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Design and Performance Evaluation of Four Port Fractal MIMO Antenna with Band Notch Characteristics

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Abstract:- For multiband applications with band notched features, a small 2 × 2 antenna array combining metamaterial Split Ring Resonators (SRRs) and second order Koch Snowflake fractal elements is created. Multiple frequency bands are supported and size is reduced by the fractal design. Fractal defects in the ground plane produce band notches at 2.4 GHz, 5.5 GHz, and 8.8 GHz, which lessen WLAN and X band interference. Gain and bandwidth are increased by SRRs positioned around the patches. For simple integration, the antenna uses a microstrip feed on a FR4 substrate. The radiation pattern, gain, and reflection coefficient of the measured and simulated results are in good agreement. It is perfect for MIMO systems because of its low Envelope Correlation Coefficient (0.02–0.05), which guarantees low mutual coupling and good spatial diversity. This small, multiband antenna is appropriate for wireless systems of the future.

Keywords: *Band Notch Characteristics, Koch Fractal Antenna, Metamaterial Integration*

1. Introduction

As the need for small, multiband, and wideband antennas to support a range of wireless systems (such as satellite communications, WLAN/WiMAX, MIMO, and UWB) grows, so does research interest in fractal and metamaterial based antenna designs. Fractal geometries, such as the Koch snowflake, Sierpinski gasket, and Hilbert curves, allow for size reduction without compromising performance by providing increased electrical length in a constrained physical

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footprint [1]–[5]. They also allow multiband operation through self similar structures, as demonstrated in Koch and Sierpinski based monopoles [6]–[8].

Fractal antennas have been shown to provide significant advantages in spatial diversity, mutual coupling reduction, and Envelope Correlation Coefficient (ECC) improvement when incorporated into MIMO systems [9]–[11]. In [12]–[14], a hybrid fractal geometry with dual and multiband MIMO properties is suggested for use in LTE/UMTS. In [15]–[18], antennas with fractal slots and defective structures that can improve bandwidth and reject bands are developed.

Ultra wideband antennas with integrated band notching capabilities have been effectively implemented using fractal slot structures, which reduce interference from Bluetooth, WLAN, X band, and WiMAX sources [19]–[22]. Band rejection properties, gain, and bandwidth are all enhanced by split ring resonators (SRRs) [23]–[25]. In [26]–[28], fractal elements are embedded into SRRs to create small and portable MIMO antennas.

In order to achieve low ECC, band notched behavior, and multiband operation, the current work focuses on designing and implementing a 2×2 Koch fractal antenna array that incorporates SRR metamaterials and fractal defects in the ground plane. This design minimizes interference from WLAN, WiMAX, and X band systems by achieving notch bands at 2.4 GHz, 5.5 GHz, and 8.8 GHz, building on the advantages of fractal MIMO configurations [12], [14]. The antenna was equipped with microstrip lines and constructed on a FR4 substrate. The antenna's suitability for MIMO, UWB, cognitive radio, and satellite communications was confirmed by the strong correlation between simulation and VNA measurements.

2. Objectives

The primary objective of this work is to develop a compact 2×2 antenna array that not only supports multiband wireless operation but also effectively suppresses interference from specific frequency bands. By utilizing Koch fractal geometries in the radiating elements and integrating metamaterial Split Ring Resonators (SRRs), the design aims to achieve enhanced electrical length within a small footprint, allowing for efficient size reduction without compromising performance. The introduction of band-notched features at 2.4 GHz, 5.5 GHz, and 8.8 GHz serves to eliminate unwanted signals from WLAN, WiMAX, and X-band sources, ensuring reliable operation even in environments prone to electromagnetic interference.

A secondary objective is to validate the suitability of the proposed antenna for use in advanced wireless systems, particularly those based on MIMO technology. This involves achieving a low Envelope Correlation Coefficient (ECC), which is essential for minimizing mutual coupling and maximizing spatial diversity among array elements. The antenna is also designed to demonstrate consistent gain, stable radiation patterns, and strong impedance matching across its intended frequency ranges. Through simulation and experimental testing, the work aims to

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confirm that this antenna meets the criteria for modern applications such as UWB, cognitive radio, satellite communication, and next-generation multi-antenna systems.

3. Methods

The distinctive star shaped geometry of the antenna's central radiating element is a result of the Koch Snowflake fractal design. This form develops over time by altering a base polygon repeatedly, getting more intricate at each stage. The patch extends the electrical path without actually enlarging the antenna thanks to the many outward projections along its edges. This method ensures efficient resonance at lower frequency bands while promoting miniaturization. Additionally, the fractal properties improve impedance matching and facilitate multiband operation by improving the surface current distribution.

A second order Koch fractal patch (N = 2) is shown in Figure 1. The structure is initially a straightforward polygon, most likely a hexagon (N = 0). To increase the perimeter and complexity, triangular segments are added along each edge in the first iteration (N = 1). By adding smaller triangular features, the second iteration (N = 2) further subdivides these edges, creating the appearance of a snowflake. Stable surface current flow and balanced radiation behavior are encouraged by this symmetrical design. For small wideband antennas, the second order configuration provides a fair balance between increased bandwidth, small size, and manufacturing feasibility.

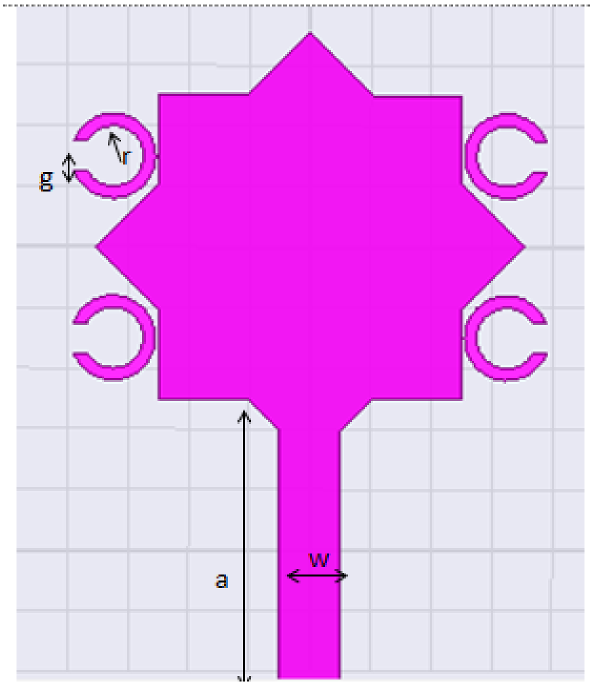

Figure 1 The proposed MIMO antenna's unit cell

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The design shown in Figure 2 includes a 2 × 2 array of identical Koch fractal antennas, with the second order star shape preserved and Split Ring Resonator (SRR) metamaterials positioned as parasitic structures around the edges of each element. These components are arranged in a symmetrical grid to produce a consistent radiation pattern. Carefully adjusting the spacing between elements to reduce mutual coupling improves gain, bandwidth, and overall array performance. The antenna array is made from FR4 epoxy, a cheap material commonly used in RF and microwave circuits. With a relative permittivity (εr) of 4, it provides structural support and affects the electromagnetic behavior of the antenna.4. A microstrip line feed, a planar and effective method that works well for integrating with other RF components, is used to excite the radiating elements. Reliable RF power delivery and low profile implementation are guaranteed by this feeding technique.

The antenna's rear view, which incorporates specially created fractal defect structures into the ground plane, is depicted in Figure 3. By introducing band notches, these fractal defects effectively suppress undesirable frequency bands and enhance the antenna's selectivity. These defects' thoughtful positioning and form preserve overall radiation performance while promoting effective band rejection behavior. The manufactured 2 × 2 Koch fractal band notch antenna array is depicted in Figure 4, and Table 1 lists the antenna's design parameters.

Table 1 Antenna Specifications

Parameter	**Description**	**Value**
len	Substrate length	50 mm
wid	Substrate width	50 mm
a	Feed line length	9 mm
b	Horizontal spacing between antenna elements	5 mm
g	Metamaterial gap width	1 mm
r	Outer ring radius of metamaterial structure	1.4 mm
w	Feed line width	2 mm

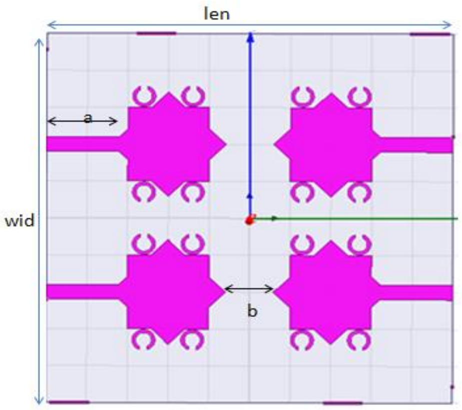

Figure 2 Four Port quad band antenna – front view

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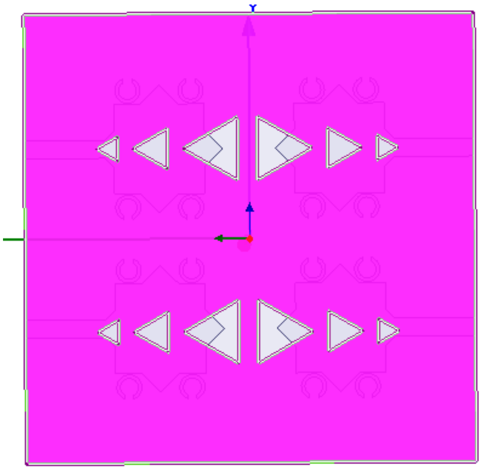

Figure 3 Four Port quad band antenna – Rear view

Figure 4a Fabricated Protoype – front view

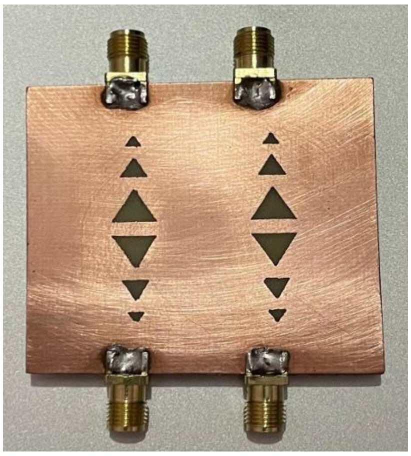

Figure 4b Fabricated Protoype – Rear view

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4. Results

The proposed antenna was built on a FR4 substrate and tested experimentally using a Vector Network Analyzer (VNA) to confirm its functionality. The properties of the simulated and measured reflection coefficients (S_{11}) are displayed in Figure. 5. The simulation results show different band notched responses at 2.4 GHz, 5.5 GHz, and 8.8 GHz. These notches are successfully replicated by the measured results, demonstrating a high level of agreement between simulation and practical use.

The antenna's selectivity and overall system performance are improved by the observed notched bands, which correlate to the suppression of particular interfering frequency ranges. The 2.4 GHz notch specifically targets WLAN (Wi-Fi) interference, the 5.5 GHz notch covers both WLAN and some lower UWB channels, and the 8.8 GHz notch handles possible X band application interference. The efficacy of the fractal defect integration in the ground plane and the validity of the design methodology are confirmed by the consistency of these notched bands between the simulated and measured results.

The suggested antenna is a good fit for contemporary wireless communication systems because of its wideband properties and strong band rejection capabilities. Applications where multi band operation and interference mitigation are essential include wearable or compact RF front end modules, cognitive radio, UWB communication, and MIMO systems. Its potential for incorporation into next generation, small, high performance wireless devices is further highlighted by the verified performance.

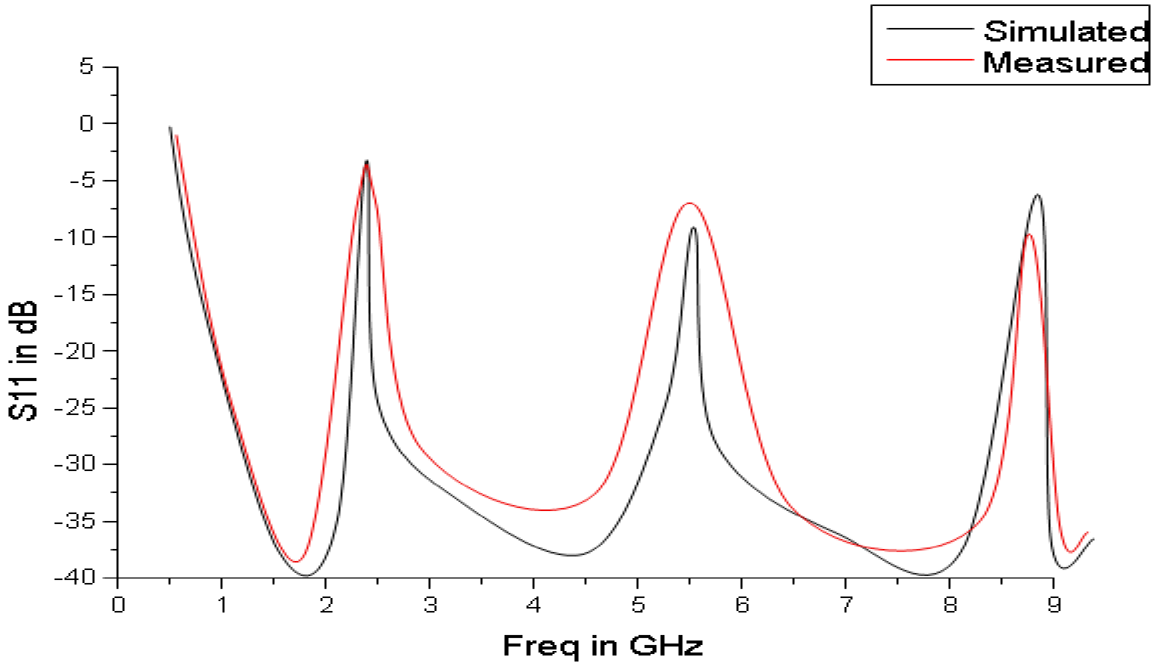

Figure 5 Simulated and Measured return loss plots of Four port band notch antenna

Figure 6 presents the Voltage Standing Wave Ratio (VSWR) versus frequency for both simulated and measured results. Both the simulated (black line) and measured (red line) curves exhibit sharp peaks at approximately 2.4 GHz, 5.5 GHz, and 8.8 GHz, indicating high VSWR values at these notched frequencies. This pattern aligns with the intended band notched behavior, effectively rejecting signals at these frequencies. Across other bands, VSWR remains low, confirming good impedance matching and efficient operation at the desired frequencies.

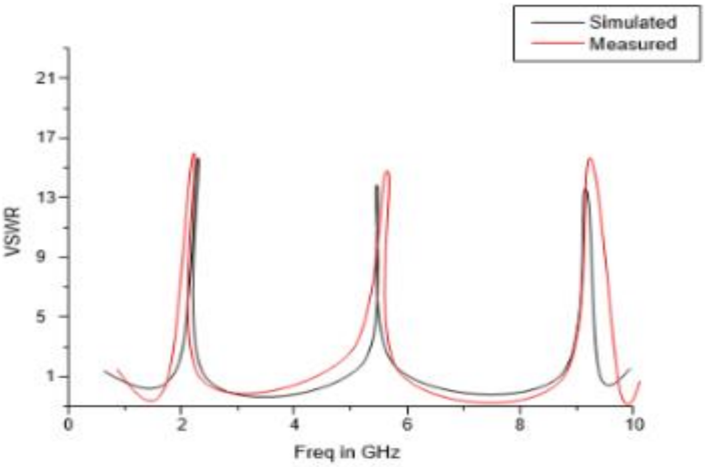

Figure 6 VSWR Plot

The reduction in gain at 5.5 GHz (Figure 7) corresponds to the presence of a band notch introduced intentionally into the design. The notched band effectively suppresses radiation at this frequency to minimize interference from WLAN signals, resulting in very low radiated power and gain.

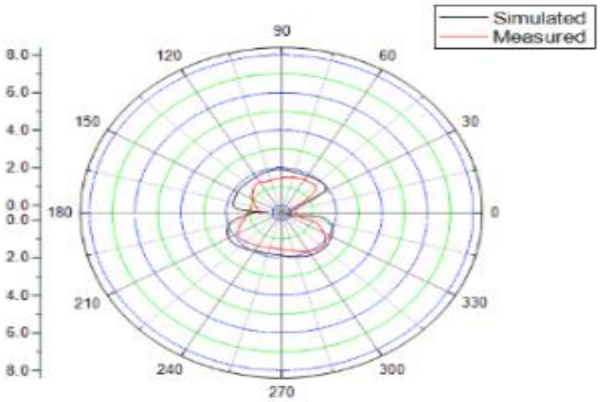

Figure 7 Simulated and Measured Radiation Pattern at 5.5 GHz

At 2 GHz, the antenna operates in the passband region, where it is designed for efficient radiation. The high gain (Figure 8) demonstrates strong and effective performance at this frequency, consistent with typical passband operation in wideband antennas.

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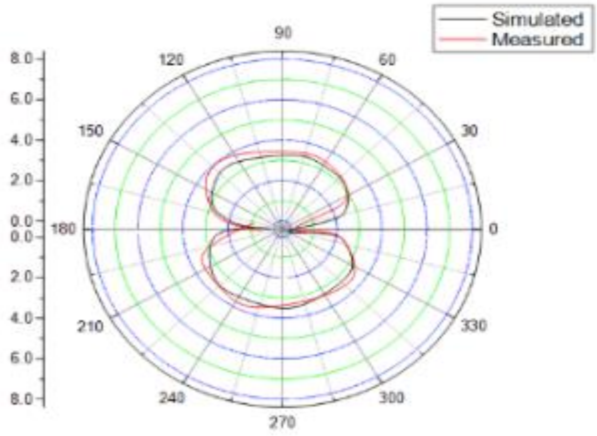

Figure 8 Simulated and Measured Radiation Pattern at 2 GHz

At the notched frequency (5.5 GHz), the antenna exhibits a strong reduction in gain (2–2.5 dBi), confirming successful suppression of unwanted signals. In contrast, at the passband frequency (2 GHz), the gain is maximized (6–7 dBi), reflecting effective transmission and reception. This quantitative difference between the two patterns directly verifies the antenna's selective band notched functionality.

A very low degree of correlation between the antenna ports is indicated by the obtained Envelope Correlation Coefficient (ECC), which ranges from 0.02 to 0.05 as shown in Figure. 9. Strong isolation between elements and little overlap in their radiation patterns are indicated by such low ECC values, which are very advantageous for MIMO systems. This improves the antenna array's overall multiplexing capabilities and guarantees efficient spatial diversity.

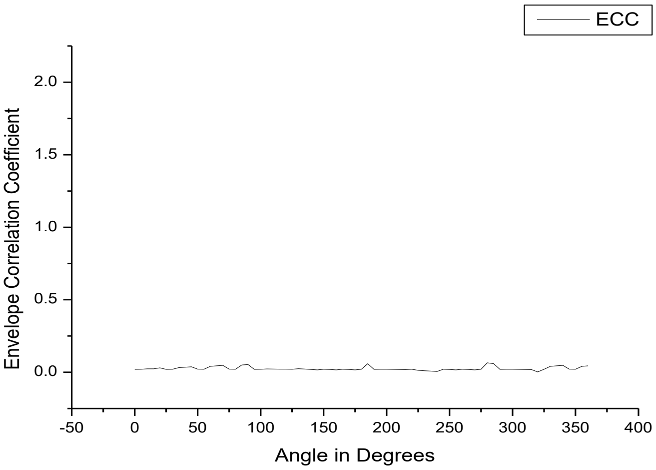

Figure 9 The proposed 2 x 2 Koch Fractal Antenna array's envelope correlation coefficient

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5. Discussion

Table 2 Comparison of the Proposed Antenna with Previous Designs

Ref.	**Antenna Type**	**Size (mm²)**	**Frequency Bands (GHz)**	**Notch Bands (GHz)**	**Substrate**	**ECC**	**Peak Gain (dBi)**	**Application**
[6]	Koch Fractal Monopole	40×40	2.5–10.5	None	FR4	–	4.2	UWB
[12]	UWB MIMO with Notch	45×45	3.1–10.6	5.2, 5.8	FR4	0.05	5.0	UWB, WLAN
[14]	Slot based Miniaturized MIMO	30×30	2.4–8.5	5.2	Rogers RT/Duroid	0.03	4.5	LTE, WLAN
[15]	Fractal Slot Antenna	50×50	3.1–12	5.8, 8.5	FR4	0.06	4.7	UWB, WiMAX
[18]	Modified Sierpinski UWB	55×50	3.1–11	5.5	FR4	0.07	5.2	Handheld UWB
[20]	Hilbert Fractal MIMO	35×35	2.4, 5.5, 6.5	None	FR4	0.04	4.8	5G Mobile
[24]	SRR based Band Notch Antenna	48×48	3.1–10.6	5.5, 8.2	Rogers RO4003	0.03	6.0	UWB, Radar
[26]	Tri band Notch Fractal Antenna	50×50	3.1–10.6	3.5, 5.5, 8.5	FR4	0.05	4.9	UWB, Cognitive Radio
[28]	Self Similar Multiband Antenna	60×60	2.2, 5.8, 9.2	None	FR4	0.06	5.1	Multiband Wireless
This Work	2×2 Koch Fractal Array + SRR	50×50	2.4, 5.5, 8.8	2.4, 5.5, 8.8	FR4	0.02 – 0.05	6.2	UWB, WLAN, X-band, MIMO

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The proposed antenna offers several advantages over existing designs. Its compact size of 50×50 mm² is competitive, matching or improving upon other fractal and metamaterial based antennas while maintaining efficient multiband operation. Unlike many previous works, the antenna integrates a 2×2 Koch fractal array combined with Split Ring Resonator (SRR) metamaterials, enabling simultaneous multiband performance and precise band notched characteristics at 2.4, 5.5, and 8.8 GHz. This targeted notch design effectively suppresses interference from common sources such as WLAN and X band, which some referenced antennas lack or address only partially.

The antenna achieves a notably low Envelope Correlation Coefficient (ECC) between 0.02 and 0.05, which indicates superior MIMO performance through reduced mutual coupling and enhanced spatial diversity compared to the ECC values reported in other studies. Additionally, the antenna provides a higher peak gain of 6.2 dBi, surpassing many referenced antennas and supporting strong signal transmission and reception in its operational bands.

Constructed on the widely used FR4 substrate with a microstrip feed, the design ensures ease of fabrication and integration for practical applications. Overall, this antenna's combination of compact size, broad multiband coverage, effective band notching, low ECC, and high gain makes it well suited for advanced wireless communication systems, including UWB, WLAN, X band, and MIMO configurations.

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