ELECTROMAGNETIC BAND GAP-BASED CIRCULAR RING-SHAPED WEARABLE ANTENNA WITH IMPROVED GAIN FOR INTERNET OF THINGS APPLICATIONS IN 5-G SUB-6 GHZ

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ABSTRACT

This paper presents an integrated electromagnetic band gap (EBG) wearable antenna for the Internet of Things (IoT) applications. The proposed antenna is designed on Jean's substrate $(\in_r = 1.7, loss\ tangent\ (tan\ \delta) = 0.085)$. *The suggested antenna's final dimensions are 66.80 × 66.80 × 0.7* mm^3. *The proposed antenna frequencyresonate at 3.53 GHz and operates in the frequency range 3.505 to 3.558 GHz. EBG's primary function is to reduce back lobe radiation in order to increase the proposed antenna's gain in the operating frequency band . After using EBG, gain is increased from 2.9 to 8.7 dBi. The radiation efficiency is 88.43 %. The bending analysis for wearable antenna at different radius is presented. An excellent consent is found between the simulated and measured outcomes, confirming that it is appropriate for IoT applications in 5G Sub-6 GHz frequency band.*

Keywords – Internet of Things (IoT), Electromagnetic bandgap (EBG), 5G, Wearable

1. INTRODUCTION

Wireless communication technology has advanced significantly in recent decades, offering endless possibilities for the Internet of Things (IoT) and a high data rate. [1]. By using IoT gateways, these antennas are used for Wireless Body Area Networks (WBANs) applications, including tracking health issues, entertainment, sports, military uses, navigation, and more. Nowadays, wearable antennas are easily integrated into clothing and portable wearable devices since they are lightweight, flexible, durable, compact, portable, and low profile [2-4]. The wearable antenna was designed to be in close proximity to the human body [5-6]. The human body has its own dielectric properties that have a harsh impact on the conviction of the antenna [7]. Due to the lossy human body and its biological tissue property, a large amount of power of the antenna is absorbed and detuned to a lower frequency and may; therefore, the gain of the antenna is reduced, and the radiation pattern changes. However, the radiation from the antenna warned at human bodies could cause serious health problems. In addition, antennas must function well in various bending conditions, including those involving a moving body or body curvature, and—above all—must produce minimal backward radiation [8-10]. The suitability of a wide range of designs for use as wearable antennas has been investigated, including EBG-based antennas [11], microstrip patch antennas [12–13], E-shaped dipole antennas [14], CPW antennas [15–16], folding slot antennas [17–18], and monopole antennas [19–20]. Large size, narrow bandwidth, low gain, low efficiency, and high back radiation were some of the drawbacks of these systems.

Electromagnetic bandgap structures (EBG) are special structures used in antenna design that reduce back lobe radiation by eliminating detuning effects and increasing gain. To enhance the antenna's performance under these circumstances, antenna modeling employs this technique. Nevertheless, these configurations raise the antenna's layer count and complexity [21–22]. This paper uses the EBG surface to reduce path loss and enhance gain. This preserves good impedance matching despite improving gain and tolerance to the human body. The structure of this letter is as follows: In Section 2, the patch antenna's fundamental design principle is explained. Section 3 then covers antenna performance; Section 4 investigates antenna performance for wearable applications; and Section 5 concludes.

2. ANTENNA AND EBG DESIGNS

2.1 Antenna designs

The proposed circular ring-shaped wearable antenna's geometry is illustrated in Figure 1. The antenna is developed on a 0.7 mm thick jeans substrate with a loss tangent (tan δ) of 0.085 and a relative permittivity of ε_r = 1.7. The antenna element's dimensions are 38 x 26 x 0.7 mm3. The copper tape of 0.035 mm wide is used to make the conducting surfaces of the intended antenna. The suggested antenna made use of a material commonly found in jeans, which is easily obtained in day-to-day activities. The thickness of the copper utilized for the ground and radiator is 0.7 mm. The antenna feed measures 3 mm in width and 12 mm in length, and it is a 50 Ω microstrip feed. The proposed antenna has three layers: There is a 4 x 4 EBG array that acts as a reflector surface on the bottom, a flexible, thin foam layer with 1 mm thick positioned between EBG array, and wearable antenna, which is developed as a ring on top. The foam layer's function is to prevent contact between the edge of the antenna and the EBG surface. Firstly, the usual equation provided in [23] is used to calculate the radii R1 of the circular patch. The circular patch antenna's initial four modes include TM_{110}^{Z}, TM_{210}^{Z}, TM_{010}^{Z}, and TM_{310}^{Z}. The TM_{110}^{Z}, is the dominant mode, and its resonant frequency is determined by

$$(f_r) = \frac{1.8421\, v_0}{2\pi R_1 \sqrt{\varepsilon_r}} \qquad (1)$$

In free space, the speed of light is represented as v_0. Fringing is taken into consideration while calculating the circular patch's radius R1, and the resultant effective radius R1e is given by

$$R_{1e} = R_1\left\{1 + \frac{2h}{\pi R_1 \varepsilon_r}\left[l_n\left(\frac{\pi R_1}{2h}\right) + 1.7726\right]\right\}^{1/2} \qquad (2)$$

Equation (2) is then used to modify the resonance frequency for the dominant mode TM_{110}^{Z} which is thus given as

$$(f_r) = \frac{1.8421\, v_0}{2\pi R_{1e} \sqrt{\varepsilon_r}} \qquad (3)$$

At first, consider the resonant frequency $f_r = 3.5$ GHz and calculate the radius R1, which is 11.5 mm. In the design procedure, first design a circular patch with a radius R1 = 11.5 mm, L = 66.80 mm, W = 66.80 mm and Lf = 14 mm. Antenna 1 represents circular patch antenna. Antenna 2 is designed as a circular patch antenna with a particular modification. The patch is then cut into a ring with an 8.5 mm radius, and a section of the ground plane is used. This adaptation is known as Antenna 2. Additionally, Antenna 3 is the C-shaped stub that is put across the circular patch and the feed line. Finally, a 4 ×4 EBG array is backed to get the final design. Figure 2 shows the various stages of the designed antenna's evaluation. The overall dimension of the proposed antenna with an EBG-backed reflector is 66.80 x 66.80 x 0.7 mm3, which is proposed for IoT applications. The CST tool is used for simulation and implementation. All the optimization parameters are illustrated in figure 1.

2.2 EBG designs

The dimensions of the circular slot-shaped EBG structure, side view of the overall antenna, and boundary conditions are shown in Figure 3, and the fabricated design is illustrated in Figure 4. A 4 × 4 EBG array is used as a reflector surface, which uses same substrate as patch, and backed with a full copper ground. The patch and the EBG framework were separated by a 1 mm thick piece of foam. By cutting down on back radiation, the EBG structure helps the antenna achieve a higher realized gain. The floquet port is used to create and simulate the unit cell structure in the CST MS tool. This EBG unit cell has a bandwidth of 3.5 to 3.6 GHz, which is either side of the center frequency at 3.53 GHz within the range of $\pm 90^0$. So, it is clear that the proposed structure is capable of operating within the desired Sub-6 GHz band of IoT applications.

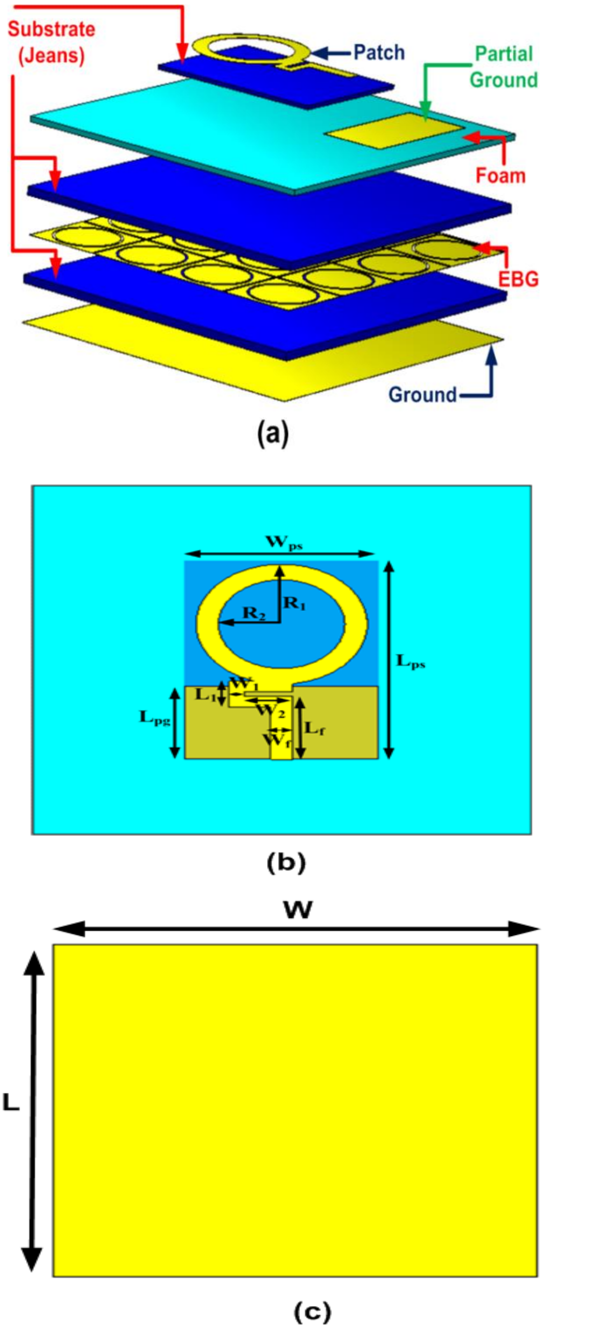

Figure 1 – Layout and structural parameter with (a) Layered diagram (b) Top, and (c) Back view (L = 66.80 mm), W = 66.80 mm), L_1 = 5 mm), W_1 = 2 mm), L_f = 12 mm), W_2= 6.5 mm), L_{pg} = 14 mm), W_f = 3 mm), L_{ps} =38 mm), W_{ps} = 26 mm), R_1 = 11.5 mm), R_2 = 8.5 mm), R_{ic} = 6.5 mm), R_{oc} = 7 mm), D_1 = 0.5 mm), D_2 = 0.5 mm), D_3 = 2.04 mm), W_{uc} = 16.08 mm), L_{uc} = 16.08 mm)

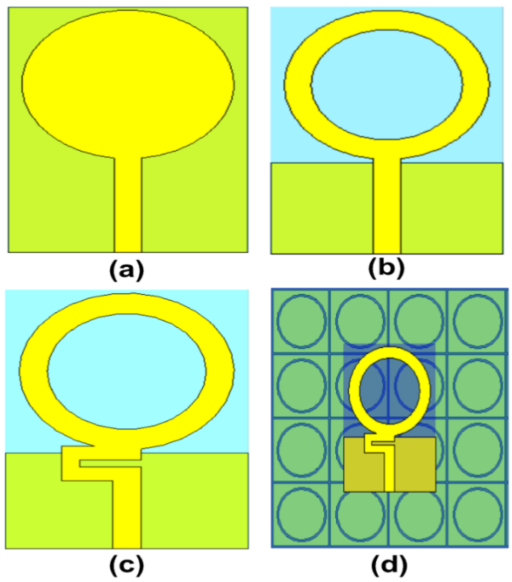

Figure 2 – Various evaluation steps of the proposed antenna

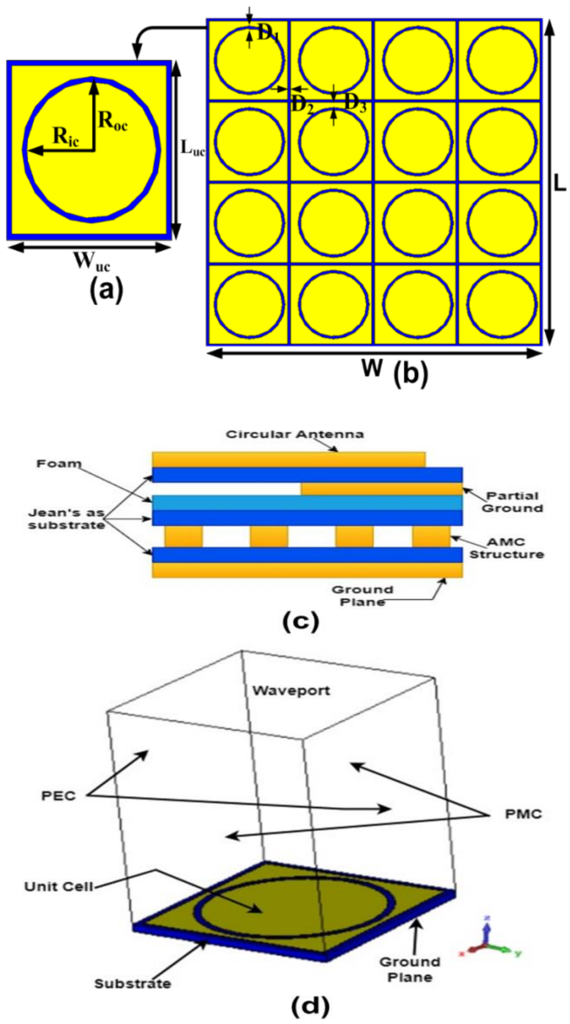

Figure – 3 circular slot-shaped EBG structure (a) Unit cell (b) A 4 × 4 EBG array (c) side view of the overall antenna (d) boundary conditions

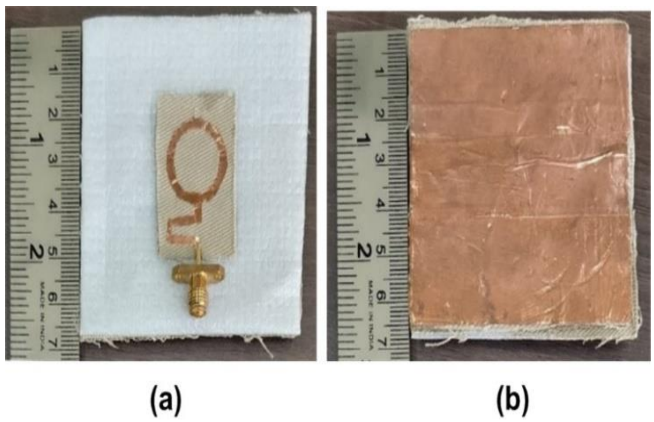

Figure 4 – Fabricated design (a) Top and (b) Bottom view

3. RESULTS AND DISCUSSION

3.1 Return Loss (S_{11})

To verify the predicted result, the proposed antenna is constructed as depicted in Figure 4. Figure 5 displays the reflection coefficients that were measured and simulated. The difference between the simulated and measured results occurs due to a mismatch in the soldering and in the fabrication of the proposed antenna.

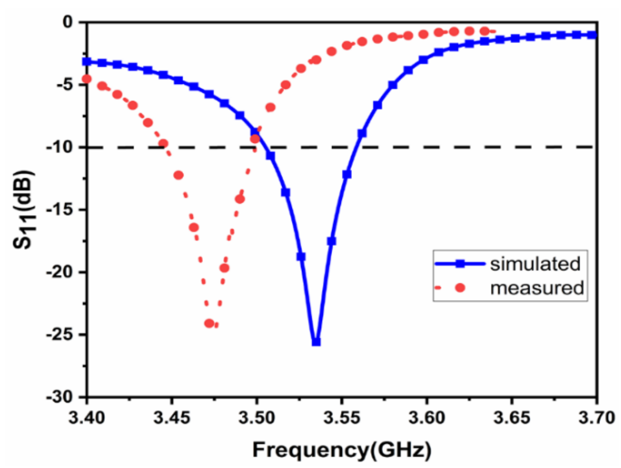

Figure 5 – Simulated and recorded S_{11} of the demonstrated antenna

3.2 Radiation Pattern

An anechoic chamber is used to measure the antenna pattern. Figure 6 exhibits the recorded and simulated Co and Cross-polarization at 3.53 GHz. The XZ and YZ Plane are used to show the co- and cross-polarization effects. If the cross-polarized value is 40 to 50 dB lower than the co-polarization, the antenna is radiating in the intended direction. Due to the biological tissues in the human body having lossy properties, several differences were found between free space and on-body measurements. Figure 6 illustrates a nearly broadside pattern at 3.53 GHz during co-polarization in both planes.

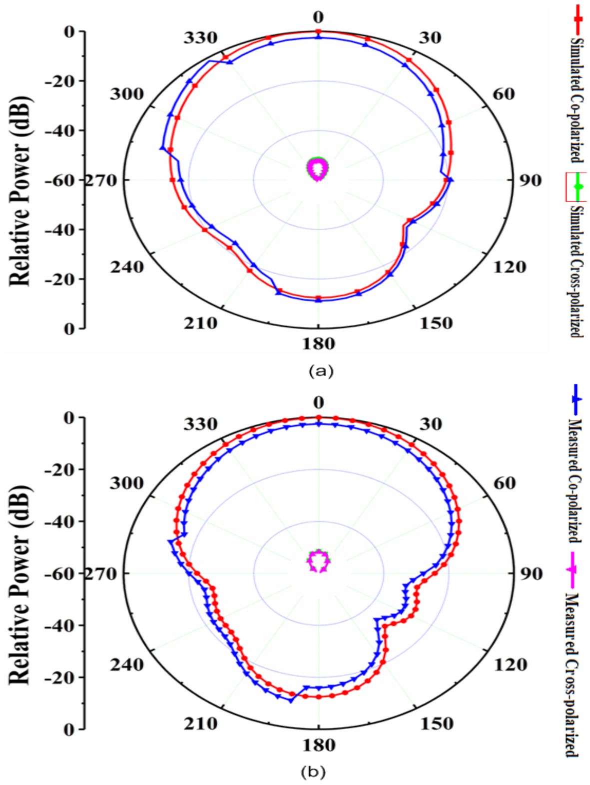

Figure 6 – Antenna pattern at 3.53 GHz (a) XZ plane (b) YZ plane with EBG

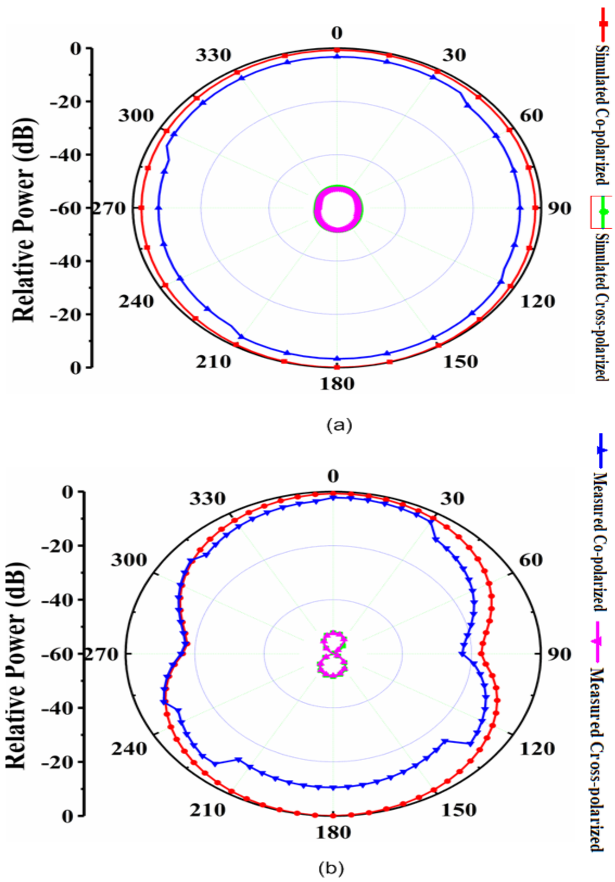

Figure 7 – Antenna pattern at 3.53 GHz (a) XZ plane (b) YZ plane without EBG

3.3 Gain and Efficiency

The proposed antenna's recorded and simulated gain with and without EBG are shown in Figure 8. The measured and simulated gain without EBG at the resonance frequency at 3.53 GHz is 2.7 dBi and 2.9 dBi, respectively. The EBG has enhanced the gain up to 8.7 dBi. The simulated radiation efficiency with EBG is enhanced up to 88.4 %, while radiation efficiency without EBG is 85% and the measured efficiency is 85 % at a resonance frequency of 3.53 GHz as shown in Figure 9.

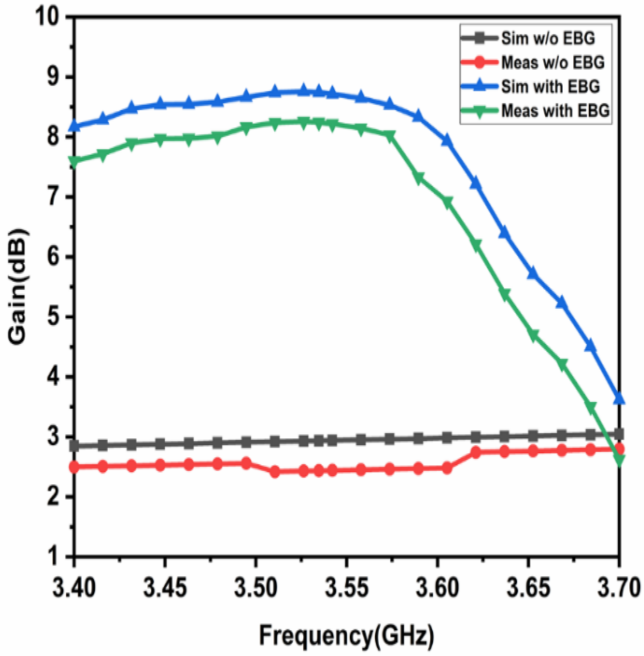

Figure 8 – Gain with and without EBG of Proposed antenna

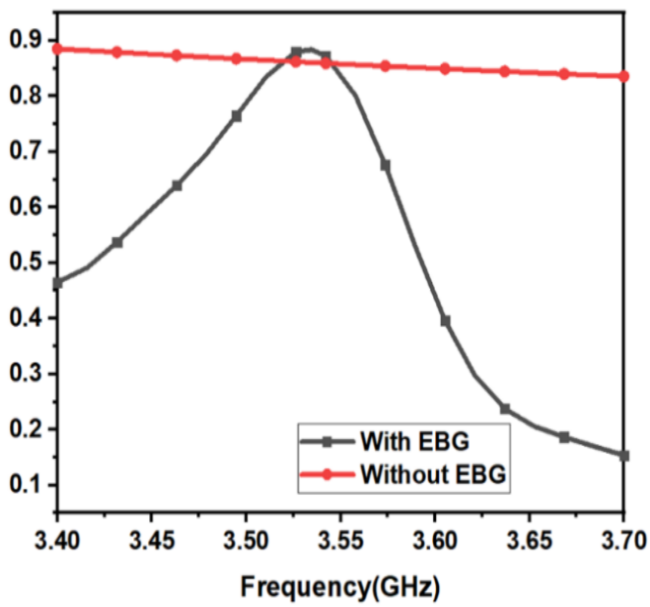

Figure 9 – Radiation efficiency with and without EBG of the proposed antenna

4. ANALYZING THE ANTENNA EFFECTIVENESS FOR WEARABLE DEVICES APPLICATIONS

4.1 Bending effect on the proposed antenna

Evaluating the integrated antenna with EBG under bending conditions comes before examining the human beings loading effect because when operating, the wearable antenna should conform to the surfaces of the human body. To evaluate the banding of the circular ring-shaped wearable antenna, it is bent over various cylindrical radius (R (mm)) at 30, 50, 70, and 90 in the y-axis, as illustrated in Figure 10. The results of simulated S_{11} demonstrated the strong stability of proposed antenna and its stable operation across the supported frequency ranges. Maintaining the same impedance range as the rest condition at the specified frequency bands, and no discernible detuning in the center frequencies was observed.

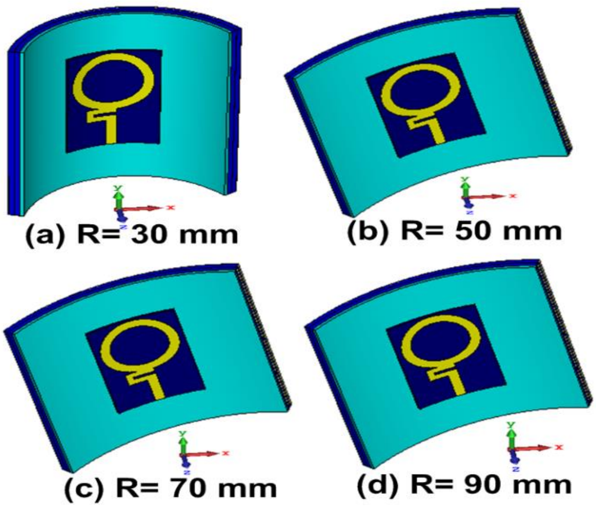

Figure 10 – The proposed antenna's bending in the Y-axis at different radius

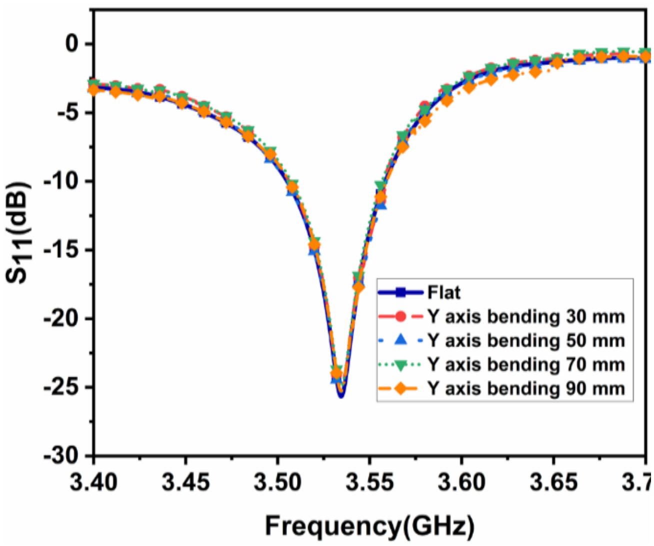

Figure 11 –Comparison of bent and flat antennas

4.2 The Effect of Antennas Interact on the Human Beings

Investigating how close the human body is to designed antennas is crucial for wearable applications. As a result, as illustrated in figure 12, the refelection coefficients of the fabricated antenna prototype with EBG was tested on various human body parts, including the hand, chest, and leg. When this fabricated antenna is placed on human hand, chest and leg, and compare to operating frequency 3.53 GHz in free space then we find that operating frequencies reduces and shifted to 3.34, 3.49 and 3.52 GHz respectively as shown in figure 13.

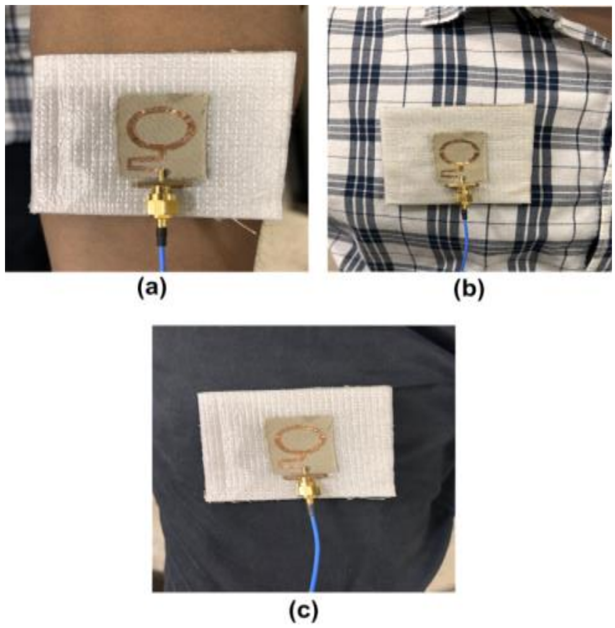

Figure 12 – Antenna measurement across various human body parts: (a) arm (b) chest (c) leg

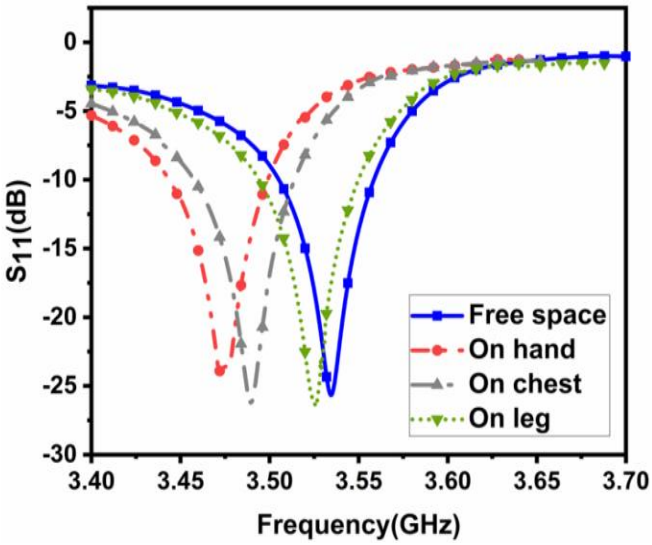

Figure 13 – Comparison of S11 in free space of proposed antenna with EBG with various parts of human body

4.3 SAR Analysis

In relation to wearable antennas or devices emitting electromagnetic radiation, it will turn out valuable to know that SAR helps in ascertaining the amount of energy absorbed that might have an effect on human tissue. Regulatory standards often limit the values such that exposure to these fields would not exceed levels known or believed to cause adverse health effects. The basic equation for calculating SAR value is given by the following equation (19).

$$\mathrm{SAR} = \frac{\sigma|E|^2}{\rho}$$

Where σ = Conductivity in S/m, E = Electric field intensity in V/m and ρ = mass density in kg/m^3. The human body three layer tissue models which is consists of skin (Relative permittivity = 36.97, Conductivity = 2.04 S/m, and Density = 1001 kg/m^3), fat (Relative permittivity = 5.17, Conductivity = 0.15 S/m, and Density = 900 kg/m^3) and muscle (Relative permittivity = 51.40, Conductivity = 2.58 S/m, and Density = 1006 kg/m^3) are used to calculate the SAR performance as depicted in figure 14. During simulation the gap is provided between the body model and the prototype is 1 mm and the thickness of Skin, Fat, and Muscle are taken 2, 5 and 20 respectively. IEEE/IEC 62704-1 for 1 g of tissue at 3.53 GHz is used to calculate the SAR. The antenna's measured SAR value of 0.933 W/kg is considerably lower than the FCC limit of 1.6 W/kg as depicted in figure 15.

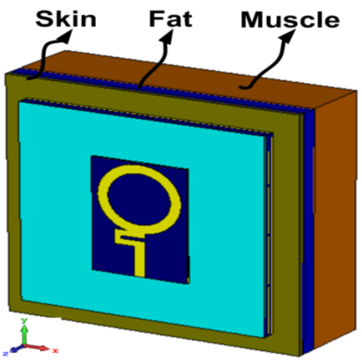

Figure 14 – 3 D fantum model of proposed antenna

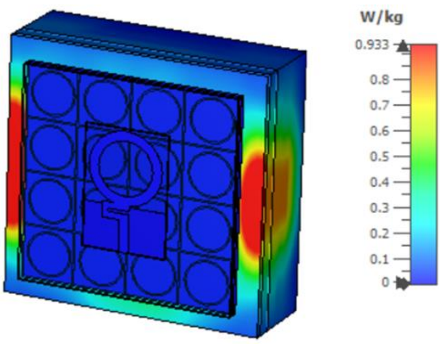

Figure 15 – Specific Absorption rate at 3.53 GHz

Table 1 – Comparision of the proposed antenna with existing literature

Ref. No.	Dim. (mm^3)	Sub. Mat.	Res. Fre. (GHz)	Peak Gain	Rad. Effi. (%)	SAR (W/kg)
[11]	150 × 150 × 1	Jeans	1.8, 2.45	-	-	0.024, 0.016
[13]	120 × 120 × 1.1	felt	2.45 5.8	6.4 7.6	-	0.48
[17]	89 × 83 × 1.52	Rogers RO3003	2.45 3.3	6.4 3	-	0.29
[19]	78 × 74 × 3.6	Epoxy FR4	2.45	7	80	0.44
[24]	100 × 100 × 3	felt	2.45	2.42	40	0.072
[25]	81 × 81 × 4	wool felt	2.45	7.3	70	0.554
Proposed Antenna	**66.80 × 66.80 × 0.7**	**Jeans**	**3.53**	**8.7**	**88.4**	

5. CONCLUSION

A wearable circular ring-shaped antenna with a 4 × 4 EBG array based on Jean's substrate has been developed and examined for IoT applications in 5 G sub 6 GHz frequency band. The proposed antenna operates at a 3.53 GHz resonant frequency. The gain of the proposed antenna is 8.7 dBi. Bending tests have been carried out using the prototype, and consistent outcomes were recorded. The proposed antenna performs satisfactorily results of radiation pattern, gain, bandwidth, and reflection coefficient. Hence, It is suitable for wearable applications.

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