

Miniaturized Wearable Fractal Antenna for Military Applications at VHF Band

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Abstract—This paper presents the design and development of Koch fractal dipole antenna for wearable applications at 450 MHz. Common jeans cotton is used as a flexible substrate material having a dielectric constant of 1.6 for the design and fabrication of the proposed antenna. Increasing the number of iterations increases the number of sections, which eventually results in 32% reduction in size. Size miniaturization is obtained using second iteration Koch geometry with the antenna bandwidth of 10%, and the return loss of -25 dB is achieved under the flat condition. The investigations are to characterize the antenna not only in flat condition, but also under different bendings and crumpling conditions. The proposed Koch fractal antenna is close to the proximity of the body, and the absorption of electromagnetic power on human body is also examined. It is found that the Specific Absorption rate (SAR) is much below a safety level of 0.119 W/kg and hence suitable for wearable applications.

1. INTRODUCTION

Wearable antenna bonds cloth into the communication system, making electronic devices less obtrusive. Recently, wearable antennas find profound applications: assistance to emergency services such as police, paramedics and fire fighters, military applications including soldier location tracking. In addition, it is used for image and video transmission for instant decentralized communications, access/identification systems by identifying individual peripheral devices, navigation support in the car or while walking, pulse rate monitoring, RFID applications, in sports, etc.

In supporting the increasing interest in antennas and propagation research for body communication systems, the IEEE 802.15 standardization group has been established to standardize applications intended for on-body, off-body or in-body communication [1]. Body worn systems with new generation of clothing endowed with sensing, processing, actuation, communication, energy harvesting and storage abilities are emerging as a solution to the challenges of ubiquitous monitoring of people in applications such as health care, lifestyle, protection and safety [2, 3]. Wearable antennas designed for military applications should meet the following requirements: thin, lightweight, low maintenance, robust, conformal, easy integration into clothing and should not affect the movement of the soldier [4–7].

Wearable antennas are realized using flexible substrate materials, and they are made up of textile and electro textile materials. Textile materials must be inexpensive, comfortable, lossless and easily available in the market. In four decades, many researchers have developed flexible wearable antennas using different textile materials such as flannel fabric, felt fabric, cotton. Gupta et al. reported electrical properties of different substrate materials such as jeans cotton, poly cotton, Shield It fabric and jean fabric, in the frequency range of 0.3 – 3 GHz [8].

The major challenge in the design of wearable antenna is the size reduction, especially one resonates at single or multiband frequencies [9]. Self-similarity of the fractal geometry can be used for size

Received 1 July 2015, Accepted 24 February 2016, Scheduled 15 March 2016

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reduction with multiband characteristics [10]. Von Koch introduced the Koch geometry in 1904, and it can be designed using an iterative function system by a set of affine transformation. Fractal shaped dipole antennas with Koch curves are generally fed at the centre of the geometry [11]. By increasing the fractal iteration, the length of the curve increases, reducing the resonant frequency of the antenna [12]. These geometries have a large number of tips and corners, a fact that helps to improve antenna efficiency. Several other self-similar geometries, Sierpinski gaskets [13], Koch curves, Minkowski curves, Sierpinski carpets, are the fractal shapes widely used in antenna design to obtain multiband or broadband miniaturized antenna [9, 14, 15]. Dual band wearable antennas are reported in [16–20].

In this paper, we propose a fractal wearable antenna with reduced size using the self similarity property and the second iteration Koch technique. Unlike the other usual flat planar antennas, the flexible jeans substrate directly affects the antenna performance as the effective length of the antenna or effective area changes while the soldier is bent. The challenging scenario in designing wearable antennas is to overcome its performance deterioration, and it is necessary to evaluate antenna performance under bending and crumpling conditions [21–24]. This paper investigation mainly focuses on the return loss and bandwidth variations when the antenna is bent in two orthogonal axes in x - z plane and y - z plane. We have calculated the Specific Absorption rate (SAR) for this antenna which is a measure of electromagnetic energy absorbed by biological tissue mass when exposed to a radiating device (ex. Mobile Phone). The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has set a limit of 1.6 W/kg absorbed per 1 g of tissue and 2 W/kg per 10 g of tissue. Simulations were carried out in 3D full-wave Finite Integration technique simulator CST microwave studio 2014. This paper is divided in to six sections. Section 2 describes the properties of Koch fractal and its iterative generation procedure applied to the antenna geometry. The performance analysis of the antenna in terms of reflection coefficient and gain characteristics is explained in Section 3, and the general performance of the antenna under bending and crumpling is presented in Section 4 and followed by the SAR performance of the antenna in Section 5. Section 6 ends with a conclusion. The study carried out in this paper shows that the proposed antenna operating in the VHF range is used for temporary point-to-point audio links, simplex talk-back and communications as portable radio, Amateur (HAM) Radios, etc.

2. ANTENNA GEOMETRY

We have chosen jeans as the substrate material ($\epsilon_r = 1.67$) with loss tangent $\tan \delta = 0.02$ and 3 mm thickness of dimension $L_s \times W_s = 320 \times 20 \text{ mm}^2$, and we have selected the initial structure as a straight half-wave dipole antenna designed to resonate at 450 MHz. The length and width of the copper foil strip are $L_A \times W_A = 298 \times 3.75 \text{ mm}^2$. Fig. 1 shows the geometry of the dipole antenna which comprises two quarter wavelength antennas connected back to back. The feed gap between the dipole arms is optimized to 0.6 mm for better performance.

The Koch fractal is a deterministic fractal for the design of the antenna. To obtain Koch geometry, one starts with a straight line, called the initiator ($L_0 = L_A$) as shown in Fig. 2. The first iteration is constructed by partitioning the left arm of the dipole into three equal segments of length ($1/s$) and replace the middle segment by two sides of an equilateral triangle of same length ($1/s$) with indentation angle ($\theta = 60^\circ$) as shown in Fig. 3. The same technique is applied to the right arm of the dipole antenna. This first iterated version of geometry L_1 is called generator. The process is reused in the generation

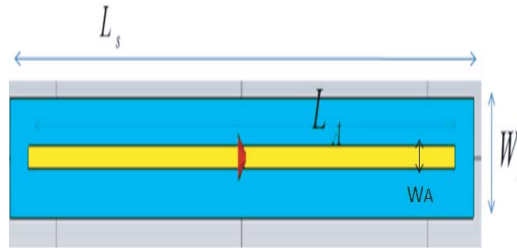


Figure 1. Initial design — straight half wave dipole antenna.

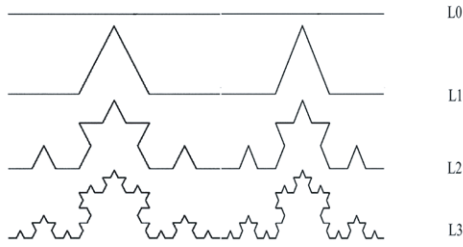


Figure 2. Iterations of Koch fractal [12, 14].

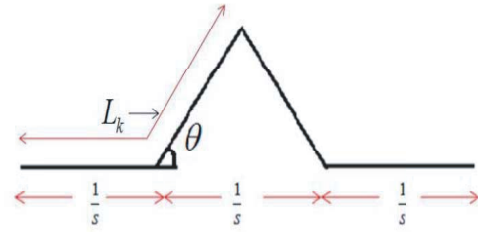


Figure 3. The four segments that form general basis of Koch fractal.

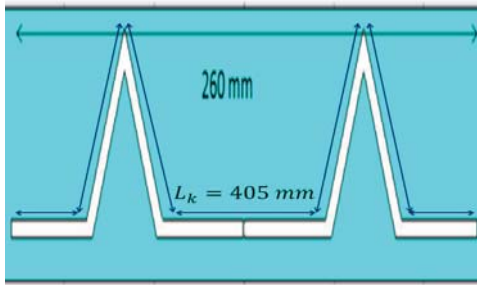


Figure 4. First iterated Koch fractal antenna.

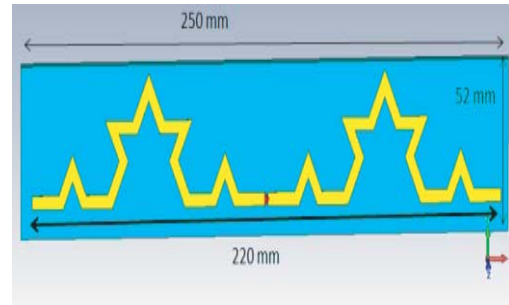


Figure 5. Second iterated Koch antenna.

of higher iterations L_2 and L_3 [8, 9]. For n th iterated curve, the unfolded length of the curve is $(4/3)^n$. The initiator size L_0 has been reduced by partitioning into six equal segments as shown in Fig. 3.

The length of the antenna can be reduced by Koch fractal iteration using Equations (1)–(3).

$$L_K = L_A \left(\frac{4}{3} \right)^n \quad (1)$$

L_k — total effective length of Koch fractal antenna, n — the number of iteration

$$D = \frac{\log(4)}{\log(s)} \quad (2)$$

$$s = 2(1 + \cos \theta) \quad (3)$$

where $n = 1$, D is the dimension = 1.26, s the scaling factor = 3 and θ the indentation angle = 60° . With every iteration, the total effective length L_k increases by $(4/3)^n$, and dimension of antenna reduces by around 1.26 times. The simulated geometry of the first iterated Koch fractal wearable antenna is shown in Fig. 4.

Further size reduction can be achieved by performing the 2nd iteration with $n = 2$ in Equation (2). The geometry of the antenna simulated in CST is shown in Fig. 5, with the jeans material dimension of $250 \times 52 \text{ mm}^2$. The lengths of the flat dipole, 1st iterated antenna and 2nd iterated antenna are compared in Table 1. It can be seen that the length of the first iterated Koch is reduced by 10.5% and second iterated antenna miniaturized by 32% compared to the conventional dipole antenna.

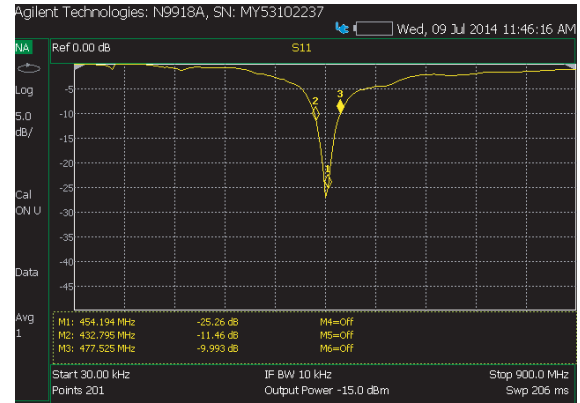
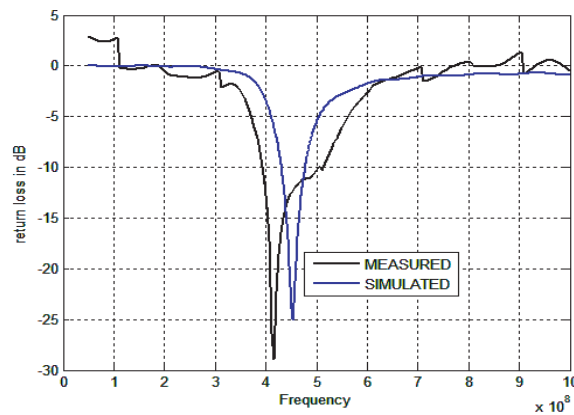
3. EXPERIMENTAL RESULTS AND DISCUSSIONS

The antenna is made using copper sheet and jeans fabric. The jeans cloth and copper sheet have been cut manually, and the fractal shaped copper sheet is pasted with fabric glue on the jeans fabric as shown in Fig. 6.

The return loss performance of the fractal antenna is analyzed using simulation and validated through vector network analyzer (VNA) measurement. The network analyzer measurement and

Table 1. Comparison between straight Dipole and Koch fractal dipole.

Antenna Dimension	Flat Dipole Antenna	Koch fractal dipole I iteration	Koch fractal II iteration dipole
Length (mm)	298	260	220
L_k Total effective length (mm)		405	530
frequency (MHz)	450	453	450
Return loss (dB)	-16	-40	-25
Bandwidth	9%	9%	10%
length reduction	-	10.5%	32%

**Figure 6.** Fabricated photograph of Koch fractal antenna on jeans cloth.**Figure 7.** Measured return loss measurement of wearable Koch fractal antenna using a network analyzer.**Figure 8.** Comparison between the measured and simulated return loss plot of Koch fractal antenna at 450 MHz.

comparison of the simulated and measured return loss characteristics are shown in Figs. 7 and 8, respectively. The comparison between the measurement and simulation results shows a good agreement. The measured antenna offers 25% bandwidth. Fig. 9 shows the surface current distribution plot, and the current is dominant near the feed and Koch edges.

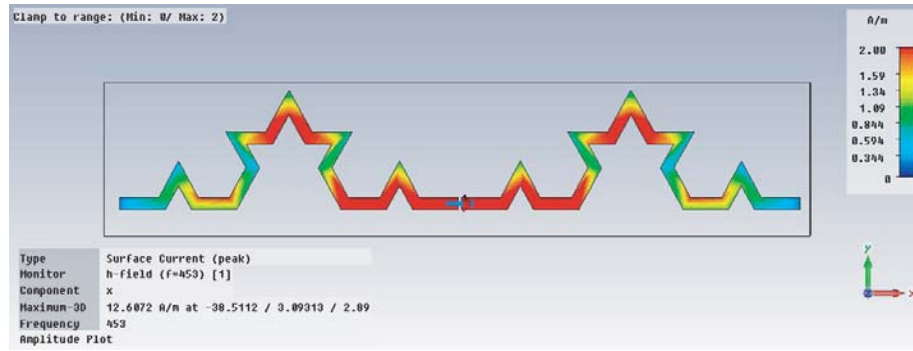


Figure 9. Surface current distribution of the antenna at 450 MHz.

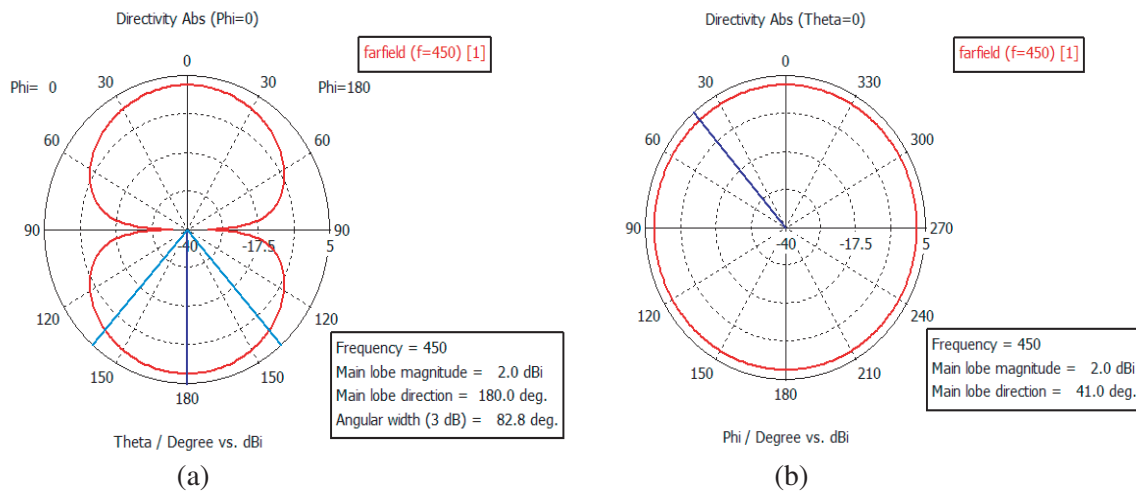


Figure 10. (a) Far field 2D pattern in x - y plane, (b) in y - z plane.

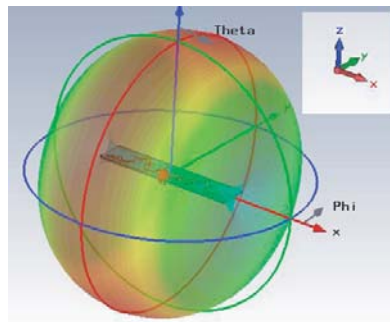


Figure 11. Far field three dimensional pattern.

The simulated surface current distribution at the resonant frequency of 450 MHz is shown in Fig. 9. It can be seen that the surface current distribution is maximum near the feed and minimum near the edges. Due to the symmetrical current distribution on either side of the Koch dipole, the maximum beam direction should be along the z axis which can be seen in Fig. 10. Based on the surface current distribution, the antenna should exhibit directional characteristics in the x - y plane and omnidirectional characteristics in the y - z plane as shown in Fig. 10(a) and Fig. 10(b), respectively. Fig. 11 illustrates the three-dimensional radiation characteristics of the antenna. Maximum gain of 2 dB is achieved using Koch dipole antenna.

4. ANTENNA PERFORMANCE UNDER BENDING AND CRUMPLING CONDITIONS

4.1. Bending Study

Antennas made on flexible textiles may change their shape and dimensions due to conformability with the surface of the body e.g., placed on curved part of the body such as arm or leg [22–24]. When an antenna is integrated into clothing, the performance of the wearable antenna is degraded due to bending. Therefore, it is essential to study the performance of the wearable antenna under bending condition. During the flat condition, the antenna reflection coefficient is -25 dB and bandwidth 10.33%.

Koch fractal antenna bending effect is performed by placing the antenna on a cylinder of different radii R such as 25 cm, 20 cm and 9 cm. These curvatures are chosen to approximate the full circumference of the human leg, arm and child arm. The antenna is bent along the H plane (x - z plane) for different radii as shown in Figs. 12(a)–(c).

The return loss characteristics of the antenna for different bending conditions is shown in Fig. 12(d). It can be observed that as the level of bending increases the performance of antenna deteriorates due to the change in electrical length. It can also be noticed that for radius less than 9 cm, reflection coefficient increases to -10 dB, and there is no significant change in bandwidth. So, the antenna should not be bent less than 9 cm. It can be noticed from Fig. 12(d) and Table 2 that the reflection coefficient and bandwidth slightly decreases from 0.5% to 1% compared to the flat condition.

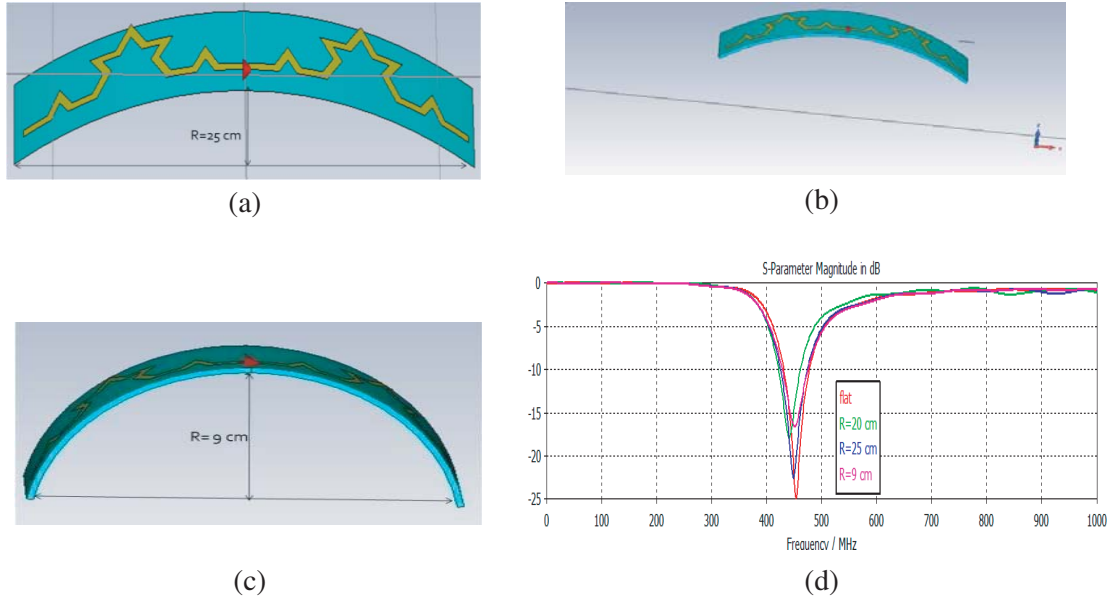


Figure 12. (a) Koch fractal antenna bend along x direction with radius 25 cm. (b) Koch fractal antenna bend 20 cm along x - y plane. (c) Koch fractal antenna bend along x - y plane with radius 9 cm. (d) Reflection coefficient characteristics comparison of different radii.

Table 2. Comparison between the flat case and the bending effect of different radii in x - y plane.

Bending radius (cm)	Frequency (MHz)	Return loss (dB)	% Bandwidth
Flat	453	-25	10.33
25	441	-17.85	8.9
20	427	-17.6	7.49
9	445	-15.75	9.8

In a similar manner, antenna bending study is also performed in E plane (y - z plane) as shown in Figs. 13(a) and (b). The antenna is placed on a cylinder of different radii 3 and 4 cm. It is observed from Fig. 13(c) and Table 3 that the resonant frequency shifts to lower range due to the change in electrical length, and the bandwidth is maintained in the same range with a slight deviation of 0.5%. It is observed that the bending along y - z plane has less impact on the antenna performance in realistic situations.

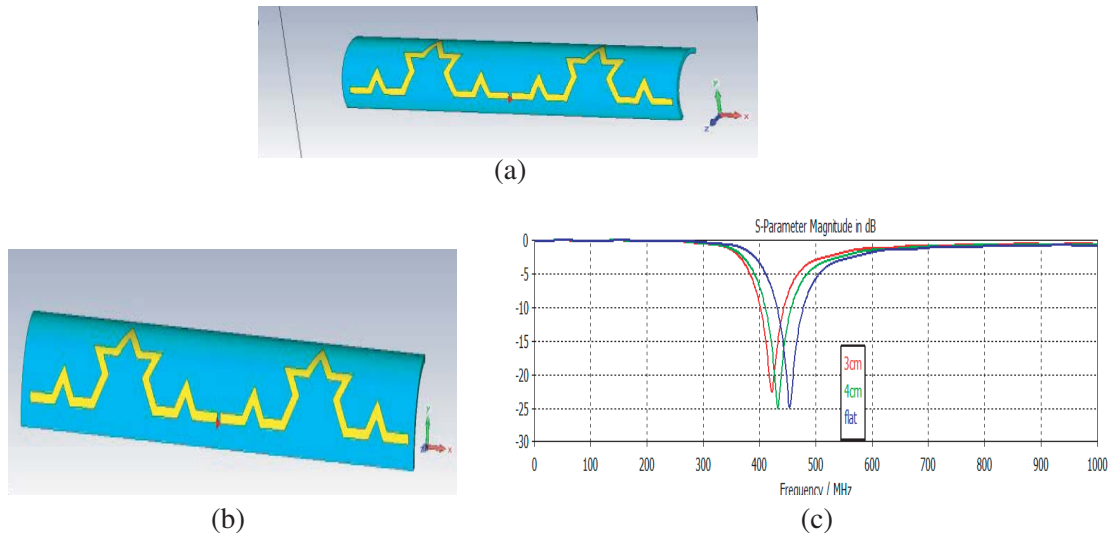


Figure 13. (a) Koch fractal antenna bend along y - z plane with radius 4 cm. (b) Koch fractal antenna bend along y - z plane with radius 3 cm. (c) Return loss characteristics of the antenna for different radii along y - z plane.

Table 3. Bending effect of different radius in y - z direction.

Bending radius (cm)	Frequency (MHz)	Return loss (dB)	% Bandwidth
Flat	453	-25	10.33
3	433	-25	10.33
4	422	-22.5	9.8

4.2. Crumpling Study

In practical situation for a wearable antenna integrated into clothing on human body, the antenna may be located in variety of places such as arm, pants near hips or elbow, and leg. As the person takes up various positions, wearable material will be not only bent, but also crumpled. Crumpling is another deformation, and this is taken along the x - z plane since the previous study shows that the bending along x - z plane gives great influence on the antenna parameters. The depth of the crumpling substrate is taken as 10 mm, 20 mm, and the peak distance between the two troughs is taken as 40 mm, 70 mm in this study. Crumpling deformations which affect the antenna performance are shown in Figs. 14(a) and (b). The number of turns = 3 shows a high degree of deformation as in Fig. 14(a), and the turns = 2 show less crumpling deformation as shown in Fig. 14(b). Here we have considered four different cases of crumpling, and the simulated crumpled structures are shown in Figs. 15(a)–(c). Case 1 turns = 3, depth = 20 mm. Case 2 turns = 3, depth = 10 mm. Case 3 turns = 2, depth = 20 mm. Case 4 turns = 2, depth = 10 mm.

Figure 15(d) shows the reflection coefficient characteristics crumpled along x direction with 3 turns and 2 turns. Table 4 shows the comparison of different cases of the crumpling effect. When the depth

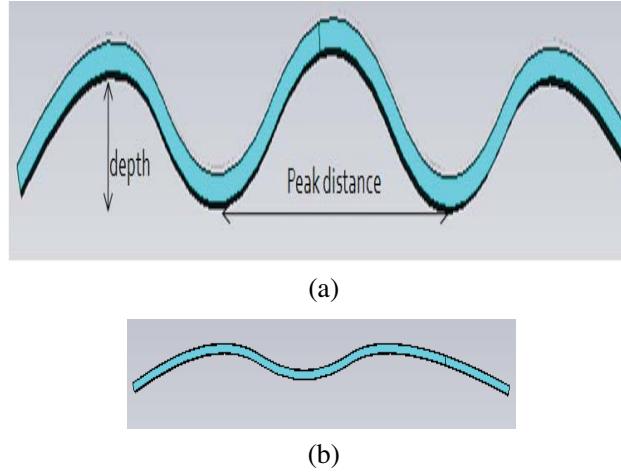


Figure 14. (a) Koch fractal antenna crumpled along x direction with 3 turns. (b) Koch fractal antenna crumpled along x direction with 2 turns.

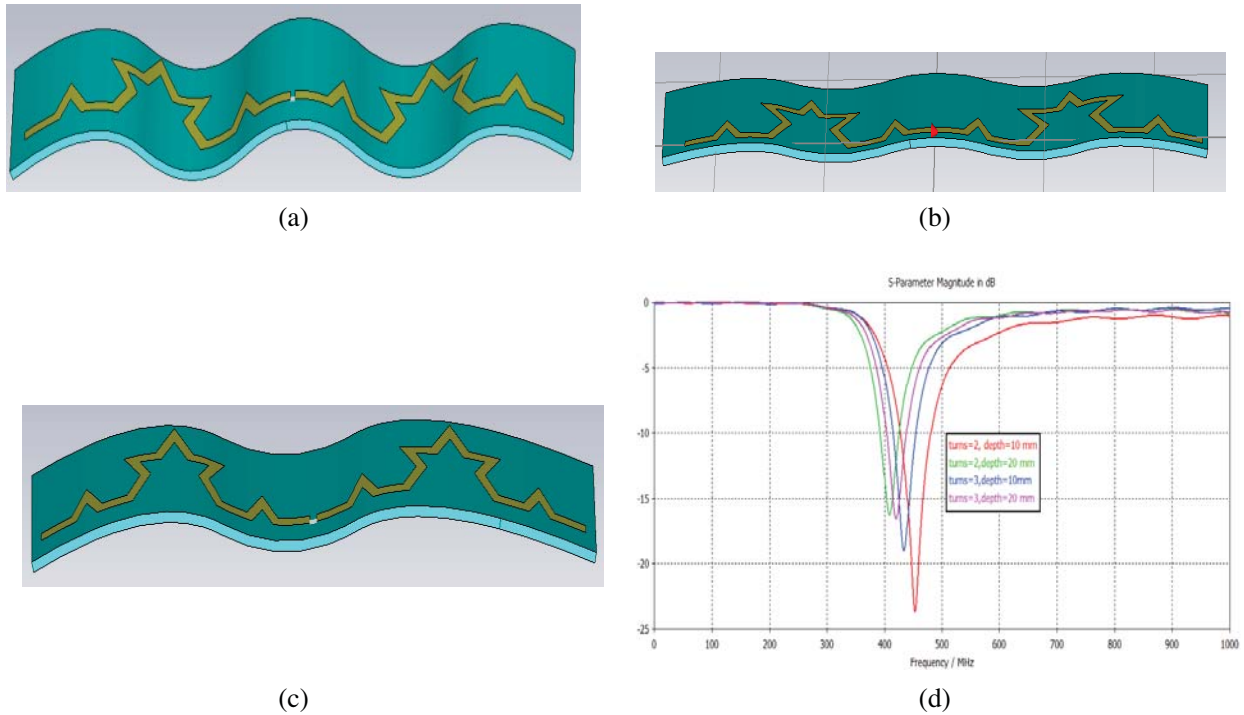


Figure 15. (a) Crumpling Case 1 Turns = 3, peak distance 40 mm and depth 20 mm. (b) Case 2 Turns = 3 peak distance 40 mm and depth 10 mm. (c) Case 3 Turns = 2, peak distance 70 mm, depth = 20 mm. (d) Reflection coefficient characteristics crumpled along x direction with 3 turns and 2 turns.

is maximum at 20 mm (more crumpling of the antenna) for case 1 and case 3, the return loss increases, and frequency and bandwidth decreases. In case 2, the depth is 10 mm less than case 1, and frequency is shifted towards a higher value and maintains the same return loss and the bandwidth approximately the same as the flat case. Case 3 reveals that when the crumpling turns are less, the resonant frequency is shifted downwards and the bandwidth reduced with a 2.5% change. In case 4, the number of turns is less, and the depth is 10 mm. The antenna resembles the flat case which shows a less impact on the antenna parameters. The return loss and bandwidth are the same as the flat case.

Table 4. Comparison between crumpling effect of different cases.

Crumpling	Frequency (MHz)	Return loss (dB)	% Bandwidth
Flat	453	−25	10.24
Case 1	420	−16.56	8.26
Case 2	434	−19.34	9.11
Case 3	408	−16.257	8.07
Case 4	453	−23.69	11

4.3. Study of Specific Absorption Rate (SAR)

A wearable antenna is specifically designed to be operated near the human body, and the Specific absorption rate (SAR) is utilized in order to address the health risks imposed by wearable communication devices to the human body. SAR is a crucial parameter to measure the amount of electromagnetic field absorbed by human tissues. The electric field intensity level, E , in volts per meter represents a directly measurable exposure parameter corresponding to a basic restriction. SAR is expressed using Equations (4)–(5) [24].

$$\text{SAR} = \frac{P}{\rho} = \frac{\sigma E^2}{2\rho} = \frac{J^2}{2\rho\sigma} \quad (4)$$

$$\text{SAR} = \sigma \frac{|E|^2}{\rho} \quad (5)$$

where $|E|$ is the root means square (rms) value of induced electric field (V/m), σ the electrical conductivity of the tissue in Siemens per meter (S/m), and ρ the density of the tissue in kilogram per cubic meter (kg/m^3). The SAR unit is in Watts/kg. The SAR is studied using CST voxel model as shown in Fig. 16(a), and the substances used in the voxel model are given in Table 5 with their ε_r and conductivity σ . The antenna is kept at different distances from 1 mm to 20 mm from the body, and they are shown in Table 6. A reference power of 1 W is excited for simulation in this SAR study.

Table 5. Specification of substance present in voxel model.

Substance	ε_r	El. Conductivity S/m
Blood	59.37	2.043
Bones	11.780	0.2751
Muscle	59.372	1.437
Skin	38.871	1.184

Table 6. SAR at 450 MHz.

Distance in mm from voxel model	SAR W/kg
1	0.142656
3	0.118936
8	0.072725
15	0.048514
20	0.0363822

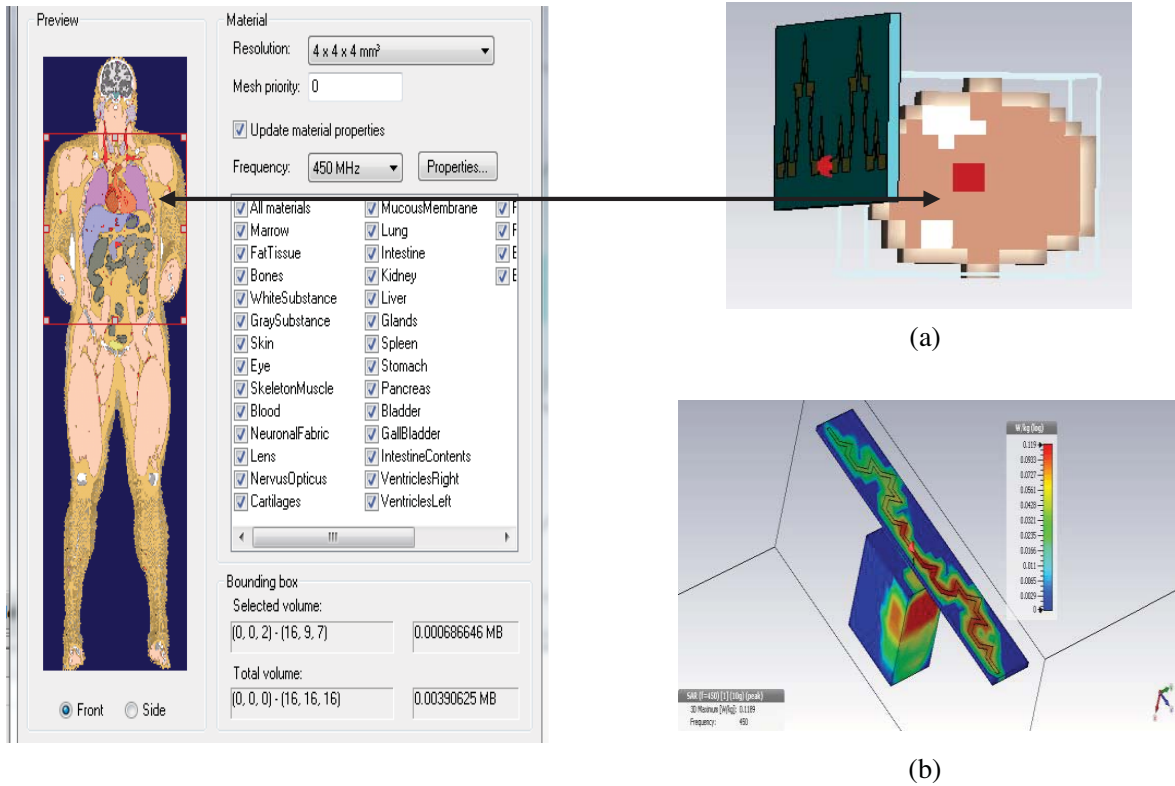


Figure 16. (a) Voxel biological tissue model. (b) SAR at 3 mm distance for 450 MHz.

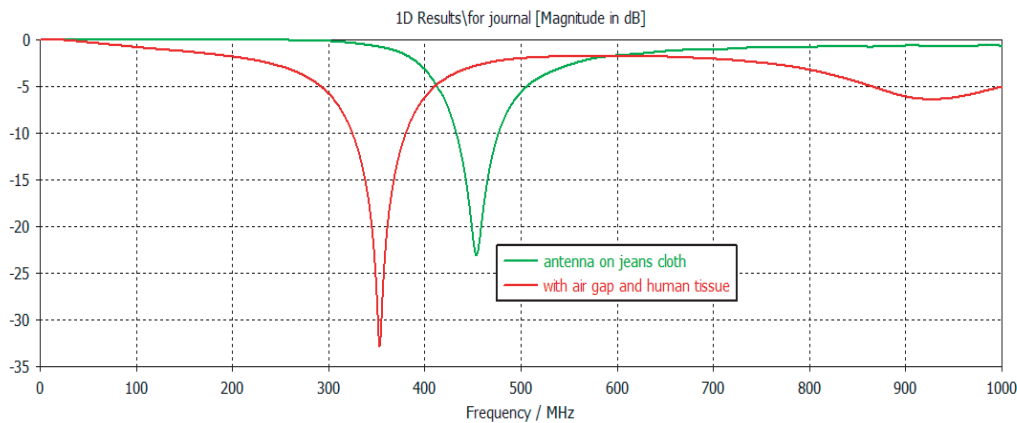


Figure 17. Reflection coefficient characteristics of the antenna on human tissue and the jeans cloth.

Figure 16(b) shows a simulated photograph of the SAR study of the antenna at 3 mm distance from the body. It is observed that SAR value decreases when the distance between wearable antenna and the body increases.

The effect of human body on antenna is studied by placing the antenna on a cylinder of radii 25 cm, 20 cm and 9 cm. These curvatures are chosen to approximate the full circumference of the human leg, arm and child arm. A three-layer cylindrical arm model consisting of skin, fat and muscle is chosen for the study [25, 26]. An air gap of 1 mm is introduced between the antenna and the layers to maintain the real scenario. The reflection coefficient characteristics comparison of the antenna on human tissue and the jeans cloth is shown in Fig. 17. A shift in resonant frequency is observed due to the impact of human body.

5. CONCLUSION

A flexible wearable Koch fractal dipole antenna is constructed using fractal geometry for 450 MHz band of operation with jeans material. The initial design is started by using a single element equation of dipole antenna with scaling factor of $1/3$. In this design, the highest iteration is Koch second iteration, and the overall simulated result is verified with the measured one under flat condition. The performance of the antenna under bending and crumpling condition is also investigated in two perpendicular planes, x - z plane and y - z plane. In all the cases, the reflection coefficient of the antenna is changed and a significant shift in resonant frequency designed at 450 MHz with deviations in bandwidth. The above study shows that the antenna can be operated at VHF band suitable for military application. The main contribution of this design is 32% reduction in size compared to the conventional antenna.

ACKNOWLEDGMENT

The authors would like to acknowledge the Defence Research and Development Organization (DRDO), Delhi, India for their valuable support of this project.

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