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Research Article

Fractal Geometries in Wireless Communication: A Focus on Sierpinski Carpet Fractal Antennas

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Abstract: This article explores the design and performance of a Sierpinski carpet fractal antenna aimed at achieving a resonant frequency of approximately 2.4 GHz, a critical band for wireless applications like Wi-Fi. The study emphasizes the advantages of fractal geometries in enhancing antenna miniaturization, bandwidth, and gain, making them suitable for modern communication systems. Using COMSOL Multiphysics, the antenna's electromagnetic characteristics were simulated and experimentally validated, focusing on reflection coefficients, radiation patterns, and impedance matching. The simulation revealed strong impedance matching at 2.432 GHz with an S11 reflection coefficient of about -30 dB, indicating minimal power loss. Experimental results closely align with simulations, confirming the design's narrowband operation and nearly spherical radiation pattern, which are suitable for applications such as RFID, Wi-Fi, and certain medical devices.

Keywords: 2.4 GHz, Antenna design, Sierpinski carpet fractal antenna, Wireless communication

Kablosuz İletişimde Fraktal Geometriler: Sierpinski Halı Fraktal Antenlerine Odaklanma

Öz: Bu makale, Wi-Fi gibi kablosuz uygulamalar için kritik bir bant olan yaklaşık 2,4 GHz'lik bir rezonans frekansına ulaşmayı amaçlayan bir Sierpinski halı fraktal anteninin tasarımını ve performansını araştırmaktadır. Çalışma, fraktal geometrilerin anten minyatürizasyonunu, bant genişliğini ve kazancını artırmadaki avantajlarını vurgulayarak onları modern iletişim sistemleri için uygun hale getiriyor. COMSOL Multiphysics kullanılarak antenin elektromanyetik özellikleri simüle edilmiş ve yansıma katsayıları, ışıma örüntüleri ve empedans eşleşmesine odaklanılarak deneysel olarak doğrulanmıştır. Simülasyon, 2,432 GHz'de yaklaşık -30 dB'lik bir S11 yansıma katsayısı ile güçlü empedans eşleşmesi ortaya çıkardı ve bu da minimum güç kaybına işaret ediyor. Deneysel sonuçlar, RFID, Wi-Fi ve bazı tıbbi cihazlar gibi uygulamalar için uygun olan tasarımın dar bant çalışmasını ve neredeyse küresel radyasyon modelini doğrulayan simülasyonlarla yakından uyumludur.

Anahtar Kelimeler: 2.4 GHz, Anten tasarımı, Kablosuz iletişim, Sierpinski halısı fraktal anten

1. Introduction

Fractal geometries have become a crucial design approach across various applications, such as antenna design, frequency selective surfaces (FSS), and electromagnetic interference shielding. Among the notable fractal designs, the Sierpinski carpet fractal has demonstrated significant potential in achieving miniaturization, improved bandwidth, and enhanced gain, making it particularly useful in antenna technology. Various studies have examined the use of fractal structures to meet the increasing demand for compact and efficient devices in modern communication systems.

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For example, nano-carbon-based materials have been widely researched for applications in electromagnetic interference (EMI) shielding and sensing, offering properties similar to traditional materials like copper (Ugale et al., 2016). Moreover, fractal-based unit cells, including those utilizing split ring resonators (SRRs), have demonstrated distinctive electromagnetic properties, producing cloaking effects within specific frequency ranges (Jagtap et al., 2018). These properties make fractal designs ideal for high-performance, compact antennas.

Microstrip patch antennas, commonly used in wireless communication devices, have been simulated using COMSOL Multiphysics, demonstrating improvements in resonant frequency, bandwidth, and reflection coefficients (Gawade & Dahotre, 2021). Furthermore, fractal designs, such as the square fractal metasurface combined with a PIN diode, have been optimized for dual-band operations in both C- and X-bands, enhancing radiation efficiency and phase distribution (Kim et al., 2022). Reflectarray antennas with fractal structures have also been shown to significantly improve gain, with one study reporting an increase from 21.6 dBi to 23.1 dBi through fractal unit cell modifications (Urul, 2022).

Furthermore, artificial neural networks (ANN) have been used to model and predict the resonant frequency of microstrip antennas, delivering precise results over various input parameters (Bayram et al., 2021). Fractal geometries such as the Minkowski shape have been particularly successful in reflectarray designs, offering compactness and improved phase agility without altering the patch size (Costanzo et al., 2016). These features make fractals a valuable tool for optimizing the performance of antennas in various applications.

In acoustic metamaterials, fractal structures like the Hilbert fractal have been found to influence transmission loss behavior, further illustrating the versatility of fractal designs across different domains (Comandini et al., 2023). Additionally, fractals have been explored for use in strain sensors, where geometries like the Sierpinski carpet and Koch curve have proven effective in miniaturizing sensor dimensions and improving sensitivity (Herbko et al., 2022). Other applications of fractal designs include their use in mechanical resonators, where fractal shapes enhance the frequency response and functionalization area, making them suitable for nanoscale devices (Tzanov et al., 2020).

Recent advances in solar absorber technology also leverage fractal tree-shaped metasurfaces to achieve high absorption efficiencies across a broad spectral range, further highlighting the adaptability of fractal designs in optimizing electromagnetic properties (Das et al., 2024). Similarly, fractal-based designs have been shown to enhance the performance of energy storage devices like supercapacitors, increasing the effective electrode area and overall capacitance (Ramesh et al., 2023).

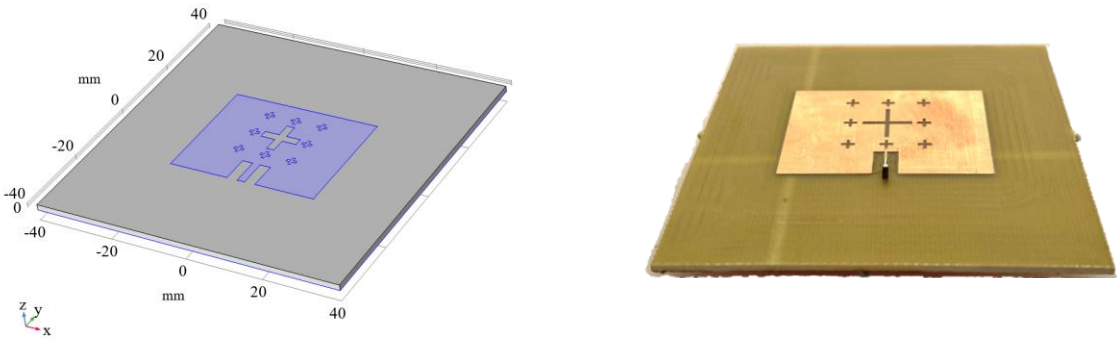
In wireless communication, fractal antennas are integral to next-generation technologies like massive multiple-input multiple-output (MIMO) systems, where their compactness and multi-band capabilities are essential for 5G networks (Palanisamy et al., 2021). Moreover, fractal geometries have been applied in terahertz (THz) antenna designs, where they influence the bandwidth and radiation properties, offering potential for advanced communication systems (Uttley et al., 2023).

This study focuses on designing and analyzing a Sierpinski carpet fractal antenna targeting a resonant frequency of 2.4 GHz, commonly used for Wi-Fi and other wireless applications. COMSOL Multiphysics software was employed for the simulation, emphasizing reflection coefficients, radiation patterns, and impedance matching. Experimental results further validate the design, providing a comprehensive assessment of its performance. By leveraging COMSOL Multiphysics software for simulation, the antenna's performance will be evaluated in terms of reflection coefficients, radiation patterns, and bandwidth (Gawade & Dahotre, 2021).

The results seek to add to the expanding body of research on fractal-based antennas, which have shown great potential in reducing size and enhancing the performance of modern communication systems (Costanzo et al., 2016, Herbko et al., 2022, Das et al., 2024).

2. Material and Methods

The Sierpinski carpet fractal antenna was designed and simulated using COMSOL Multiphysics. The methodology involved modeling the antenna with specific parameters for the patch, substrate, and surrounding air domain. The simulation targeted a frequency of 2.432 GHz, which is within the 2.4 GHz ISM band commonly utilized for wireless communication (Figure 1).



a) b)

Figure 1. Structure of the Sierpinski carpet fractal patch microstrip antenna: a) Simulation model b) Fabricated sample.

To simulate electromagnetic wave propagation and analyze antenna radiation patterns, a three-dimensional model was selected from the Model Wizard using the Electromagnetic Waves, Frequency Domain (emw) physics interface in COMSOL Multiphysics. The simulation was set up to operate in the frequency domain, targeting a frequency of 2.432 GHz, which is standard for the Wi-Fi band and falls within the 2.4 GHz ISM (Industrial, Scientific, and Medical) band, commonly used for various wireless communications.

A set of parameters was defined globally to facilitate the configuration of geometry and material dimensions (Figure 2) efficiently. The parametric sizes of the antenna are listed in Table 1.

Table 1. Antenna size parameters

Parameter	Length (mm)
w	70
l	70
w1	38.37
w2	16.935
w3	2
w4	0.5
l1	28
t1	0.75
t2	0.5
d	1.6

An extra block was created for the patch, positioned on the surface of the substrate. The dimensions of the patch were specified as width (w1), length (l1), and thickness (d).

Subsequently, additional blocks were introduced to represent the impedance matching stub and the 50Ω feed line. The stub was defined with the following parameters: width (w4) and length (l2). Its position was determined relative to the patch.

To model the antenna's electromagnetic behavior, a Perfect Electric Conductor (PEC) boundary condition was applied to the conductive surfaces, and a lumped port simulated the feed point. PML (Perfectly Matched Layer) was used to eliminate boundary reflections, ensuring accurate far-field radiation pattern analysis (Figure 3). This ensures that the antenna’s S-parameter and radiation pattern results reflect its true performance, free from distortions caused by boundary effects.

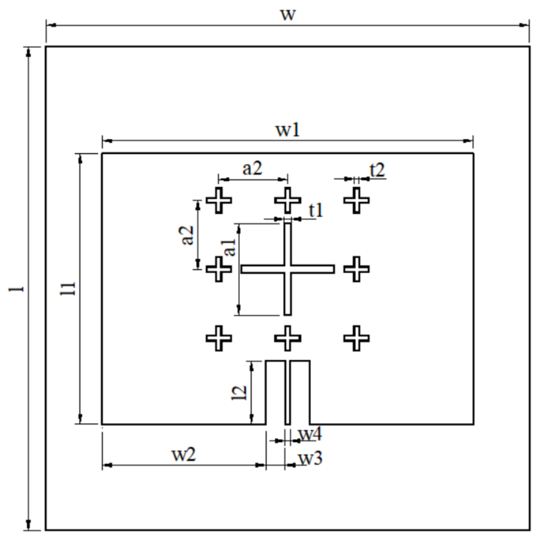


Figure 2. Dimensions of the proposed Sierpinski carpet fractal antenna.

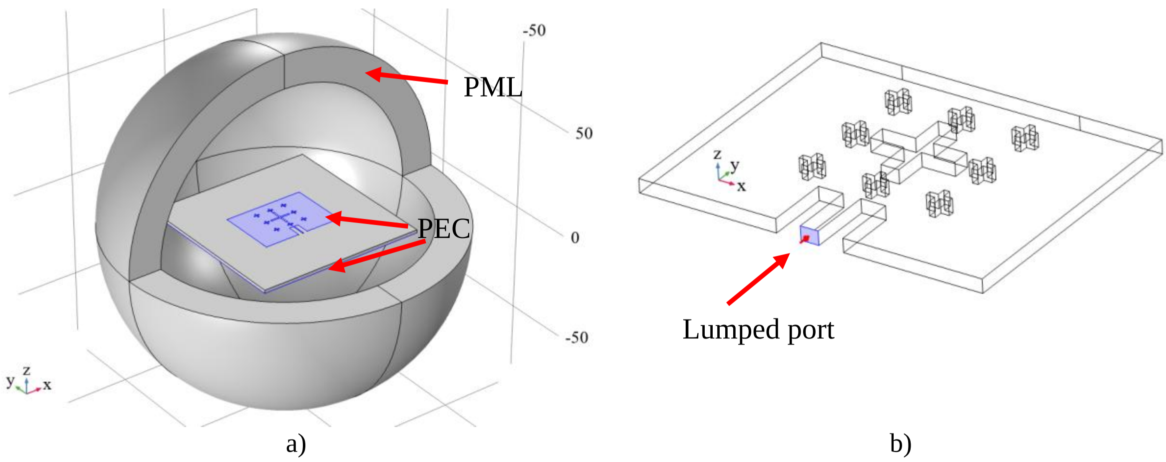


Figure 3. a) 3D view of the finite element model; b) lumped port boundary condition.

The built-in Air material was selected from the material library provided by COMSOL and applied to the spherical domain surrounding the antenna structure, with the objective of simulating the propagation of electromagnetic waves in free space. The substrate material was identified as FR4. A Perfect Electric Conductor (PEC) is defined as a material that allows the unrestricted movement of electric charge without any resistance. The conducting components, including the patch and feed line, were modeled using the PEC condition to represent ideal conductor behavior, thus simplifying the simulation process.

The Electromagnetic Waves, Frequency Domain (emw) physics interface was set up to simulate the antenna's performance, using the following parameters. A lumped port was used to simulate the feed point of the antenna. The wave excitation feature was activated by default, and this port was used for calculating the input impedance and S-parameters during the simulation. A far-field domain condition was applied to calculate the far-field radiation patterns.

A mesh was automatically generated for the entire model using COMSOL's meshing tools. The study configuration was based on a frequency domain analysis, which allowed for the examination of electromagnetic behavior at a specific frequency. The frequency of interest was set at 2.432 GHz.

In the experimental setup, FR4 (Flame Retardant 4) was used as the substrate material, with a relative permittivity (εr) of 4.4 and a thickness of 1.6 mm. FR4 was selected due to its widespread availability, cost-effectiveness, and suitability for high-frequency applications. In the fabricated sample, these components were implemented using copper to replicate the designed structure and validate the simulation results.

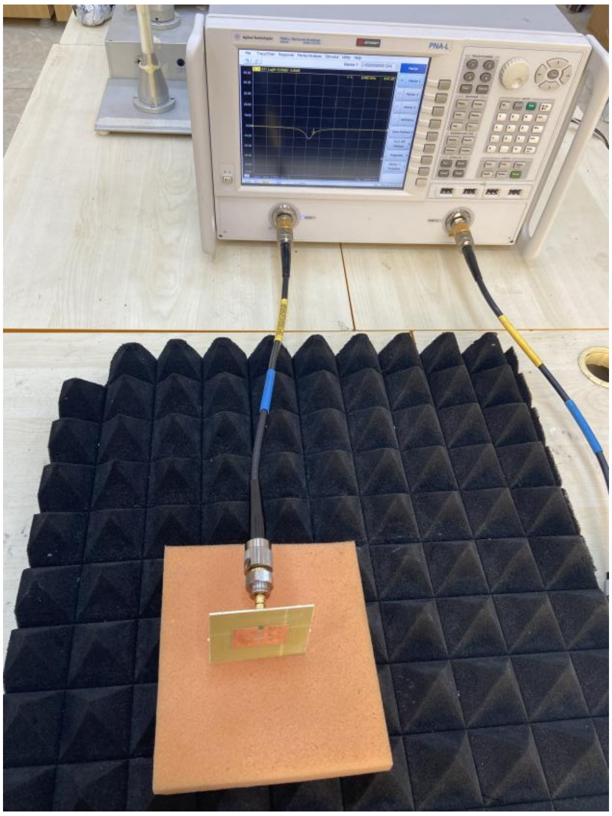


Figure 4. Measurement setup of fabricated sample.

The reflection coefficient S11 of the Sierpinski fractal patch antenna was measured using an Agilent Technologies PNA-L Network Analyzer. The antenna was designed to operate within the 2–3 GHz frequency range. The measurement setup involved placing the antenna on a foam block to minimize unwanted reflections and interference. The device was calibrated prior to the measurement to ensure accuracy, and the S11 parameter was recorded over the designated frequency range to assess the antenna's impedance matching performance (Figure 4).

3. Results

The simulated S-parameter (S11) response of the antenna, as shown in Figure 5, demonstrates a clear resonance at 2.432 GHz, with a minimum reflection coefficient of approximately -30 dB. This indicates strong impedance matching at the target frequency, minimizing reflected power and maximizing power transfer to the antenna. The S11 curve shows a bandwidth (defined by S11 ≤ -10 dB) covering a narrow frequency range centered around 2.432 GHz, suggesting that the antenna is well-suited for narrowband applications operating at this frequency. The distinct dip in S11 at the resonant frequency confirms the design's effectiveness and validates the antenna's expected operating characteristics.

Although the experimental results in the graphs are consistent, they may not exactly match the simulated results due to inherent differences between real-world measurements and idealized simulations. While the experimental data shows internal consistency, it could still be influenced by factors such as measurement system limitations, calibration errors, or environmental influences like temperature or humidity, which aren't fully captured in the simulation. Additionally, the physical device may have slight variations from the model due to manufacturing tolerances, misalignments, or material properties that differ from the idealized assumptions used in the simulation. These differences can lead to variations in S11 values between the experimental and simulated data, even though both sets of results are internally consistent.

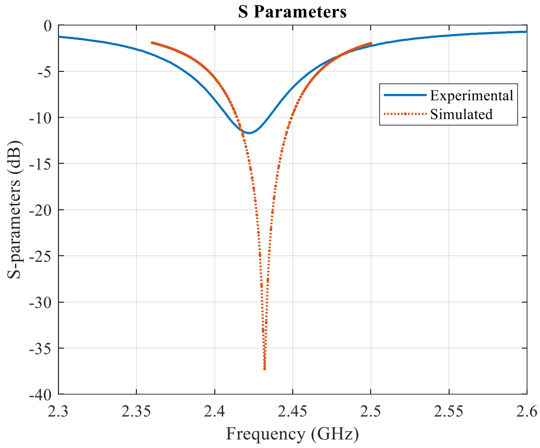


Figure 5. The simulated and experimental S-parameter (S11) response of the Sierpinski carpet fractal antenna.

The simulated far-field gain pattern in dBi, shown in Figure 6, illustrates the antenna's performance across the E-plane and H-plane at 2.432 GHz. The E-plane pattern (solid blue line) displays a bidirectional main lobe structure with a peak gain of approximately -10 dBi at around ±70°, achieving compactness compared to conventional microstrip patch antennas, which typically have higher directivity but larger dimensions. The fractal geometry also offers multi-band capabilities and size reduction benefits, as supported by prior studies, making it suitable for narrowband applications. Optimized for operation at 2.4 GHz, the antenna achieves a nearly spherical radiation pattern, ideal for omnidirectional coverage in applications such as IoT devices, RFID systems, and Wi-Fi access points.

Compared to other fractal designs, such as Minkowski or Koch, the Sierpinski Carpet geometry provides a unique balance of compactness and performance, contributing to advancements in fractal-based antenna design. Its uniform power distribution supports reliable connectivity regardless of the receiver's orientation or placement.

In contrast, the H-plane pattern (dashed green line) shows a more consistent gain distribution, with a broader lobe and peak values near -12 dBi. These patterns indicate that the antenna radiates more effectively in certain directions within the E-plane, while the H-plane exhibits a relatively uniform gain distribution. This result suggests that the antenna's design could be optimized for applications that benefit from bidirectional coverage in the E-plane. Further design adjustments could enhance the gain and directivity to improve performance for specific directional requirements.

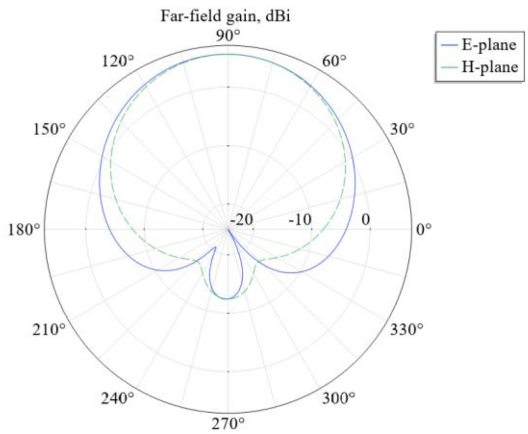


Figure 6. Simulated far-field gain pattern in dBi of the Sierpinski carpet fractal antenna.

The simulated far-field radiation pattern of the antenna at 2.432 GHz, shown in Figure 7, exhibits a nearly spherical distribution with a peak electric field intensity of approximately 1.48 V/m. The pattern indicates an omnidirectional radiation characteristic, with a gradual decrease in intensity from the top (red) to the bottom (blue) regions. This suggests a relatively uniform power distribution across the upper hemisphere, which is desirable for applications requiring broad coverage in multiple directions. However, the results also suggest potential for further design adjustments to improve directivity, depending on specific application requirements. The uniformity in the radiation pattern confirms that the antenna achieves its intended frequency response, validating both the design and simulation approach.

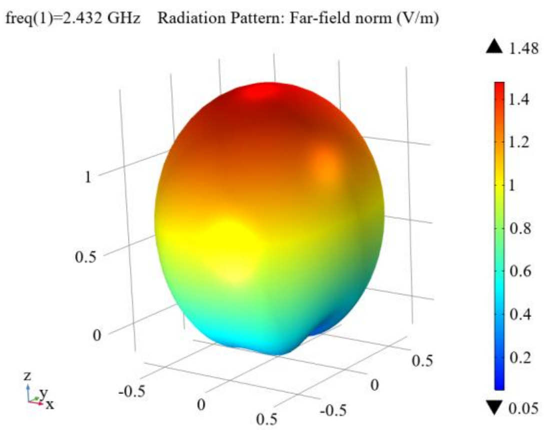


Figure 7. Simulated far-field radiation pattern of the Sierpinski carpet fractal antenna.

Figure 8 illustrates the current density distribution on the Sierpinski fractal antenna at the operating frequency of 2.432 GHz. The results reveal a significant concentration of surface currents in the central regions of the patch and feedline, confirming the effective resonance of the fractal structure. This distribution demonstrates how the fractal design optimally guides the current flow, facilitating efficient electromagnetic radiation and ensuring proper impedance matching. The analysis further supports the hypothesis that the fractal geometry contributes to the antenna's broadband characteristics and enhanced performance at high frequencies.

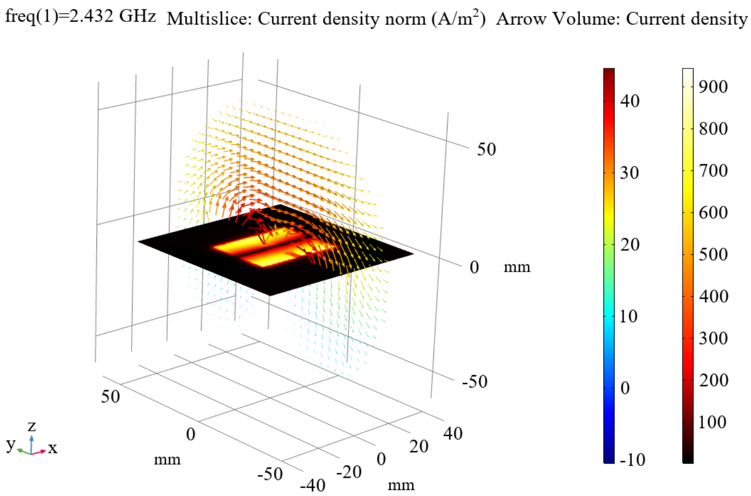


Figure 8. Current density distribution on the Sierpinski fractal antenna at the operating frequency of 2.432 GHz.

4. Conclusion

The principal objective of this study is to fabricate a high-gain directional antenna comprising square and rectangular patches at a frequency of 2.45 GHz. Theoretical studies and practical applications indicate that the antenna is optimized at 2.45 GHz, with a gain of -15 dBm achieved in both cases. Furthermore, a high-gain region of use was identified at angles greater than 180° with respect to the antenna surface. In future studies, the number of rectangular patches can be increased to enable operation at different frequencies.

In conclusion, the simulated results indicate that the designed antenna performs efficiently at 2.432 GHz, exhibiting a well-matched impedance with an S11 value of -30 dB, a nearly spherical radiation pattern, and a gain pattern ideal for applications that demand broad coverage in the E-plane. The narrowband characteristic, as indicated by the S11 response, makes this antenna ideal for applications that require minimal interference and operate within a restricted frequency range, such as IoT devices, RFID systems, Wi-Fi communication, and certain medical devices. These findings validate the design's suitability for targeted narrowband applications, confirming its potential for efficient and reliable performance in these domains.

Future work could explore higher iteration levels of the fractal geometry to further enhance gain and bandwidth. Introducing multilayer configurations or tuning the substrate material and patch dimensions could support multiband operation, making the design adaptable for emerging technologies like 5G or advanced IoT applications.

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