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Performance Analysis of a Rectangular Nested Fractal Antenna for Multiband Applications

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***Abstract-* This paper presents the design, fabrication, and measurement of a novel rectangular nested fractal antenna tailored for multiband applications in diverse communication systems. The proposed antenna introduces a unique nested fractal geometry that optimizes resonant frequency allocation and enhances gain, a significant improvement over traditional fractal designs. With compact dimensions of 40×50×0.8 mm^3, the antenna is fabricated using FR4 glass epoxy, a widely adopted dielectric material with a relative permittivity of 4.7 and a low loss tangent of 0.0197. Unlike conventional designs, this antenna achieves seven distinct resonant frequency bands at 1.99, 3.68, 4.91, 6.11, 7.60, 8.06, and 9.39 GHz, with corresponding bandwidths of 90, 80, 90, 100, 70, 22, and 210 MHz. Moreover, it demonstrates superior gains of 0.88, 2.18, 18.86, 8.89, 13.22, 12.24, and 4.01 dBi, surpassing prior designs in terms of performance consistency across multiple bands. The innovative nested fractal structure enhances multiband capabilities while maintaining a compact footprint, ensuring compatibility with emerging communication standards. Rigorous laboratory testing of the fabricated prototype confirmed the accuracy of simulated results, validating the antenna's high reliability and precision. These advancements make the proposed antenna a cutting-edge solution for applications including mobile communications, Wi-Fi, 5G, satellite communications, radar systems, and microwave communications.**

***Index Terms-* Fractal antenna, multiband applications, performance optimization, rectangular antenna.**

I. INTRODUCTION

The Modern communication technologies rely heavily on antennas that are lightweight and capable of multi-band operation, and fractal antennas are particularly effective in fulfilling these needs. As a result, many recent studies have concentrated on fractal antennas, investigating various modifications on rectangular fractal antenna designs to further improve their already outstanding performance. Harshit Srivastava et al. [1] presented an enhancement of bandwidth and gain in a rectangular patch element implemented in a microstrip configuration and employing a slotted array technique. Dhakshinamoorthi M. K. et al. [2] proposed the implementing miniaturization techniques on a rectangular microstrip patch antenna through an enhanced genetic algorithm. Ramesh Kumar Verma and D. K. Srivastava [3] proposed the development and examination of a triple-band rectangular microstrip antenna with integrated notches and slots for wireless use. Yufeng Zhu et al. [4] presented an application involving dual-band base stations. through the integration of a rectangular MIMO antenna array for 5G applications with a GSM antenna. Dheeraj Tripathi et al. [5] proposed enhancing the bandwidth concerning a wideband microstrip antenna incorporating rectangular slots for WLAN/WiMAX applications. Oscar Ossa-Molina and Francisco López-Giraldo [6] presented a simplified model for calculating the defining parameters of a slotted rectangular microstrip patch antenna. Pandey Rajat Girjashankar and Trushit Upadhyaya [7] proposed a substrate integrated waveguide-fed dual-band quad-element rectangular dielectric resonator-based MIMO capabilities configuration. Usman Illahi et al. [9] proposed the design and development of a rectangular dielectric resonator antenna with single feeding that exhibits circular polarization for WiMAX and satellite applications, and 5G NR band applications. Andrea Martínez-Lozano et al. [10] presented a UWB-printed rectangular monopole antenna for analyzing biological tissue. Anees Abbas et al. [11] presented a UWB antenna with triple rectangular notches employing EBG and SRR. Anuradha A. Palsokar and S. L. Lahudkar [12] proposed a rectangular patch antenna characterized by its frequency and radiation pattern reconfigurability utilizing a single PIN diode. Om Prakash Kumar et al. [13] presented a novel ultrawideband antenna with a corner-etched rectangular shape and implementing a compact ground plane in microwave imaging. Lijaddis Getnet Ayalew and Fanuel Melak Asmare [14] proposed the development and optimization of a dual-band rectangular-shaped dual-band microstrip patch antenna equipped with Pi-slots employing surface response techniques for applications in 5G technology. R. Samson Daniel [15] proposed a CPW-fed nested loop antenna with a rectangular design for pentaband wireless applications. Chandraveer Singh and Gaurav Kumawat [16] presented a compact microstrip patch antenna designed for ultra-wideband applications featuring a dual band notch targeting WiMAX and WLAN. Jinhao Wang and Jiade Yuan [17] proposed a small-sized UHF RFID tag antenna featuring a rectangular loop design for dual-sided anti-metal applications. M. Nouri et al. [18] presented an optimized small metamaterial-enhanced rectangular antennas designed for 5G mobile communication using fast multi-objective optimization. Said Douhi et al. [19] presented the development of a high-gain flexible rectangular antenna array for RF energy harvesting and wearable devices. Salah-Eddine Didi et al. [20] proposed the development of a microstrip patch antenna featuring a rectangular slot configuration for 5G applications operating at 28 GHz. In our previous work [21], we presented Latest Developments and Cutting-Edge Innovations in Multiband Fractal Antennas Iftikhar Ahmad et al. [22] proposed a high-gain microstrip patch antenna designed in a rectangular shape slot for 5G millimeter-wave wireless communication. Fardeen Mahbub et al. [23] presented a rectangular-shaped microstrip patch antenna for single-band 28.5 GHz operation in 5G communications technology. Preet Kaur [24] presented the development of a compact and wideband rectangular patch antenna utilizing artificial dielectrics made from cylindrical rods. Abdul Wahab Memon et al. [25] presented a microstrip patch antenna featuring a rectangular ring structure designed for 2.45 GHz used for wearable applications using breathable textile. Anees Abbas et al. [26] proposed an ultra-wideband antenna designed with a rectangular notch in its frequency response, featuring adjustable notched bandwidth and center frequency. However, these studies often focus on narrow performance aspects, such as gain, bandwidth, or single-band improvements, and lack a comprehensive solution that combines multiband operation, compactness, and high gain.

This work introduces a rectangular nested fractal antenna, offering a novel design approach that iteratively incorporates smaller rectangular patterns within the original patch, creating a unique nested fractal geometry. This design achieves, seven distinct resonant frequency bands, ranging from 1.99 GHz to 9.39 GHz, with bandwidths up to 210 MHz, demonstrating superior multiband capabilities compared to existing designs. Enhanced gain, with a maximum value of 18.86 dBi, outperforming similar structures in the literature. A compact footprint ($40 \times 50 \times 0.8$ mm^3), ensuring practical applicability for modern communication devices. The proposed antenna design addresses key limitations of prior works by providing a balanced performance across multiple bands while maintaining a simple and easily fabricable structure. Its novel geometry enhances electromagnetic coupling and resonant mode distribution, setting it apart from conventional fractal designs. Applications of the antenna include mobile communications, Wi-Fi, 5G networks, satellite communications, radar systems, and microwave communications, making it a versatile and cutting-edge solution for modern and emerging technologies.

The structure of this research paper is organized as follows: Section 2 explains the development process of the rectangular nested fractal antenna design, detailing the methodology, theoretical considerations, and implementation steps. Section 3 provides an in-depth analysis of simulation results, evaluates each design iteration, and validates the fabricated antenna's performance through comprehensive measurements and experimental tests. Finally, Section 4 concludes the paper, summarizing the key findings, emphasizing the novelty of the proposed design, and discussing its potential applications and future research directions in advanced wireless communication systems.

II. ANTENNA DESIGN

The development of the proposed antenna design is comprehensively illustrated in Fig. 1, which showcases the iterative design process, highlighting the evolution of the antenna's structure and performance enhancements across different stages. Fig. 2 further complements this by providing a detailed schematic of the antenna's geometry, emphasizing its intricate structural features and the selection of materials. The antenna is fabricated using an economical and widely available FR-4 substrate, chosen for its balance of performance and affordability. This substrate is characterized by a relative permittivity of 4.7, a loss tangent of 0.02, and a thickness of 0.8 mm. The conductive layer, responsible for the antenna's radiative and transmission capabilities, is composed of copper with a uniform thickness of 35 µm, ensuring reliable conductivity and minimal resistive losses. The overall dimensions of the antenna are compact, with a length of 40 mm, a width of 50 mm, and a total height of 0.8 mm, making it suitable for integration into modern communication systems requiring space-efficient solutions. Despite its compact size, the design achieves high performance, ensuring applicability across a range of frequency bands. The compactness, combined with cost-effective materials and efficient design.

Designing a rectangular patch antenna involves essential calculations and equations from (1) to (6) to ensure optimal performance at the desired resonant frequency. The resonant frequency (fr) is determined by the effective length (L) of the patch, which depends on the substrate's relative permittivity (ε) and the speed of light (c). The patch width (W) is calculated to achieve efficient radiation while considering the dielectric constant and the resonant frequency. To address fringing effects at the edges of the patch, the effective dielectric constant (ε_eff) and the length extension (ΔL) are evaluated. These corrections refine the effective length (L_eff) and help in determining the actual patch length (L), which is obtained by subtracting the length extension from the effective length. These calculations are fundamental for designing a patch antenna that meets performance goals for specific frequency applications.

$$f_r = \frac{c}{2L\sqrt{\varepsilon_r}} \tag{1}$$

$$w = \frac{C}{2f_r\sqrt{\frac{\varepsilon_r+1}{2}}} \tag{2}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{w}\right)^{-\frac{1}{2}} \tag{3}$$

$$L_{eff} = \frac{C}{2f_r\sqrt{\varepsilon_{eff}}} \tag{4}$$

$$\Delta_L = 0.412h\frac{\left(\varepsilon_{eff}+0.3\right)\left(\frac{w}{h}+0.264\right)}{\left(\varepsilon_{eff}-0.298\right)\left(\frac{W}{h}+0.8\right)} \tag{5}$$

$$L = L_{eff} - 2\cdot\Delta L \tag{6}$$

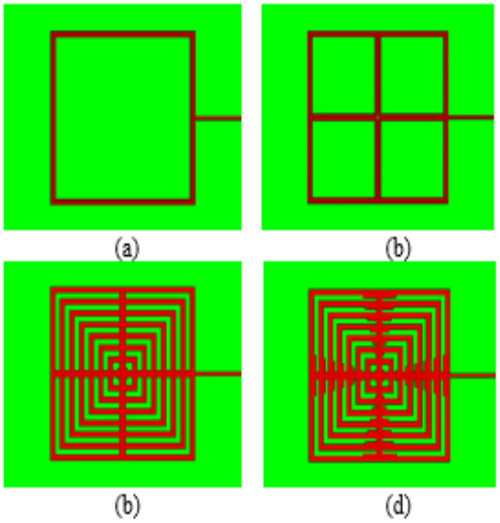
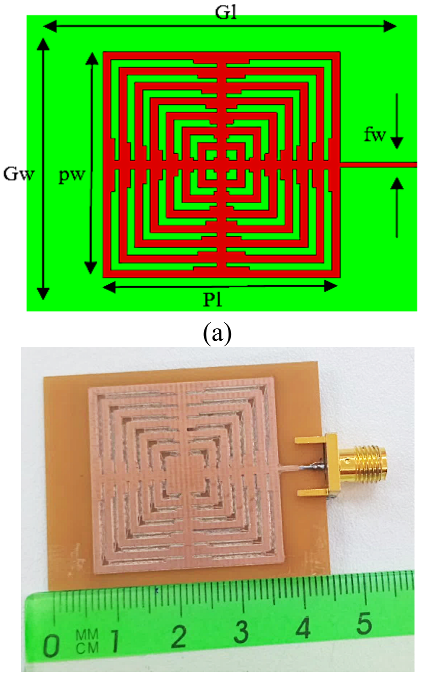

(a) (b) (b) (d)

Fig .1. Evolution iterations of the proposed fabricated rectangular fractal antenna.



(a)

(b)

Fig .2. Evolution proposed antenna structure (a) fabricated antenna prototype (b)

Table 1: Optimized dimensions of designed antenna.

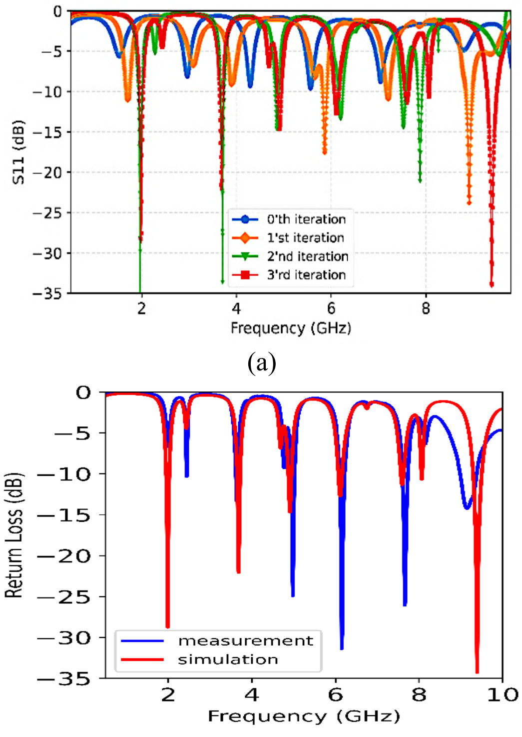
Dimensions	Values(mm)
Gw	50
Gl	40
Pw	30
Pl	30
Fw	0.6

III.RESULTS

All simulations of the proposed design for the antenna were carried out using the High-Frequency Structural Simulation Tool (HFSS), an advanced EM solver. This section examines the simulations of the hexagonal fractal antenna, focusing on several key performance metrics like return loss, VSWR, surface current distribution, gain, and radiation pattern.

A. Return Loss

Return Loss, denoted as S11, is a critical parameter in evaluating antenna performance, representing the ratio of reflected power to incident power at the input port. Optimal antenna operation is typically achieved when S11 values are below -10 dB, indicating minimal power reflection and efficient radiation. Figure 3(a) presents the measured return loss from 1 to 10 GHz, sampled at 0.001 GHz intervals. The antenna resonates at 1.99, 3.68, 4.91, 6.11, 7.60, 8.06, and 9.39 GHz, with return loss values of -28.76, -22.06, -14.66, -12.73, -11.33, -10.67, and -34.30 dB, and corresponding bandwidths of 90, 80, 90, 100, 70, 22, and 210 MHz. This broad coverage highlights its multiband capability. Figure 3(b) compares measured and simulated return loss for the third design iteration.



(a)

(b)

Fig .3. Return loss characteristics during evolution. (a) return loss characteristics comparison of the results obtained through simulation and experimentation of the proposed rectangular fractal antenna (b)

B. VSWR

The ratio representing voltage standing waves (VSWR) ideally should be equal to one, indicating perfect impedance matching for an antenna. Figure 4 showcases the VSWR plot for the proposed rectangular nested fractal antenna. The simulated VSWR values at the resonant frequencies are 1.07, 1.17, 1.45, 1.06, 1.74, 1.82, and 1.03, all of which range between 1 and 2, demonstrating excellent impedance matching.

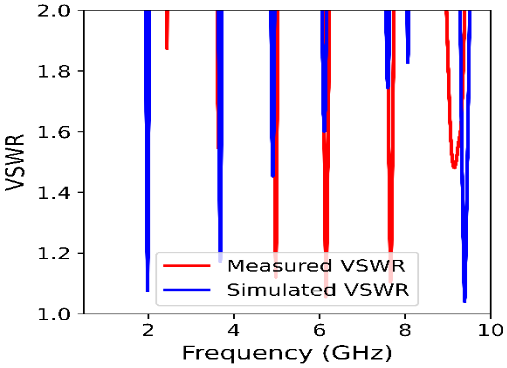


Fig .4. VSWR characteristics of the antenna

The equivalent circuit of the proposed antenna is represented by a sequence of series-parallel RLC elements, as depicted in Figure 5. This circuit effectively models the antenna's resonant behavior, where the radiation resistance (Rr) accounts for the power radiated by the antenna, the reactance (X) represents the stored energy and varies with frequency, and the feed-point impedance (Zin) combines these components to characterize the interaction between the antenna and the feed line. The proposed design employs an inset feed configuration due to its ability to provide excellent impedance matching and minimize spurious radiation. This feeding technique is also cost-effective and simple, making it a practical choice for fabrication. The inset depth and feedline width were initially determined analytically using transmission line theory and further refined through simulation to achieve optimal performance across the resonant frequencies.

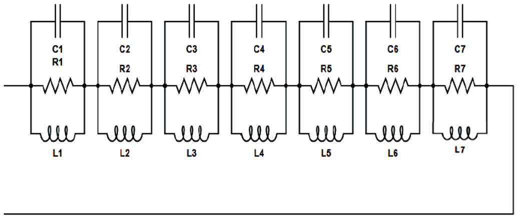


Fig .5. Equivalent circuit of the proposed antenna.

C. Radiation Pattern

Figure 6 illustrates the simulated and measured radiation patterns of an antenna in both the E-plane and H-plane at six frequencies: 1.98 GHz, 3.68 GHz, 4.91 GHz, 6.11 GHz, 7.59 GHz, and 9.39 GHz. The patterns, presented in polar plots, compare the simulated results (solid lines) with the measured results (dotted lines) for the electric field (E-plane) and magnetic field (H-plane) distributions. At lower frequencies, such as 1.98 GHz, the patterns exhibit a more omnidirectional behavior, while at higher frequencies, like 9.39 GHz, the radiation becomes more directional with narrower beamwidths, indicating increased antenna gain. The close alignment between the simulated and measured patterns across all frequencies demonstrates the accuracy of the design, though slight discrepancies may arise due to fabrication imperfections or measurement conditions. This comparison confirms the antenna's effectiveness and its capability for multi-frequency operation.

D. Gain

The proposed antenna demonstrated exceptional gain, achieving a peak total gain of 18.86 dBi. The antenna resonates at frequencies of 1.99 GHz, 3.68 GHz, 4.91 GHz, 6.11 GHz, 7.60 GHz, 8.06 GHz, and 9.39 GHz, with corresponding gain values of 0.88, 2.18, 18.86, 8.89, 13.22, 12.24, and 4.01 dBi, respectively. This impressive performance is depicted in Figure 7, which illustrates the gain scales and provides a visual representation of the antenna's efficiency. Such a high gain not only meets but significantly exceeds the standard requirements, highlighting the antenna's potential for high-performance applications in various fields, including telecommunications, satellite communications, and radar systems. The substantial gain also underscores the antenna's capability to operate effectively over a broad range of frequencies, ensuring robust and reliable signal transmission. Furthermore, the antenna's design incorporates advanced materials and innovative structural features that enhance its overall performance and durability.

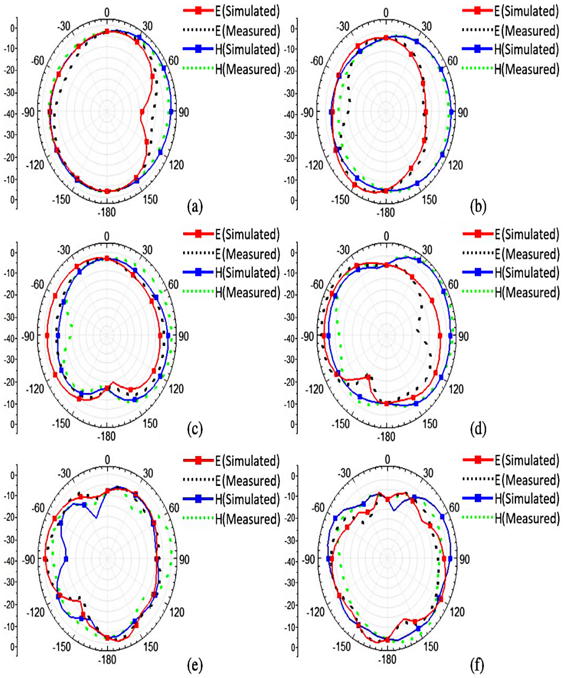
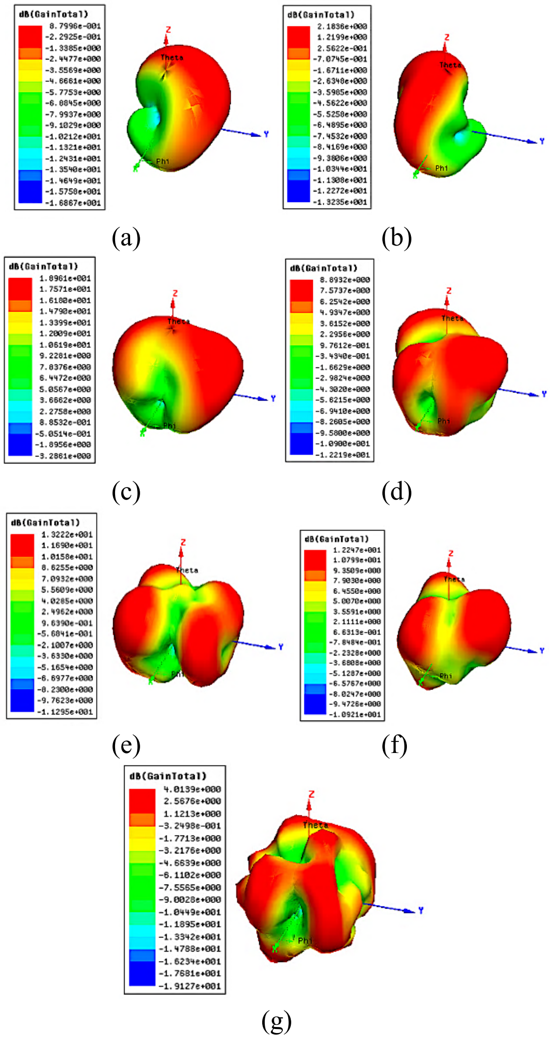


Fig .6. Simulated and measured radiation patterns in both E- and H-planes at: (a) 1.98 GHz, (b) 3.68 GHz, (c) 4.91 GHz, (d) 6.11 GHz, (e) 7.59 GHz, and (f) 9.39 GHz.

E. Current Distribution

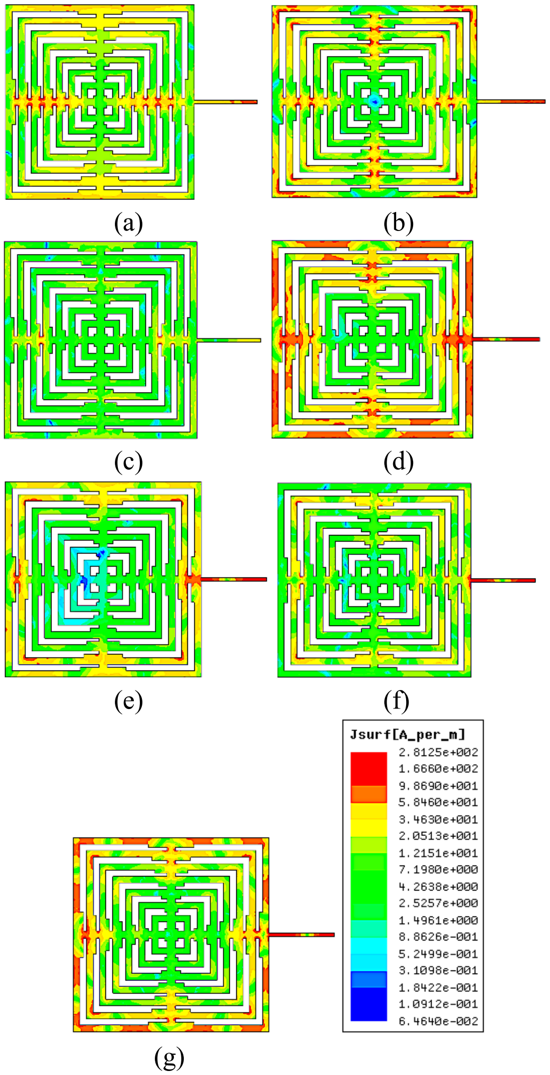
The manner in which current is distributed on the surface provides insight into the current density at various points on the radiating element across different frequencies. Understanding this distribution is crucial for optimizing antenna design and performance. Figure 8 presents the pattern of current flow on the surface plots for each resonant frequency of the proposed antenna. These plots highlight how the current density varies at specific frequencies, offering valuable information on the antenna's operational efficiency and potential areas for further enhancement. By analyzing these distributions, designers can identify regions with high current concentrations and make targeted adjustments to improve the antenna's radiation pattern and bandwidth. Additionally, this analysis aids in minimizing losses and strengthening the overall gain .



(a) (b) (c) (d) (e) (f) (g)

Fig .7. Characteristics of gain of the rectangular fractal antenna when phi=0 deg with phi=90 deg (a) 1.98 GHz (b) 3.68 GHz (c) 4.91 GHz (d) 6.11 GHz (e) 7.59 GHz (f) 8.06 GHz (g) 9.39 GHz

of the antenna, leading to more effective and reliable communication systems. Furthermore, understanding surface current distribution helps in reducing unwanted emissions and interference. This approach also facilitates the development of antennas with better impedance matching, which is critical for achieving maximum power transfer and operational stability across different environmental conditions.



(a) (b) (c) (d) (e) (f) (g)

Fig .8. Current distribution of the rectangular fractal antenna when phi=0 deg with phi=90 deg (a) 1.98 GHz (b) 3.68 GHz (c) 4.91 GHz (d) 6.11 GHz (e) 7.59 GHz (f) 8.06 GHz (e) 9.39 GHz

The proposed antenna excels with its compact size, multiband functionality, and high gain, marking a significant advancement in antenna technology. At 40×50 mm², it is more compact than designs like [6] (74×76 mm²) and [19] (75×47 mm²) while delivering superior performance. It supports seven frequency bands, far surpassing the three bands in [3], [6], and [12], making it versatile for applications such as 5G, IoT, and broadband networks. Its maximum gain of 18.96 dBi outperforms [3] (3.5 dBi), [12] (5.34 dBi), and [19] (14.54 dBi), which is limited to a single band. The use of FR4 as a dielectric ensures cost-effectiveness and scalability, unlike the single-band fabric design in [19]. This antenna sets a new benchmark in combining compactness, multiband capability, high gain, and practicality for advanced wireless communication systems.

The bandwidth (BW) and Voltage Standing Wave Ratio (VSWR) of the proposed antenna with previously reported designs. The proposed antenna offers bandwidths between 22 MHz and 210 MHz, outperforming [3] and [6] in the 70–100 MHz range and supporting both narrowband and broadband applications. While the ultra-wideband antennas in [10] achieve significantly larger bandwidths, they target different use cases. With VSWR values ranging from 1.03 to 1.82, the proposed antenna ensures excellent impedance matching, surpassing [12] and [19] in most bands. Its ability to operate efficiently at multiple frequencies highlights its advantage over single-band designs. Although it does not match the bandwidth of ultra-wideband designs like [10], the proposed antenna's combination of multiband functionality, good bandwidth, and low VSWR makes it highly suitable for modern wireless communication systems. The S11 performance of the proposed antenna with previously reported rectangular antennas in the literature. It highlights the broader range of operating frequencies and the superior multiband capability of the proposed design, which resonates at seven frequencies: -28, -22, -14, -12, -11, -10, and -34 dB. In comparison, references such as [3] and [6] achieve deep return losses (-34 dB and -32 dB, respectively) but with fewer bands. Other references like [10], [12], and [19] demonstrate fewer resonances or less diversity in return loss values.

Table 2: Performance comparison of the proposed antenna with previously reported rectangular antennas

Ref	Size (mm^2)	No. Of freq bands	Max. gain	VSWR	BW(MHz)	S11(dB)	D. mat
[3]	47×39	3	3.5	1.281, 1.596, 1.038	28, 188, 813	-18, -12, -34	Fr4
[6]	74×76	3	--	1.02, 1.29, 1.67	50, 70, 100	-32, -12, -13	Fr4
[10]	36×40	2	6.6	1.33; 1.05	2400, 11400	-30, -20	Fr4
[12]	66×58	3	5.34	1.19, 1.4, 1.5	50, 20, 40	-16, -15, -13	Fr4
[19]	75×47	1	14.54	1.11	170	-28	Fab
Prop	40×50	7	18.96	1.07, 1.17, 1.45, 1.06, 1.74, 1.82, 1.03	90, 80, 90, 100, 70, 22, 210	-28, -22, -14, -12, -11, -10, -34	Fr4

IV. CONCLUSION

This article details the design and construction of a novel rectangular nested fractal antenna with overall size of 40x50 mm². It operates across multiple frequency bands, specifically at 1.98, 3.68, 4.91, 6.11, 7.59, 8.06, and 9.39 GHz, with an impressive peak gain of 18.96 dBi. The simulation results align closely through empirical testing conducted on the fabricated antenna, revealing excellent radiation patterns at the resonant frequencies in both vertical and horizontal planes. Additionally, the VSWR values are maintained at ≤ 2 across these frequencies. Compared to existing rectangular antennas, this proposed design exhibits superior performance with its high gain and multiband functionality, making it suitable for a wide variety of applications.

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