Fractal Geometry-Inspired Microstrip Patch Antenna Design for Vehicular Communication

Virendra Sehwag[1] Dr. Anirban Chatterjee[2]
[1]B.Tech. Student [2]Associate Professor
[1,2]Department of Electronics & Communication Engineering
[1,2]National Institute of Technology, Goa, India

Abstract — The paper introduces a new kind of fractal microstrip antenna for short-range communication in a specific frequency band (5.850–5.925 GHz) (IEEE 802.11p) used for vehicular communication. The proposed structure of antenna is obtained by etching and modifying a rectangular shape, cutting certain patterns in the corners, and carving out smaller shapes. To achieve the final design the resultant configuration is achieved through a sequential process. Initially, a 50% scaling transformation is applied to the original square shape, followed by the removal of rectangle from all corners. Finally, this modified structure is combined with its 45-degree rotated version, resulting in the ultimate configuration. A achieve good linearly polarization and desirable S11 characteristics, we carved four rectangular diagonal grooves and four interconnected elliptical thin cuts in a specific fractal pattern. The proposed antenna designed this using a single-layered Roger 5880 PCB material [εr=2.2] and simulated it using CST Microwave Studio 2019. The proposed antenna provides a return loss of -23.45 dB, VSWR (Voltage Standing Wave Ratio) of 1.14, Directivity of 7.45dB and a gain of 5.34 dB at the operating frequency 5.9 GHz.

Keywords: Fractal Antenna, Microstrip Patch, Vehicular Communication, IEEE 802.11p

I. Introduction

Intelligent Transport Systems (ITS) have experienced significant growth, leveraging advanced features to facilitate robust communication channels among vehicles (V2V), vehicle-to-roadway infrastructure (V2R), and vehicle-to-infrastructure (V2I). This connectivity operates within the Dedicated Short-Range Communication (DSRC) service band, specifically utilizing the resonating frequency of 5.90 GHz [1], [2]. Within this band, applications like electronic toll collection, vehicle-to-base station communication, blind-spot detection in adverse weather, and collision avoidance systems thrive [3].

Microstrip antennas have emerged as a pivotal component within DSRC service due to their compactness, lightweight design, cost-effectiveness in fabrication, simplified matching networks, seamless integration with microwave devices, and effortless mounting onto vehicle rooftops. Despite their advantages, conventional patch antennas face a significant limitation: a narrow operating bandwidth stemming from a high-quality factor. To address this constraint, numerous methodologies have been proposed. These encompass strategies such as augmenting the dielectric material thickness and reducing the substrate's dielectric constant, [4]. These modifications aim to mitigate the inherent narrow bandwidth issue, paving the way for enhanced performance and broader frequency coverage in patch antenna technology.

In a particular study referenced as [5], offered a method to help choose the right material for making microstrip patch antennas. Meanwhile, Douglas et al. [6] delved into the potential of using fractal antennas in systems that can adapt and change, examining how to create and analyze these intricate fractal designs. Additionally, Jiang and collaborators [7] highlighted the significance of DSRC technology as a crucial element for the future of safety communication services in vehicles.

In this study, the authors introduced a small-sized linearly polarized microstrip patch antenna tailored for DSRC band applications spanning from 5.850 to 5.925 GHz [8]. Their antenna design resonates precisely at 5.90 GHz and is achieved by etching Minkowski boxes at each corner of a rectangle and elliptical geometry [9]. Subsequently, a scaled-down rectangle box is removed from these corners, and the resulting structure is combined with its 45-degree rotated version. To ensure proper linear polarization and desirable S_{11} characteristics, four elliptical diagonal grooves and four cross-coupled rectangular thin slits are intricately carved into the fractal geometry [10]. Using CST Microwave studio 2019 simulations, the antenna's parameter of return loss, axial ratio, surface current, far-field pattern, gain, directivity, and radiation patterns were studied to determine its appropriateness for Vehicular applications [11],[12]. Furthermore, a sensitivity analysis was conducted to explore how well the antenna holds up against manufacturing differences and changes in the environment.

The designed antenna significant linearly polarization gain, measuring at 5.34 dB at 5.90 GHz, with a linear polarization bandwidth reaching 100 MHz and having directivity of 7.45 dB [13].

II. Methodology

A microstrip patch antenna like a sandwich made of three layers. The top and bottom layers are like the bread, but instead of bread, they are made of conducting materials (one on top called the patch, the other at the bottom called the ground). In between these layers is a filling called the substrate, which is an insulating material is crucial for the antenna's performance. For this antenna to work well at 5.90 GHz, copper is used for the conducting part and Roger duroid 5880 for the insulating substrate. The CST Microwave studio tools was used for designing and simulating the antenna, and the transmission line feed technique was used to excite the antenna externally.

The antenna's patch measures 6.42 mm × 9.12 mm, with the substrate being 0.767 mm thick. The ground and substrate together measure 16.02 mm × 18.72 mm. To simulate its behavior, a cuboidal radiation box of 28 mm × 28 mm × 14 mm was used. The goal was to achieve resonance at a frequency of 5.9 GHz. These are a step-by-step design methodology [14] of antenna design: -

1) Selection of frequency: The operating frequency should be selected for designing antenna in which we have to use. Here we are selecting frequency between in range of *5.850–5.925* GHz so taken 5.9 GHz as operating frequency.
2) Selection of ground and substrate: Chosen copper material as ground plane. Then reason behind the choose copper material is high conductivity (e.g., copper) to minimize losses and provide efficient radiation. Size of the ground plane is sufficiently large compared to the wavelength of the operating frequency for proper antenna performance. Select a substrate material with an appropriate dielectric constant that influences the antenna's size and performance so chosen is Roger RT duroid 5880 as substrate material with dielectric constant ε_r=2.2
3) Determination of length and width of patch: The length (*L*) and width (*W*) of a microstrip patch antenna operating at 5.90 GHz can be approximated using formulas. For instance, *L* is around half the wavelength in the substrate, while *W* considers the effective dielectric constant and resonant frequency. Using εeff calculations and resonance equations, *W* adjusts based on *L* to ensure proper impedance matching. Fine-tuning through simulations or practical testing might be needed for optimal performance.
4) Simulation using CST Software result analysis: Import the all-antenna geometry into CST Microwave studio and set up the simulation. After simulating the data then analyse the antenna simulation result parameter like Gain, VSWR, surface current, S11and far field.

III. Antenna Design

The Fractal shaped patch antenna, illustrated in Fig.1, operates at 5.9 GHz on Roger RT duroid 5880 substrates. Its dimensions, length, and width are determined through a design procedure detailed in [15]. The dimensions of ground are taken 40mm×40mm×0.017mm and substrate as 40mm×40mm×0.787mm. This procedure precisely calculates the antenna's measurements for optimal performance. The calculation of dimensions of a patch antenna with dielectric constant 2.2 on operating frequency 5.9 GHz. The design of the antenna is based on standard design equations as shown below.

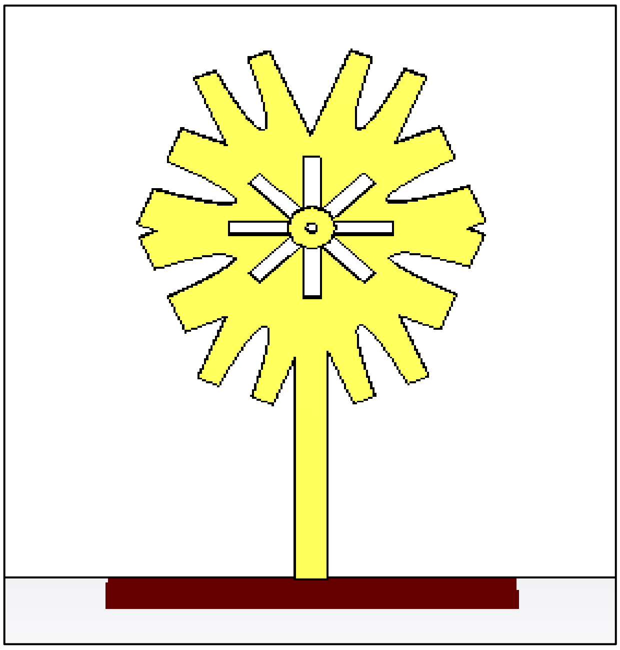


Fig. 1: Proposed fractal patch antenna for vehicular application at 5.90 GHz

The following formulas are used for the determination Width, Length, and bandwidth of the micro strip patch Antenna.

– Dielectric constant = 2.2.
– Frequency (f) = 5.9 GHz.
– Height (h_s) = 0.787 mm.

1) Calculation of Width of Patch (W_P):

The width of a patch antenna can be determined by various design methodologies, but a common formula for calculating the width W_P of a rectangular microstrip patch antenna is given by:

$$W_P = \frac{c}{2f\sqrt{\frac{(\epsilon+1)}{2}}} \quad (1)$$

$$W_P = \frac{3\times10^{8}}{2\times5.9\times10^{9}}\times\frac{1}{\sqrt{\frac{2.2+1}{2}}}$$

$$W_P = 20 \text{ mm}$$

Where ($\boldsymbol{f}$ = 5.9 GHz) is resonant frequency and (ε_r = 2.2) is the dielectric constant of the substrate material.

2) Calculation of effective dielectric constant (ε_{eff}):

The effective dielectric constant can be approximated by considering the actual dielectric constant of the substrate material and the patch dimensions.

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

$$\varepsilon_{eff} = \frac{2.2+1}{2}+\frac{2.2-1}{2}\left[\frac{1}{\sqrt{\left(1+12\frac{0.787}{0.017}\right)}}\right]$$

$$\varepsilon_{eff} = 1.62$$

where:
ε_r = Dielectric constant of the substrate material
h_s = Thickness of the substrate
W_P = Width of the patch

3) Extension length (Δl):

The extension length (Δl) in the context of antennas typically refers to an additional length added to a basic antenna structure to enhance its performance or tuning. This extension is usually determined empirically or through simulations to optimize antenna characteristics like impedance matching, radiation pattern, or bandwidth.

$$\Delta l = 0.412\frac{(\frac{W}{h}+0.264)(\varepsilon_{eff}+0.3)}{(\varepsilon_{eff}-0.258)(\frac{W}{h}+0.8)} \quad (3)$$

$$\Delta l = 0.412\frac{(\frac{20}{0.787}+0.264)(1.62+0.3)}{(1.62-0.258)(\frac{20}{0.787}+0.8)}$$

$$\Delta l = 11.2 \text{ mm}$$

Where:

Δl = Extension length

h = Thickness of the substrate

W = Width of the microstrip patch

ε_{eff} = Effective dielectric constant of the substrate material

4) Effective Length of patch (L_{eff}):

$$L_{eff} = \frac{c}{2\times f\sqrt{\varepsilon_{eff}}} \quad (4)$$

$$L_{eff} = \frac{3\times10^8}{2\times5.9\times10^9\sqrt{1.62}}$$

$$L_{eff} = 40 \text{ mm}$$

Where $c = 3\times10^8$

5) Length of patch (L_P):

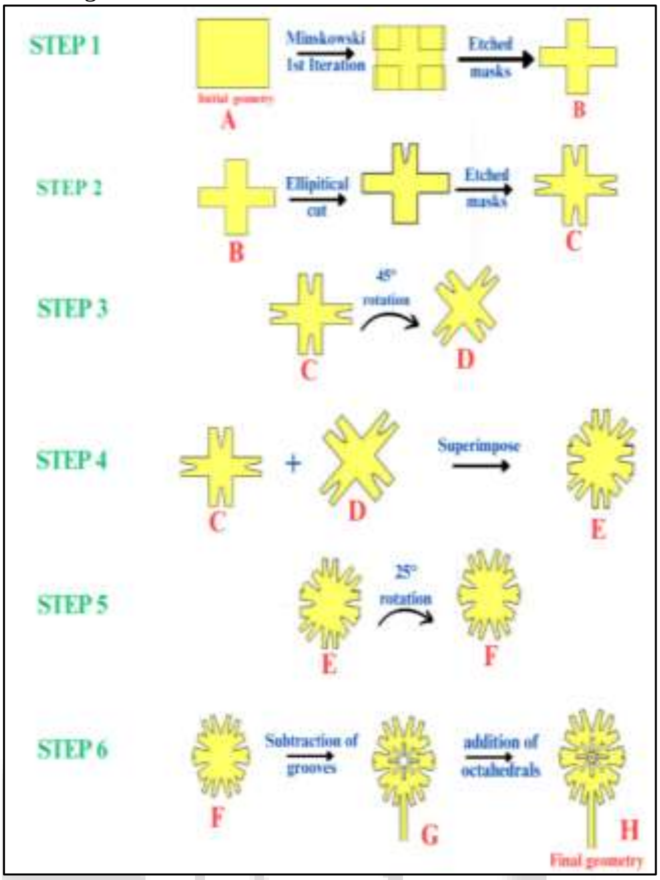
Length of patch is given as: -

$$L_P = L_{eff} - 2\Delta l \quad (5)$$

$$L_P = 16\text{mm}$$

A. Step-Wise Formation proposed antenna:

The picture in Fig.1 shows how the fractal structure is made step by step. Imagine it like a series of pictures showing each stage of building something complex from smaller, simpler pieces. he initial geometry of antenna is taken a rectangular shape of geometry of dimensions 20 mm×16 mm. In step 1, the rectangular. In step 1, the 4 rectangular shapes have cut at corners of initial geometry of rectangular shape with 8 mm ×6 mm each. The resultant geometry after cutting is shown in fig. B in next step, another cut of resultant geometry fig B with four elliptical shape geometry at middle of all sides of rectangle. The resultant geometry, as shown in figure C. Now, the next step is the resultant geometry C, as shown in Fig. 1d is rotated by 45 degrees in anti-clockwise directions the obtained geometry, which is shown in 1c. In the next step, the geometry C and resultant geometry of step 3 has superimposed to get resultant geometry of D as shown in figure. For obtained symmetrical geometry, which is rotated by 25 degrees in anti-clock directions to obtained geometry E as shown in figure. In the final step, the resultant geometry E is get etched with small 8 rectangular geometry with dimensions 8*0.8 are 22.5 degrees to each other at the center of symmetrical geometry E At the center of geometry, F a small shape of octahedral with size length 0.2 mm is added to geometry of F. So, the final proposed geometry G has shown in the figure.



B. Calculation of Fractal Length and Radiating Area of Patch:

Calculating the length of a fractal antenna involves understanding the iteration process and the pattern's geometry [16]. Fractal antennas are complex structures that exhibit self-similar patterns at different scales, making their length calculation challenging. The dimensions of the fractal length are determined by using CST Microwave studio 2019 dimensions calculator. Now conclude the all length of fractal geometry by CST.

So, length of patch (L_P) = 16 mm and width of patch (W_P) = 20 mm,

fractal length F_{LE} of elliptical shape the geometry B is 4 mm and width F_{EW}=0.5 mm is proposed in step 2 geometry C.

Fractal length F_{LT1} of triangular shape the geometry F is 5.17 mm and width F_{WT1} = 3.96 mm, length F_{LT2} of triangular shape the geometry F is 2.37 mm and width F_{WT2} = 2.37 mm, length F_{LT3} of triangular shape the geometry F is 1.04 mm and width F_{WT3}= 0.77 mm, length F_{LTE} of triangular plus elliptical shape the geometry F is 3.40 mm and width F_{WTE} = 1.73 mm.

The dimensions of the proposed antenna geometry in terms of length are shown in Fig.2 and the numerical values are tabulate in TABLE 1.

Symbol	Value (mm)	Symbol	Value (mm)	Symbol	Value (mm)
L_G	40	W_G	40	L_P	16
W_P	20	L_S	40	W_S	40

L_F	12	W_F	3	h_s	0.787
h_t	0.017	**ε eff**	1.62	Δl	40

Table 1: Dimensions of proposed antenna's parameters

The area of the initial rectangle geometry A as shown in Fig. 2 step 1, is computed as follows:

$$A_A = L_P \times W_P = 320 \text{ mm}^2$$

Now the resultant area of C, as shown in Fig.2 step 2, is computed as follows:

$$A_C = \frac{\pi \times a \times b}{2} = 12.56 \text{ mm}^2$$

As we see 4 ellipticals half of shape in geometry C and four same shapes composed in geometry H in Fig. 2 So total area of this geometry A_{FE} is,

$$A_{FE} = 8 \times A_C = 8 \times 12.56 = 100.48 \text{ mm}^2$$

Now, in geometry F has three different triangle cuts so the area of the triangular shapes is,

Calculating area of triangles with un-equal size by using Heron's formula,

$$A = \sqrt{s(s-a)(s-b)(s-c)}$$

Now, the total obtained area assumed to A_{FT} A_{FT1} = 9.456 mm^2, A_{FT2} = 3.38 mm^2 and A_{FT3} = 0.35 mm^2.So,

$$A_{FT} = A_{FT1} + A_{FT2} + A_{FT3} = 13.186 \text{ mm}^2$$

In geometry H, area of recto-elliptical shape cut in step 6 of final geometry is,

$$A_{RE} = 2 \times (\pi \times 3.40 \times 1.73 - 0.76 \times \frac{1}{2} \times 0.50)$$

$$A_{RE} = 36.55 \text{ mm}^2$$

Similarly, the area of the geometry F of eight number of Grooves, one small octahedral shape of side length O_{L2}=0.23 mm and adding one octahedral shape of side length O_{L1}= 0.43 mm from the center of F, as shown in Fig. 1e, is obtained as follows:

Area of eight rectangular grooves,

$$A_R = 8 \times L_R \times W_R = 8 \times 2.97 \times 0.80$$

$$A_R = 19.008 \text{ mm}^2$$

Now, effective area of regular concentric octahedral (side length a_1 = 0.43 mm, a_2= 0.23mm) which is located at Centre of proposed antenna is,

$$A_{CO} = 2 \times \sqrt{3}\,(a_1^2 - a_2^2) = 0.457 \text{ mm}^2$$

Similarly, the total fractal area (A_{FC}) of the final geometry H computed as,

$$A_{FC} = A_C + A_{FE} + A_{FT} + A_{RE} + A_R + A_{CO} = 182.241 \text{ mm}^2$$

$$A_{FC} = 182.241 \text{ mm}^2$$

The total radiated fractal area (A_{Red}) is,

$$A_{Red} = A_A - A_{FC} = 137.759 \text{ mm}^2$$

Hence, the computed total effective radiated area of the final geometry H i.e. proposed antenna, occupying an area of 137.759 square millimeters, is designed for emitting electromagnetic waves at a specific frequency and in a targeted direction.

IV. SIMULATION RESULT AND ANALYSIS

The analysis of a fractal linearly polarized microstrip patch antenna involved modeling and simulation using CST Microwave Studio 2019. The antenna, constructed on a Roger RT Duroid 5880 substrate with a dielectric constant of 2.2 and loss tangent 0.0009 with 0.787 mm thickness. The all-copper layer material 0.017 mm thickness. exhibited resonant frequencies at 5.9 GHz. In this analysis part will show important parameters of antenna used to evaluate the antenna's performance are Voltage Standing Wave Ratio (VSWR), Return loss(S_{11}), surface current, 3D Pattern, gain and directivity Parameter.

A. Return Loss (S_{11})

The S11 parameter, also known as return loss, measures how much power sent into an antenna reflect due to impedance mismatch. The designed antenna's S11 parameter, indicating return loss is -23.45 dB at its resonant frequency of 5.9GHz as shown in Fig.3.This value signifies strong impedance matching, showcasing efficient power transfer.

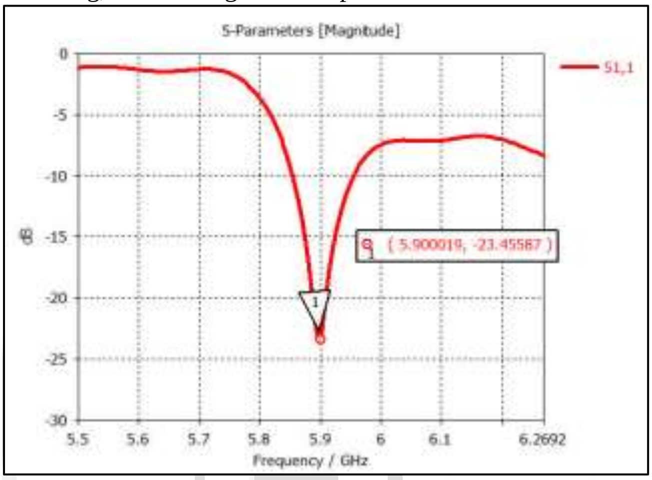


Fig. 3: Return loss (S_{11}) of designed antenna at 5.9 GHz

B. VSWR (Voltage Standing Wave Ratio):

The Voltage Standing Wave Ratio (VSWR) indicates how well the antenna is matched to the transmission line and the connected system. This is the ratio of the maximum voltage (standing waves) to the minimum voltage along the transmission line. A VSWR of 1:1 denotes a perfect match, while higher ratios reveal increasing discrepancies between the antenna and the transmission line. The obtained VSWR values of designed antenna as shown in Fig.1 is 1.14 at resonating frequency 5.9 GHz. The graph of VSWR value vs frequency is shown in Fig.4.

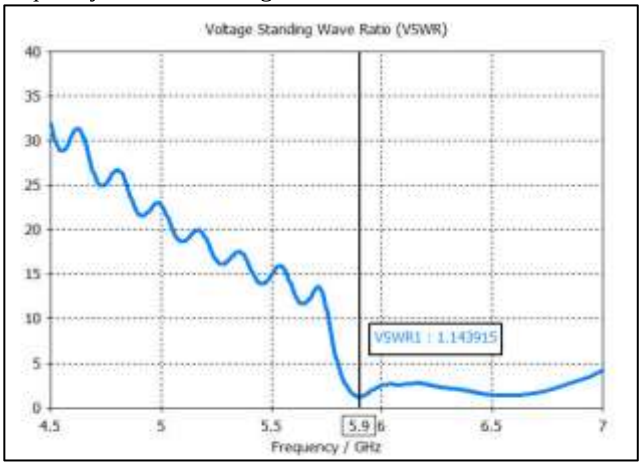


Fig. 4: VSWR of designed antenna at 5.9 GHz

C. Surface Current

The surface current (maximum) of a designed antenna as shown in Fig.5 that refers to the distribution of electric current along its structure's surface [17]. It plays a crucial role in determining the antenna's radiation properties and performance characteristics.

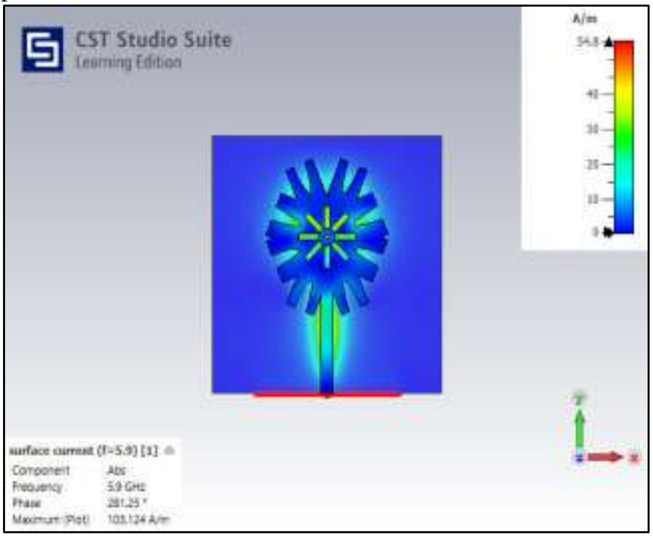


Fig. 5: Surface current distribution of designed antenna

D. 3D Radiation Pattern

The 3D radiation pattern of designed antenna as shown in Fig.6

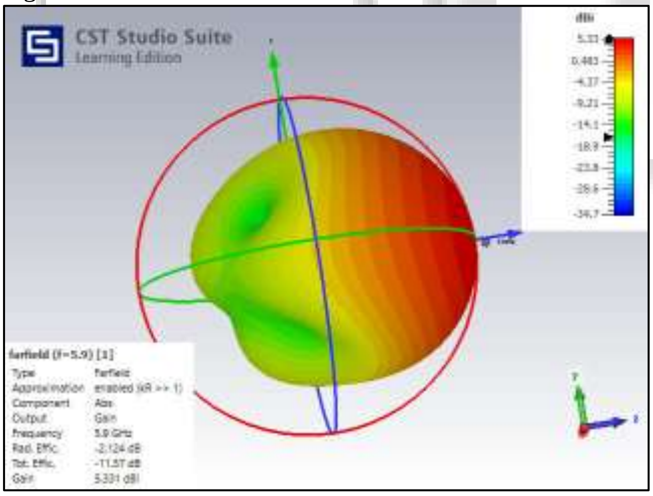


Fig. 6: 3D Radiation pattern of designed antenna

E. Gain

The gain of an antenna refers to its ability to direct or concentrate transmitted or received electromagnetic radiation in a particular direction. One more important parameter of antenna is gain and directivity that is 5.34dB and 7.45dB as presented in Fig. 7 along with antenna far field pattern.

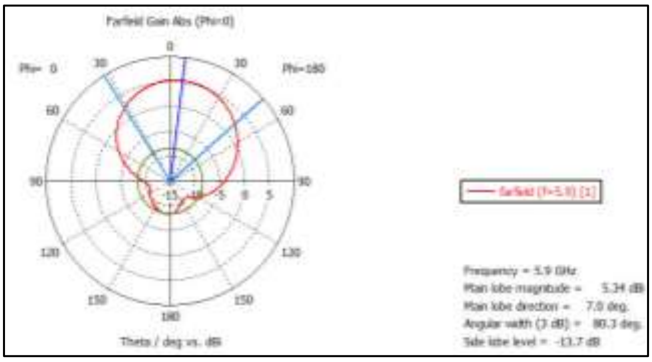


Fig. 7: 3D-Radiation pattern at 5.9 GHz

The values of simulated antenna parameters are tabulated in TABLE 2.

Parameters	value
Return Loss(S_{11})	-23.45 dB
VSWR	1.14
Gain	5.34 dB
Directivity	7.45 dB
Impedance	Ω

V. CONCLUSION

The fractal microstrip patch antenna successfully designed, simulated using CST Microwave Studio 2019, and constructed for vehicular application, performs remarkably well. Utilizing the Roger RT Duroid 5880 substrate with a relative permittivity (ε_r) of 2.2 and a thickness of 0.787 mm, this antenna demonstrates outstanding performance. Operating at 5.9GHz, it achieves a wide bandwidth of 100 MHz, showcasing excellent return loss (VSWR of 1.14 and -23.45dB). Simulations reveal an impressive absolute gain of 5.34 dB and a directivity of 7.45 dB.

REFERENCES

[1] Balanis CA. Antenna theory: analysis and design. John wiley & sons; 2016 Feb 1.

[2] Carver K, Mink J. Microstrip antenna technology. IEEE transactions on antennas and propagation. 1981 Jan;29(1):2-4.

[3] Bankey V, Kumar NA. Design, and performance issues of Microstrip Antennas. International Journal of Scientific and Engineering Research. 2015 Mar 25;6(3):1572-80.

[4] Hassoun ZA, Wali MH, Hussein HA, Haroon NH, Alkhayyat A. Study the Effect of Dielectric Permittivity and Changing Substrates Material on Microstrip Patch Antenna. In2022 International Congress on Human-Computer Interaction, Optimization and Robotic Applications (HORA) 2022 Jun 9 (pp. 1-5). IEEE.

[5] Werner DH, Ganguly S. An overview of fractal antenna engineering research. IEEE Antennas and propagation Magazine. 2003 Feb;45(1):38-57.

[6] Gianvittorio JP, Rahmat-Samii Y. Fractal element antennas: A compilation of configurations with novel characteristics. InIEEE Antennas and Propagation Society International Symposium. Transmitting Waves of Progress to the Next Millennium. 2000 Digest. Held in conjunction with: USNC/URSI National Radio

Science Meeting (C 2000 Jul 16 (Vol. 3, pp. 1688-1691). IEEE.
[7] Jiang D, Taliwal V, Meier A, Holfelder W, Herrtwich R. Design of 5.9 GHz DSRC-based vehicular safety communication. IEEE wireless communications. 2006 Oct;13(5):36-43.
[8] Kihei B, Copeland JA, Chang Y. Improved 5.9 GHz V2V short range path loss model. In2015 IEEE 12th International Conference on Mobile Ad Hoc and Sensor Systems 2015 Oct 19 (pp. 244-252). IEEE.
[9] Zhang L, Eibert TF, Tong MS. A Self-complementary Minkowski Fractal Patch Antenna for Multiband Applications. In2023 Photonics & Electromagnetics Research Symposium (PIERS) 2023 Jul 3 (pp. 1354-1360). IEEE.
[10] Rani RB. A compendious review on fractal antenna geometries in wireless communication. In2020 International Conference on Inventive Computation Technologies (ICICT) 2020 Feb 26 (pp. 888-893). IEEE.
[11] Abbas T, Karedal J, Tufvesson F. Measurement-based analysis: The effect of complementary antennas and diversity on vehicle-to-vehicle communication. IEEE Antennas and Wireless Propagation Letters. 2013 Mar 7; 12:309-12.
[12] Neira EC, Carlberg U, Carlsson J, Karlsson K, Ström EG. Evaluation of V2X antenna performance using a multipath simulation tool. InThe 8th European Conference on Antennas and Propagation (EuCAP 2014) 2014 Apr 6 (pp. 2534-2538). IEEE.
[13] Cismasu M, Gustafsson M. Antenna bandwidth optimization with single frequency simulation. IEEE Transactions on Antennas and Propagation. 2013 Dec 20;62(3):1304-11.
[14] Siakavara K. Methods to design microstrip antennas for modern applications. Microstrip Antennas. 2011 Apr 4:173-236.
[15] Bharghava P, Pachiyaannan M. Design of Rectangular Patch Antenna: Analysis with Different Feed Positions and Bandwidth Improvement. International Journal of Recent Technology and Engineering (IJRTE). 2019;7(5S4).
[16] Jena, M.R., Mishra, G.P., BhusanaSahoo, A. and Mangaraj, B.B., 2019. Fractal geometry and its application to antenna designs. International Journal of Engineering and Advanced Technology, 9(1), pp.3726-3743.
[17] Godaymi, W.I.A., Mohammed, A.K.A.A. and Ahmed, Z.A., 2012. Determination of surface currents on circular microstrip antennas. Journal of electromagnetic engineering and science, 12(4), pp.260-270.

