shows measured return loss of -33dB without EBG. The antenna's performance has been enhanced, with an increase in gain from 2.65 to 4 dBi at a frequency of 2.45 GHz. as shown in Fig. 4a and 4b.

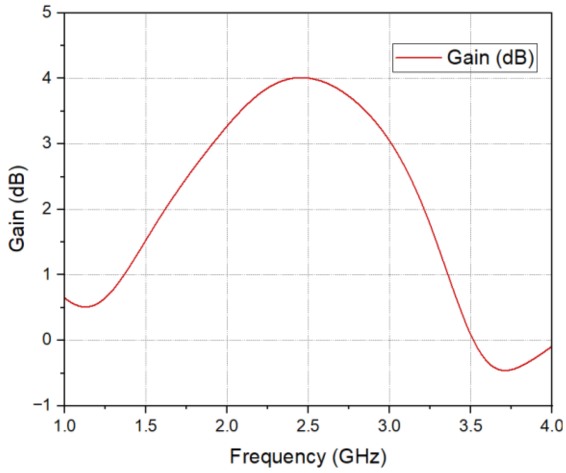



(a)

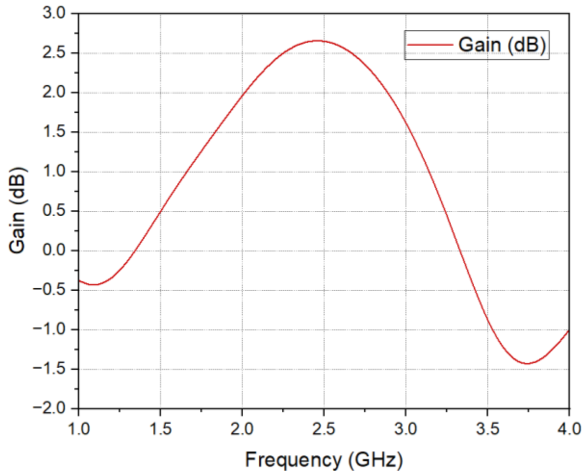
(b)

**Fig.3.** (a) Simulated Reflection Coefficient covers 2.45 GHz

(b) S11 without EBG on VNA




(a)




(b)

**Fig.4.** (a) Gain of antenna

(b) Gain of EBG based antenna

*3.2 Effect of Bending*

Figure 6 illustrates the influence of bending on the resonant frequency and return loss of antennas in both the E and H-plane. Bending leads to a small change in the frequency at which resonance occurs across all antennas, indicating a change in their effective length. Theoretically, bending reduces the effective antenna's length, which alters frequency at which it resonates, to shift to a higher band. Figure 7 demonstrates a significant shift in resonant frequency when bending occurs along the E-plane, primarily due to bending at the antenna's radiating element. Despite bending, all antennas maintain a return loss below -10 dB, indicating a typical increase in return loss magnitude during bending.

*3.3 SAR Analysis*

The calculation of SAR involves utilizing equation (8). In equation (8),

σ- tissue electrical conductivity,

E- electric field, and

P- the density of biological tissue.

$$SAR = \frac{\sigma E^2}{\rho} \tag{8}$$

Designed antenna is used on a human tissue model representing the back part of the body. The structure consists of a skin layer measuring 2 mm in thickness, followed by a layer of fat also 2 mm thick, then a muscle layer 23 mm thick, and finally an 8 mm thick layer of bone, with complete dielectric properties provided in table1. The dimensions of the biological tissue model were 85 mm × 85 mm × 35 mm as shown in Fig. 5.

A foam-based air-gap separation was introduced between antenna structure and the model simulating biological tissue. The objective was to find the ideal distance that would enable the antenna to sustain its wideband functionality, attain satisfactory gain, and reduce back radiation. The identified optimal separation distance was determined to be 10 mm.

**Table 1:** Parameters for human body phantom layers [4,15-17]

| Parameters | Layer | | | |
|---|---|---|---|---|
| | Bone | Muscle | Fat | Skin |
| Thickness (mm) | 8 | 23 | 2 | 2 |
| Density (Kg/m$^3$) | 1007 | 1005 | 895 | 1000 |
| $\sigma$ (S/m) | 0.79 | 1.73 | 0.13 | 13.45 |
| $\varepsilon_r$ | 18.5 | 52.7 | 5.27 | 37.85 |

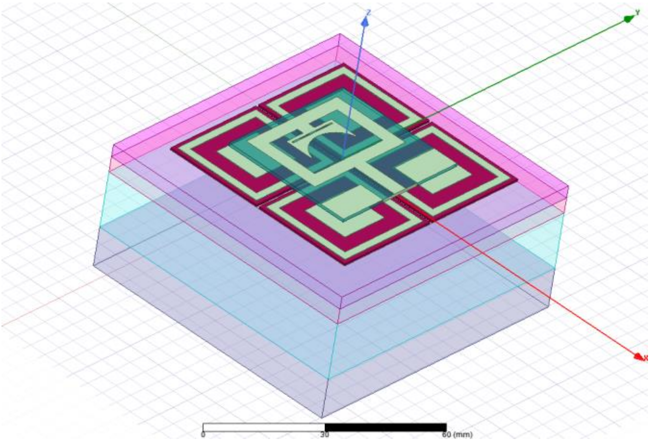
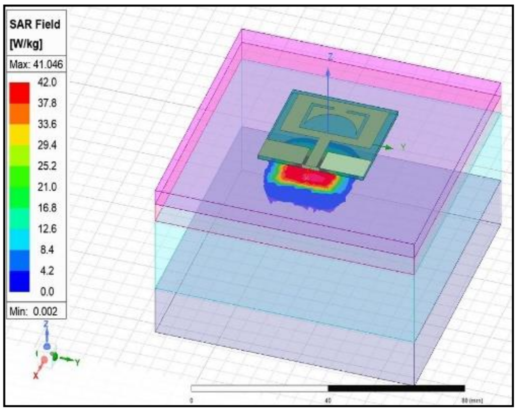


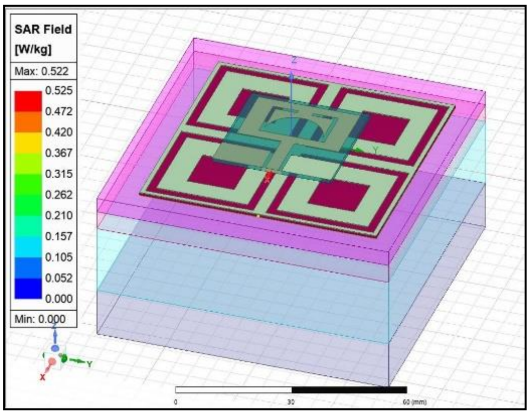
**Fig.5.** Electromagnetic Band Gap structure and a human body model.

To assess the effectiveness of the fabric antenna as an integrated system without causing any negative effects on the human body, simulations were carried out to determine the highest Specific Absorption Rate (SAR) under two conditions. The results are presented in Figures 6a and 6b for scenarios without EBG and with EBG structure, respectively. In Figure 6a, the maximum SAR reaches 41.046 W/kg, whereas in Figure 6b, the SAR value is 0.55 W/kg.

These findings meet safety standards, with the maximum SAR aligning with a maximum of 1.6 watts per kilogram averaged over one gram of tissue and the SAR for the EBG structure complying with the limit of 2 watts per kilogram averaged across 10 grams of tissue.




*(a)*




*(b)*

**Fig.6.** (a) SAR- antenna without EBG

(b) SAR- antenna with EBG

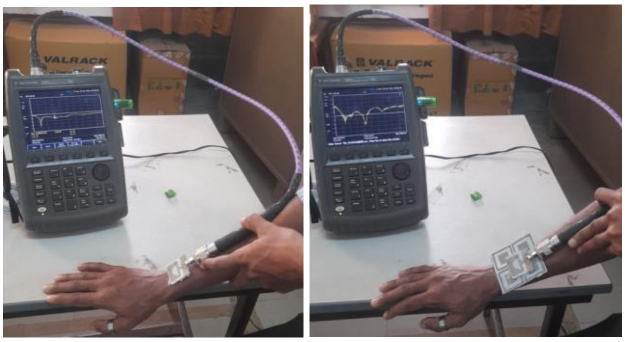


**Fig.7.** A fabricated integrated design positioned on the human arm.

The diagram in Figure 7 illustrates how the newly developed integrated system is positioned on to the arm of a male subject to assess the reflection coefficient. Fig.8 shows comparison of simulated results with the measured ones of the reflection coefficient. Despite of the effect of the biological tissues, there is consistent frequency resonance at 2.45 GHz, suggesting successful correlation and coverage across the 2.45 GHz ISM band.

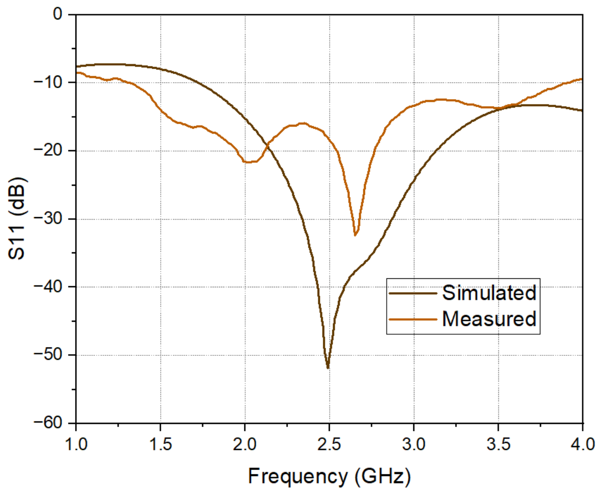



**Fig.8**. Simulated and measured reflection coefficient

## 3. Conclusion

A compact conformal coplanar waveguide (CPW) antenna is tailored for use in Wireless Body Area Network (WBAN) scenarios and functions within the specified operational parameters at 2.45 GHz, is discussed. This system utilizes textile materials that can seamlessly integrate with everyday clothing. The antenna and Frequency Selective Surface with Electromagnetic Band Gap were designed for this purpose. The antenna of size 32mm x 24mm is based on denim fabric with $\varepsilon_r$ of 1.6, and dimensions of 40 x 40 x 3 $mm^3$.

Using HFSS simulator, effect of bending on S11 in E and H plane is evaluated.It is observed that, bending reduces the effective antenna's length, which alters frequency at which it resonates, to shift it to a higher band. Further, SAR value is evaluated on a human body phantom. Without EBG, the SAR value was determined to be 41.04 Watts per Kg and gain 2.65 dB at 2.45 GHz frequency. After incorporating a 2x2 array of EBG-FSS with CPW-fed antenna, it significantly decreased to 0.522 W/Kg.

This configuration effectively reduces radiation in backward direction, and resulted in a gain of 4 dB. In future, research aimed at enhancing antenna effectiveness in practical applications, one potential area of focus involves examining different antenna locations. For instance, the antenna could undergo testing on various parts of the body, including the chest, shoulder, and neck (such as the shirt collar). Machine learning (ML) algorithms can be utilized to enhance the design of textile antennas by fine-tuning their parameters. ML algorithms are capable of navigating vast design possibilities to identify the most effective configuration meeting predefined performance standards like impedance matching, radiation pattern, and bandwidth. Machine learning offers support in choosing appropriate materials for both the substrate and conductive elements of antennas, relying on their electromagnetic characteristics. Through extensive analysis of large datasets encompassing material properties and antenna performance, machine learning algorithms can suggest the optimal materials tailored to specific applications.

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