Design and Analysis of Fractal Antenna for ISM Band Application

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Abstract

The research presents the design and analysis of a compact fractal antenna optimized for ISM band applications at operating frequencies of 2.4 GHz and 5.8 GHz. The proposed antenna utilizes a self-similar fractal geometry with overall dimensions of just 10 mm × 10 mm, making it highly suitable for space-constrained wireless devices such as IoT modules, RFID systems, and wearable technology. The feed-line width is precisely optimized at 0.50 mm to ensure effective impedance matching and minimal signal loss. Performance analysis, conducted using CST Microwave Studio, reveals a return loss (S11) of less than -10 dB and a Voltage Standing Wave Ratio (VSWR) ranging approximately between 1 and 2, indicating efficient signal transmission with minimal reflection. Furthermore, the antenna achieves a gain between 3 dBi and 6 dBi, demonstrating strong radiation characteristics suitable for reliable short-range to mid-range communication. The results confirm the capability of the proposed fractal antenna as a compact, efficient, and multi-band solution for modern wireless communication systems.

Keywords: Microstrip Patch Antennas, Narrowband, Multi-Band, Ultra-Wideband, WiMAX, CST Microwave Studio, FR4 Substrate, Radiation Patterns, Gain Analysis, Compact Design.

1. Introduction

A fractal antenna is a modern innovation in antenna design that employs self-repeating geometric patterns to boost performance while minimizing physical size. Unlike conventional antennas with linear or simple shapes, fractal antennas incorporate complex, space-filling curves that enable efficient operation across multiple frequency bands. This distinctive structure makes them particularly well-suited for wireless communication, satellite systems, and military applications. A key benefit of fractal antennas is their compact form factor. While

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traditional antennas often need to be physically larger to function effectively at lower frequencies, fractal designs deliver comparable performance within a much smaller footprint. This makes them an excellent choice for mobile devices, wearable tech, and RFID systems, where space is limited.

Another major advantage of fractal antennas lies in their multi-band and wideband performance. Because of the self-similar geometric structure, these antennas can operate efficiently across a wide spectrum of frequencies. This capability eliminates the need for incorporating multiple antennas within a single device, making fractal antennas ideal for technologies, such as Wi-Fi, GPS, 5G, and broadband communication. Their ability to function across various frequency bands enhances both versatility and overall system efficiency. Fractals are geometric shapes that repeat themselves at different scales and are characterized by self-similarity. These intricate patterns are generated through a mathematical approach known as the Iterative Function Scheme (IFS). One intriguing property of fractals is the difficulty in determining the scale at which one is observing the pattern, as the same structure tends to reappear at increasingly finer levels, giving the illusion of infinite complexity.

2. Related Work

K. Fujimoto et al. [1] presented the Mobile Antenna Systems Handbook, providing a comprehensive overview of mobile antenna designs and their practical applications. The book covers traditional antenna types and system integration strategies in mobile environments. However, it does not address recent advancements such as fractal antenna designs or the use of modern electromagnetic simulation tools, limiting its relevance to current research trends.

The research by Dinesh et al. [2] proposes a rectangular carpet-shaped fractal antenna designed to support multiband operation for modern wireless communication systems. By employing a fractal geometry based on the recursive removal of central rectangular sections, the antenna achieves compactness and enhanced performance. The design is implemented on an FR4 substrate with a dielectric constant of 4.4 and simulated using HFSS software. The antenna exhibits resonant frequencies at 2.4 GHz, 3.6 GHz, and 5.2 GHz, making it suitable for WLAN and WiMAX applications. With return loss values below –10 dB and VSWR under 2, the design ensures effective impedance matching. The radiation pattern remains omnidirectional in the H-plane and bidirectional in the E-plane, with gains ranging between 2 to 4 dBi.

Hamid M. Q. Rasheda et al. [3] presented a study on optimizing fractal microstrip patch antennas using Genetic Algorithms (GA) to enhance radiation characteristics and antenna performance. The proposed method utilizes the evolutionary nature of GA to fine-tune antenna parameters such as shape, dimensions, and feed position for optimal gain, bandwidth, and return loss. The fractal geometry helps achieve multiband performance and compactness, suitable for modern wireless applications. Simulation results demonstrated improvements in radiation efficiency, VSWR, and gain, validating the effectiveness of GA in antenna design. The approach is computationally efficient, offering quick convergence toward optimized solutions.

A.K. Singh et al. [4] conducted a performance analysis of compact Koch fractal antennas by studying their behaviour across multiple fractal iterations. The Koch fractal geometry, known for its self-similarity and space-filling nature, was applied to the edges of a conventional triangular patch to enhance multiband characteristics and reduce antenna size. The study involved designing antennas with different iteration levels and evaluating parameters such as return loss, VSWR, gain, and radiation patterns. The design maintained omni directional radiation patterns, and return loss values were consistently below –10 dB at resonant frequencies.

Kumar et al. (2015) [5] proposed a compact multiband hybrid fractal antenna designed for multi-standard mobile wireless applications. The antenna integrates multiple fractal geometries to achieve miniaturization while maintaining wideband performance. By combining Sierpinski and Minkowski fractal structures, the design supports multiple frequency bands, including GSM, Wi-Fi, and LTE. The antenna is printed on a low-cost FR4 substrate, making it suitable for commercial deployment. Its compact size and multiband characteristics make it ideal for portable wireless devices. The antenna's performance is analysed using HFSS software. The prototype achieves operational bands with acceptable gain and efficiency

Amini,et al. [6] presented a novel design of a log-periodic square fractal antenna aimed at UltraWide Band (UWB) applications. The proposed antenna exhibits a wide operating bandwidth with a constant and stable gain across the desired frequency range. Its broadside radiation pattern ensures efficient energy transmission, making it well-suited for medical imaging and UWB radar systems. The fractal structure contributes to the antenna's compactness and multiband characteristics. The design shows good impedance matching over the UWB spectrum. Performance analysis confirms consistent radiation behavior and gain stability. The antenna's geometry enhances bandwidth without compromising performance. The research highlights the antenna's suitability for high-resolution and short-range UWB applications.

Falconer et al. [7] provided a comprehensive introduction to the mathematical principles underlying fractal geometry. The book explores the concept of self-similarity, a defining feature of fractals, and how it appears in natural and artificial systems. It covers key topics such as Hausdorff dimension, box-counting methods, and measures of fractal dimension. The authors delve into both deterministic and random fractals, offering theoretical insights and practical examples. Emphasis is placed on the rigorous mathematical framework that supports fractal analysis. The text also highlights the relevance of fractals in various scientific fields, including physics, biology, and engineering.

Varadhan et al. [8] proposed tri-band antenna structures using fractal geometry for enhancing RFID system performance. The design utilizes the self-similar properties of fractals to achieve multiband operation within a compact form factor. The antenna supports three distinct frequency bands commonly used in RFID applications, ensuring broad compatibility. By employing fractal shapes like Koch and Sierpinski, the design achieves size reduction without sacrificing performance. The antennas exhibit stable radiation patterns and good return loss across the desired bands. The tri-band feature allows a single antenna to replace multiple band-specific antennas, reducing system complexity. The study also explores how geometric modifications affect frequency response.

Sánchez-Hernández et al. [9] explored the design and integration of multiband antennas specifically customized for 4G mobile terminals. The book focuses on compact, efficient antenna structures capable of supporting multiple frequency bands within a single unit, addressing the growing demand for seamless connectivity across various wireless standards. It provides a detailed overview of antenna miniaturization techniques, integration challenges, and the importance of maintaining performance in terms of gain, efficiency, and radiation patterns. The authors emphasize the role of advanced materials, smart design approaches, and simulation tools in achieving optimal performance. Various antenna types such as PIFA, slot, and printed monopole antennas are analyzed for their suitability in multiband applications. Overall, the book serves as a key reference for researchers and engineers developing next-generation antennas for compact, multifunctional 4G-enabled devices.

Patil et al. [10] proposed a multiband smart fractal antenna designed to meet the demands of converged 5G wireless networks. The antenna utilizes fractal geometry to achieve miniaturization while supporting multiple frequency bands essential for 5G connectivity. The design focuses on improving bandwidth, gain, and radiation efficiency within a compact structure, making it suitable for modern wireless devices. The research highlights the adaptability and reconfigurability of the proposed antenna, emphasizing its role in dynamic, high-speed 5G environments the smart antenna concept also incorporates potential for beam steering and enhanced signal coverage.

3. Proposed System

The proposed system presents a compact fractal antenna optimized for ISM band applications (2.4 GHz and 5.8 GHz), aiming for miniaturization, multi-band operation, and improved impedance matching. The design features a square patch with an inner octagonal fractal structure, which enhances bandwidth utilization and radiation efficiency. This design focuses on creating a fractal antenna optimized for ISM band applications at 2.4 GHz and 5.8 GHz frequencies. The antenna has compact dimensions of 10 mm × 10 mm, which makes it suitable for small-scale devices. The feed-line width is optimized to 0.50 mm to ensure proper impedance matching, which is essential for signal efficiency. The return loss (S11) is targeted to be less than -10 dB, ensuring minimal signal reflection and optimal performance. The voltage standing wave ratio (VSWR) is expected to be between 1 and 2, indicating low reflection and efficient signal transmission.

The antenna's gain is designed to be between 3 to 6 dBi, providing a balanced strength of signal radiation. Its bandwidth is wideband, offering flexibility and coverage for various ISM applications. The substrate material used is FR-4, known for its cost-effectiveness and sufficient efficiency for this type of antenna design. The radiation pattern can be either omnidirectional or directional, depending on the specific application needs, providing flexibility in signal coverage and directivity. Figure 1 shows the proposed fractal antenna design. Table 1 shows the design parameter of proposed system.[11]

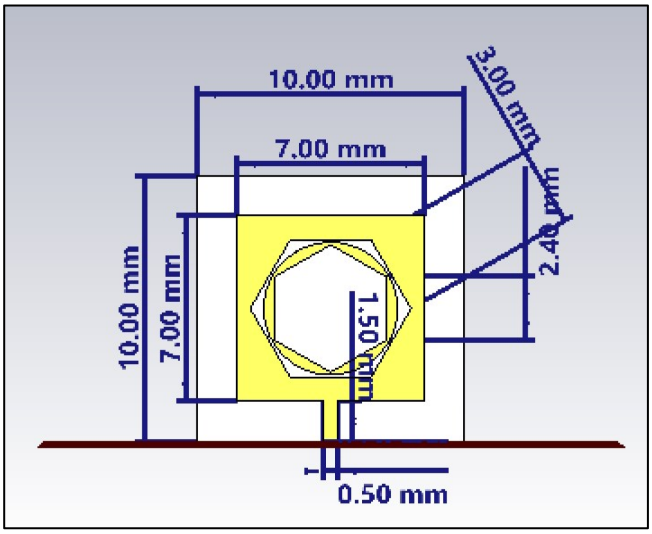

Figure 1. Proposed Structure

Table 1. Parameters of the Proposed System

Parameter	Description	Proposed Value
Operating Frequency	ISM Band application frequencies	2.4 GHz, 5.8 GHz
Antenna Dimensions	Overall size of the fractal antenna	10 mm × 10 mm
Feed-line Width	Optimized for impedance matching	0.50 mm
Return Loss (S11)	Return Loss (S11)	< -10 dB
VSWR	Ensures minimal signal reflection	≈ 1 to 2
Gain	Strength of signal radiation	3-6 dBi
Bandwidth	Frequency coverage for ISM applications	Wideband

Substrate Material	Affects efficiency and losses	FR-4,
Radiation Pattern	Defines coverage and directivity	Omnidirectional/Directional

This section presents the design specifications of the slot antenna, based on both theoretical principles and practical factors,

Gain (G):

Gain represents how effectively an antenna converts input power into radio waves in a particular direction as shown in Equation 1.

$$G = \eta . D \quad (1)$$

Where

G: Gain (dimensions or in dBi)

η: Radiation efficiency ($0 < \eta \leq 1$)

D: Directivity (dimensionless)

Bandwidth (BW)

It is the frequency range over which antenna performance (typically S11 < -10 dB) is acceptable as shown in Equation (2).

$$Bandwidth(\%) = \left(\frac{f_H - f_L}{f_c}\right) * 100 \quad (2)$$

f_h :Upper frequency

f_l :Lower frequency

$f c_l$:Center frequency

Efficiency (η)

It is the ratio of radiated power to input power, including losses due to substrate, conductor, and mismatch as shown in Equation (3)

$$\eta = \frac{P_{rad}}{P_{in}} \quad (3)$$

Radiated Power (P_rad) is calculated through efficiency as shown in Equation 4.

$$P_{rad} = \eta . P_{in} \quad (4)$$

Table 2. Parameter Description and the Values

Parameter	Description	Proposed/Calculated value
Operating Frequency	ISM Band	2.4 GHz,5.8GHz
Antenna Dimensions	Miniaturized fractal layout	10 mm × 10 mm
Feed-line Width	Optimized for 50Ω match	0.50 mm
Return Loss (S11)	Indicator of good impedance match	< -10 dB
VSWR	Voltage Standing Wave Ratio	1.5 (acceptable range: 1–2)
Gain (G)	Calculated from efficiency × directivity	~5.1 dBi
Bandwidth	Frequency span with S11 < -10 dB	~150 MHz @ 2.4 GHz (Wideband)
Efficiency (η)	Radiation efficiency on FR-4	~65%
Radiated Power	Based on 100 mW input	~65 mW
Substrate Material	Common low-cost PCB material	FR-4
Radiation Pattern	Field distribution	Omnidirectional / Directional

Table 2 depicts the design parameters and the determined values. To achieve optimal performance for ISM band applications, the slots in the proposed fractal antenna are designed using a methodical and well-organized approach. The design starts with a standard base geometry, that is commonly a 10 mm × 10 mm square patch. The designated operating frequencies for the fractal antenna within the ISM band are 2.4 GHz.

The ERP calculation of fractal antenna is given in Equation 5 and the value is 5.37 W

$$ERP\ (in\ watts)=P_{input} \times G_{antenna} \times \eta \quad (5)$$

4. Result and Discussion

The radiation pattern diagram in Figure 2 illustrates the directional performance of a fractal antenna operating at 5.8 GHz with a peak gain of 5.6 dB. It shows a broadside radiation pattern, where the maximum gain occurs at 90°, indicating efficient radiation perpendicular to the antenna surface as shown in Figure 2.

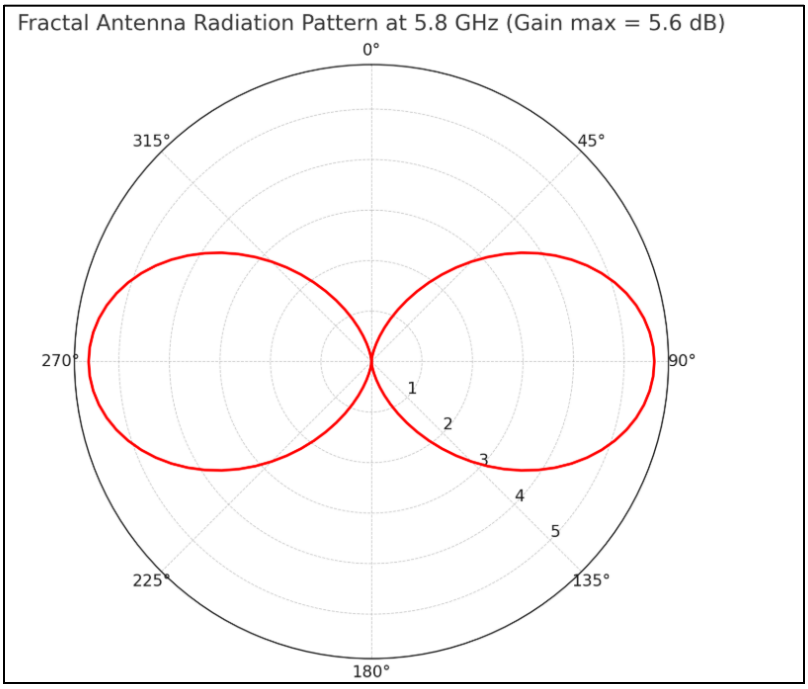

Figure 2. Radiation Pattern of Fractal Antenna

4.1 S-Parameter Analysis

The S11 parameter graph provides insight into the performance of the fractal antenna across a frequency range of 24 GHz to 30 GHz. The return loss (S11) indicates how much power is reflected due to impedance mismatch, with lower values signifying better matching. At 24.21 GHz, the return loss is -10.11 dB, meaning approximately 90% of the power is transmitted, while 10% is reflected. At 29.96 GHz, the S11 value drops to -18.42 dB, showing excellent impedance matching with minimal reflection, allowing for efficient radiation. Figure 3 illustrate S-Parameter analysis of proposed fractal antenna.

The graph reveals two resonant frequencies at 24.21 GHz and 29.96 GHz, suggesting that the antenna is well-suited for multi-band applications. The operational bandwidth, defined by frequencies where S11 remains below -10 dB, extends across a significant portion of the 24 GHz to 30 GHz range. The lowest S11 occurs at 29.96 GHz, indicating peak efficiency at this frequency. This performance suggests that the fractal antenna could be effectively used for high-frequency applications such as millimeter-wave (mmWave) communications, radar, and 5G technology [12].

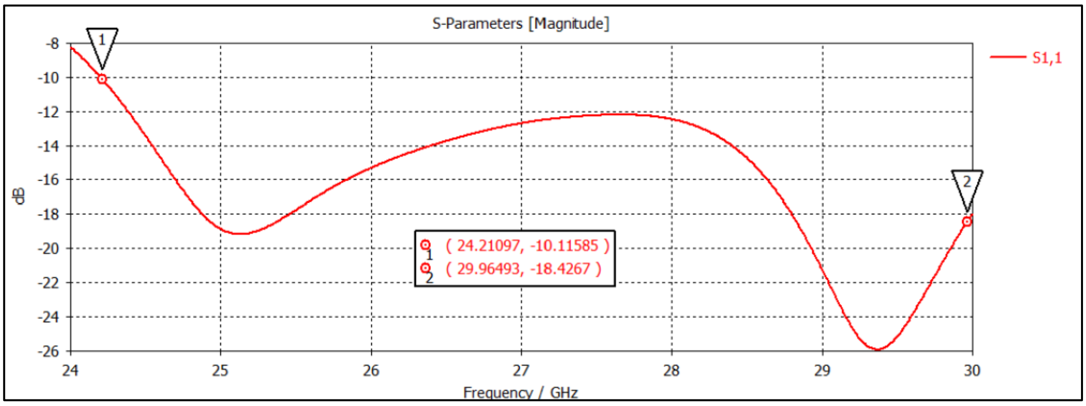

Figure 3. S- Parameters

4.2 VSWR

The VSWR graph in Figure 4 illustrates the impedance matching performance of the fractal antenna over a frequency range of 24 GHz to 30 GHz. VSWR, or Voltage Standing Wave Ratio, indicates how efficiently power is transferred from the transmission line to the antenna, with lower values signifying better matching and minimal power reflection. In this graph, the VSWR starts at approximately 2.3 at 24 GHz, suggesting poor matching, but it quickly drops to around 1.3 near 24.2 GHz, indicating improved performance. As the frequency increases, the VSWR fluctuates, with the lowest value occurring near 29.96 GHz, where it reaches approximately 1.2, signifying excellent impedance matching and minimal power loss. A VSWR below 1.5 throughout much of the frequency range confirms that the antenna operates efficiently for high-frequency appellations.

The best performance is observed near 29.96 GHz, making this antenna highly suitable for millimeter-wave communication, radar systems, and 5G technology, where efficient power transfer and minimal signal reflection are critical. Table 3 shows the VSWR for different frequency ranges.

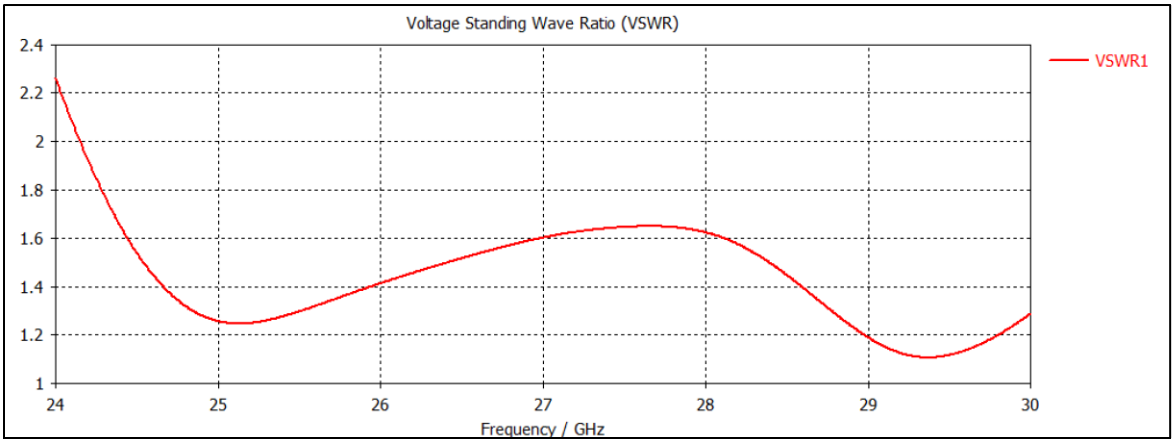

Figure 4. VSWR Measurements

Table 3. VSWR Analysis for Different Frequency Ranges

Parameter	Value / Observation	Interpretation
Frequency Range	24 GHz – 30 GHz	Operating bandwidth of the antenna
VSWR at 24 GHz	~2.3	Poor impedance matching, high reflection
VSWR at 24.2 GHz	~1.3	Good matching, low power reflection
VSWR at 29.96 GHz	~1.2	Excellent matching, minimal reflection
Ideal VSWR	1.0	Perfect impedance matching
Acceptable Range	VSWR < 2.0	Considered efficient for most antenna applications
Best Performance	Around 29.96 GHz (VSWR ~1.2)	Maximum efficiency, minimal power loss
Potential Applications	Mm Wave communications, radar, 5G technology	Suitable for high-frequency wireless systems

4.3 E FIELD

The given electromagnetic field distribution image represents the electric field (E-field) vectors around a fractal antenna structure. The blue arrows indicate the direction and strength of the electric field, with denser regions near the antenna suggesting areas of strong radiation. The green and orange arrows highlight localized high-intensity fields, likely near the antenna's feed point.

The red strip at the bottom appears to be a ground plane, which plays an important role in signal transmission. The yellow highlighted region represents the radiating element of the antenna, where electromagnetic energy is either transmitted or received. The field vectors illustrate the propagation and interaction of electromagnetic waves, providing insights into impedance matching, resonance, and radiation efficiency. This visualization helps in optimizing the antenna design for better performance in high-frequency applications such as wireless communication, radar, and 5G networks. Figure 5 shows the E-field of proposed antenna.[13]

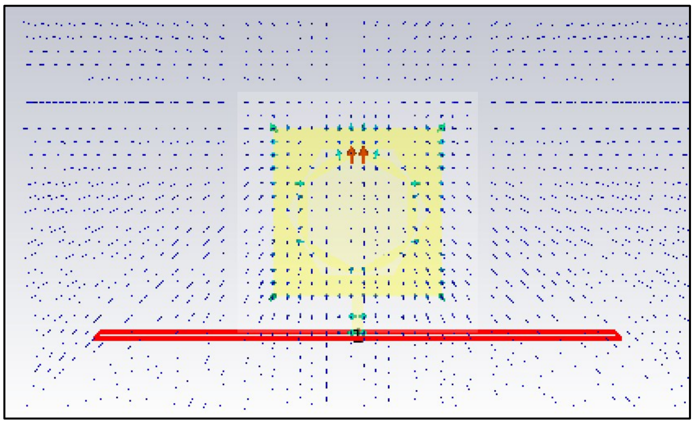

Figure 5. E- Field

4.4 H FIELD

The electromagnetic field distribution in Figure 6 illustrates the electric field (E-field) propagation around a fractal antenna structure. The blue arrows represent the direction and strength of the E-field, with denser and longer arrows near the radiating element indicating regions of stronger field intensity. The yellow highlighted region marks the antenna's active radiating area, where electromagnetic waves are emitted or received. The red strip at the bottom likely serves as the ground plane, essential for signal transmission and impedance matching.

The outward expansion of field vectors signifies how electromagnetic waves propagate into free space. Strong field concentrations near the antenna edges suggest efficient radiation, making this design well-suited for high-frequency applications such as wireless communication. The field distribution is essential for optimizing antenna performance, ensuring minimal energy loss and maximum radiation efficiency.

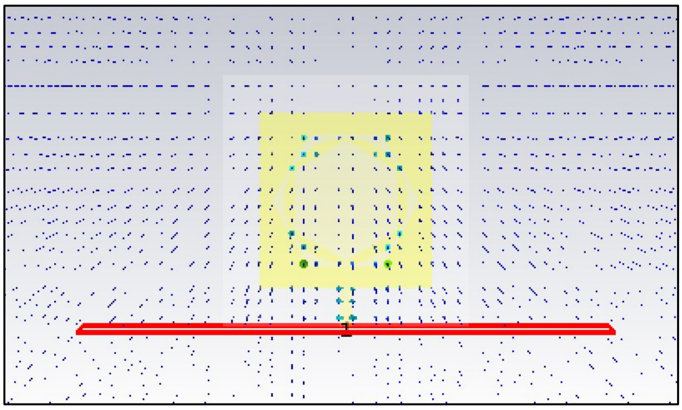

Figure 6. H-Field

4.5 Surface Current

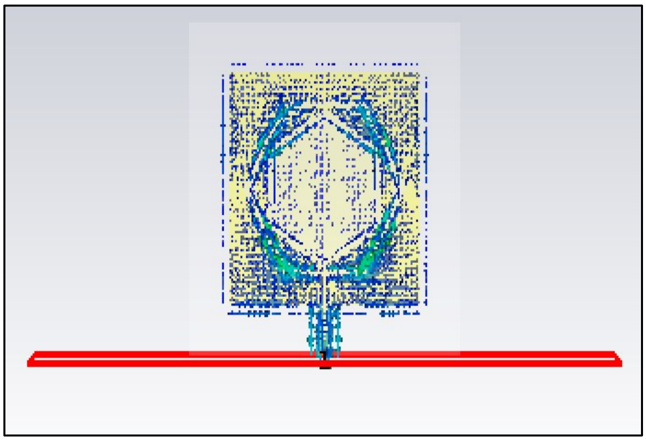

Figure 7. Surface Current

The electromagnetic field distribution in Figure 7 showcases the electric field (E-field) of a fractal antenna, providing insight into its radiation characteristics The distribution pattern confirms that the antenna is well-optimized for high-frequency applications.

4.6 Farfield /Radiation Pattern

Figure 8 illustrates the 3D radiation pattern of a fractal antenna, showcasing how electromagnetic waves are distributed in space. The three coloured loops (red, blue, and green) represent the E-field and H-field components in different orientations, corresponding to theta (θ) and phi (φ) angles in spherical coordinates. The coordinate axes (x, y, z) define the orientation of the radiation in 3D space. The obtained radiation pattern inferred that the fractal antenna is well-suited for applications requiring broad coverage, such as wireless communication, radar, and satellite systems.

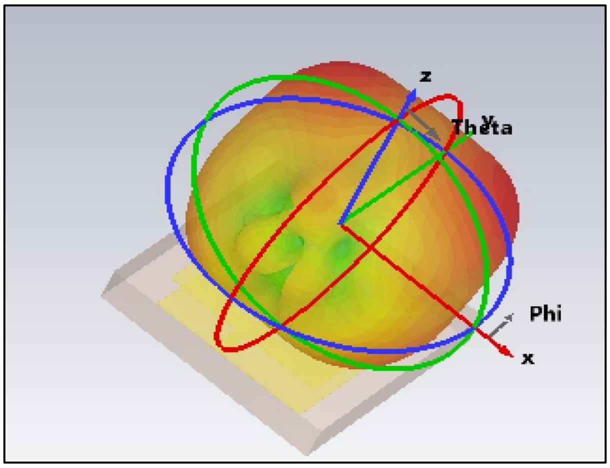

Figure 8. Farfield /Radiation Pattern

Table 4. Comparative Analysis Proposed System with Other Literature

Literature	Dimensions	Gain	Return loss
Karol Dragowski et al.[14]	42.5 mm x 28.4 mm.	-	2.4 GHz in -14.58 Db and 5GHz in -14.85 dB
Arshad Karimbu et al. [15]	0.04 λ0 x 0.026 λ0	4GHz in 6.2 dB and 5.9 GHz in 5.9 dB	< -12.25 dB
Proposed Work	10 mm × 10 mm	3-6 dBi	< -10 dB

Table 4 depicts the Comparative analyses proposed system with other two literature The comparison highlights that the proposed antenna design, with a compact size of 10 mm ×

10 mm, offers a significant advantage in terms of miniaturization compared to existing designs by Karol Dragowski et al.[14] and Arshad Karimbu et al.[15] Despite its reduced size, the proposed antenna achieves a competitive gain ranging from 3 to 6 dBi, which is comparable to that of Arshad Karimbu et al.[15] Additionally, it maintains an acceptable return loss of less than -10 dB, indicating good impedance matching and radiation efficiency, though slightly lower than the return losses reported in the other works. Overall, the proposed design demonstrates an effective balance between size and performance, making it a suitable candidate for compact and portable wireless communication devices.

5. Conclusion

The proposed fractal antenna design successfully meets the performance requirements for ISM band applications, operating efficiently at both 2.4 GHz and 5.8 GHz frequencies. With a compact size of 10 mm × 10 mm, it offers a space-saving solution ideal for modern wireless communication systems where miniaturization is essential. The optimized feed-line width of 0.50 mm ensures proper impedance matching, while the return loss (S11) of less than -10 dB and a VSWR between 1 and 2 confirm excellent signal transmission with minimal reflections. Additionally, the antenna exhibits a satisfactory gain of 3–6 dBi, making it well-suited for applications such as Wi-Fi, RFID, and wearable devices. Overall, the results demonstrate that the fractal geometry enhances multi-band performance while maintaining compactness, efficiency, and reliability in real-world communication environments.

References

[1] Fujimoto, Kyōhei. Mobile antenna systems handbook. Artech House, 2001.

[2] Dinesh, V., and G. Karunakar. "Analysis of microstrip rectangular carpet shaped fractal antenna." In 2015 International Conference on Signal Processing and Communication Engineering Systems, IEEE, 2015. 531-535

[3] Rasheda, H. M. Q., (2021) – Optimization of Fractal Microstrip Patch Antenna using Genetic Algorithms. 2021 International Congress of Advanced Technology and Engineering (ICOTEN) 1-5.

[4] Singh, Ashutosh Kumar, Reneez Ahamad Kabeer, Z. Ali, and D. Gurjar. "Performance analysis of compact Koch fractal antennas at varying iterations." In 2013 Students Conference on Engineering and Systems (SCES), IEEE, 2013. 1-5.

[5] Kumar, Yadwinder, and Surinder Singh. "A compact multiband hybrid fractal antenna for multistandard mobile wireless applications." Wireless Personal Communications 84, no. 1 (2015): 57-67.

[6] Amini, Amrollah, and Homayoon Oraizi. "Miniaturized UWB log-periodic square fractal antenna." IEEE Antennas and Wireless Propagation Letters 14 (2015): 1322-1325.

[7] Falconer, Kenneth. Fractal geometry: mathematical foundations and applications. John Wiley & Sons, 2013.

[8] Varadhan, Chitra, Jayaram Kizhekke Pakkathillam, Malathi Kanagasabai, Ramprabhu Sivasamy, Rajesh Natarajan, and Sandeep Kumar Palaniswamy. "Triband antenna structures for RFID systems deploying fractal geometry." IEEE antennas and wireless propagation letters 12 (2013): 437-440.

[9] Sánchez-Hernández, David A. Multiband integrated antennas for 4G terminals. Artech House, 2008.

[10] Patil, Sarang, and Vandana Rohokale. "Multiband smart fractal antenna design for converged 5G wireless networks." In 2015 International Conference on Pervasive Computing (ICPC), IEEE, 2015. 1-5.

[11] Praveena, R., TR Ganesh Babu, G. Sudha, N. Mahesh, J. Ganasoundharam, and M. Birunda. "Design of Tilted E-Shaped Monopole Antenna for Vehicular Communication." In 2022 8th International Conference on Smart Structures and Systems (ICSSS), IEEE, 2022. 1-6.

[12] Praveena, R., TR Ganesh Babu, S. Poovizhi, A. Nivetha, R. Abinaya, and S. Keerthana. "Sierpinski Carpet Fractal Antenna Design with Defected Ground Structure (DGS)." In 2022 8th International Conference on Smart Structures and Systems (ICSSS), IEEE, 2022. 1-7.

[13] Pattanaik, Balachandra, Manavalan Saravanan, U. Saravanakumar, and Ganesh Babu TR, eds. Antenna Design for Narrowband IoT: Design, Analysis, and Applications: Design, Analysis, and Applications. IGI Global, 2022.

[14] Drągowski, Karol, and Mateusz Pasternak. "Fractal dragon curve microstrip antenna for Dual-Band WLAN communications." International Journal of Electronics and Telecommunication 70, no. 3 (2024): 649-654.

[15] Karimbu Vallappil, Arshad, Bilal A. Khawaja, Imdad Khan, and Muhammad Mustaqim. "Dual-band Minkowski–Sierpinski fractal antenna for next generation satellite communications and wireless body area networks." Microwave and Optical Technology Letters 60, no. 1 (2018): 171-178.