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Design And Performance Analysis of a Hybrid BΩ-Indexing Fractal Slotted Multiband Antenna for Wireless Sensor Applications

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Abstract: "This research presents the design, fabrication, and performance evaluation of a hybrid βΩ-indexing fractal slotted multiband antenna tailored for wireless sensor and communication applications. The antenna, developed on an FR4 substrate with compact dimensions of 39.05mm × 32.25mm × 1.6mm, demonstrates resonance at five narrow bands: 1.91 GHz, 3.12 GHz, 5.56 GHz, 10.75 GHz, and 13.94 GHz." Its compatibility with PCS, rail mobile radio, WCDMA, X-band, and Ku-band systems establishes it as a versatile candidate for next-generation communication systems. Through hybrid fractal geometry integration, ground length optimization, and inset-fed design, the antenna exhibits improved gain, directivity, and impedance matching.

Keywords: Hybrid βΩ-Indexing, Antenna, Wireless Sensor.

1. Introduction

Microstrip patch antennas have emerged as critical enablers in compact wireless systems due to their planar structure, lightweight, and ease of integration. Conventional patch designs, while effective, often face challenges in achieving multi-band and wideband performance. The exploration of fractal geometries—owing to their self-similarity and space-filling properties—has enabled substantial improvements in antenna miniaturization, bandwidth enhancement, and multiband characteristics (Singh & Kaur, 2017). The proposed work introduces a "hybrid Ind-Indexing Fractal Slot Design for Multiband Wireless Sensor applications." Unlike traditional antennas using single fractal shapes, it integrates the approach and overs, which produces better performance in several narrow frequency bands. The aim of the antenna is to provide strong connectivity for mobile communication, satellite links and radar-based applications (Figure 1).

2. Literature Review

The growth of microstrip patch antenna has been largely studied in various wireless communication systems due to their compactness, low profile, and gratuity. Traditional rectangular, spherical, triangular, and ring -shaped patches are widely adopted; However, their limited bandwidth and benefits require further discovery in advanced geometric and feeding mechanisms (Balanis, 2009; Kasabagordar, 2021). To address these issues, slot-based designs have been examined. For example, Elrahman et al., (2019) developed an L-slander antenna for compactness and circular polarization for satellite applications (Similarly, Thakur et al. 2021).

Fractal geometry has gained prominence in the last two decades due to its self-respect and space-filled properties, which enable both small and multiband operations. Preliminary functions, such as Cohen and Hohald (1996) and Puunt et al. (1998), highlighted the ability of fructal loops and cierpinsky gasket for efficient multiband performance. Subsequent studies were employed in Minkovsky, coaches, Sierpinski carpets, and Hilbert Curvs (Punte et al., 1998; Singh & Kaur, 2017), "which demonstrates improvement in bandwidth and resonance tuning. In particular, the Hilbert Curve Slots were shown to get four times in the 2.4 GHz (Shehni et al., 2012) to achieve until the bandwidth growth".

Comparative studies suggest that fractal-shaped antenna performs better than traditional patch designs in multiband behavior and reduction in size. Sharma and Sharma (2018) proposed a hybrid coach-Minkowski slot for widband applications, while Singh and Kaur (2017) reviewed the fractal antennas and confirmed their better

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radiation stability and efficiency in many bands. These findings outline the benefits of fructal-based small techniques, although challenges remain in structural complexity and measurement deviations on high frequencies.

Overall, literature establishes that hybrid fructal slot techniques provide a promising approach to compact, high-profit and multiband antenna. While many studies depend on single fructal geometry, limited research has detected hybrid space-filing approaches such as β and VIRS curves (Shehni et al., 2012; Viaum, 2002). This difference novels the need for the need for novel hybrid fructal antenna designs, which is capable of covering a wide resonance range to ensure better impedance matching, radiation efficiency and prevention in KU-band communication systems..

3. Materials And Methodology

3.1 Basic Geometry

The antenna is designed using β and ract fractal curves obtained from U-shaped segments. Interation hybrid fructal patterns are made by combining these space-filled geometrics, resulting in the electrical length within the compact dimensions (Viaram, 2002). Figure 1 shows fundamental β and of fructal curves.

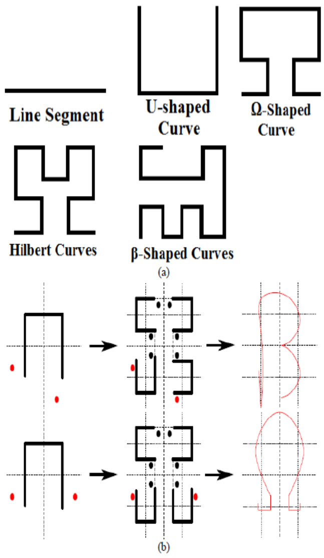

Figure 1. Fundamental fractal curves: (a) U-shape and Ω-shape generation; (b) β-shape generation from U-shape.

3.2 Iterative Design Development

The design evolved through five iterations, starting from a conventional rectangular patch (Iteration 0) to a fully slotted βΩ hybrid fractal structure (Iteration 5). Progressive iterations revealed increased resonance stability, with the final design achieving five resonance frequencies with narrow bandwidths (Figure 2).

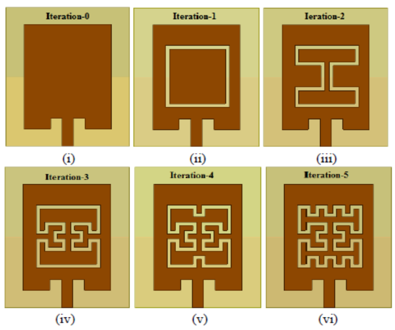

Figure 2. Iterative design development of βΩ fractal antenna (Iteration 0 to Iteration 5).

3.3 Ground Length Optimization

The ground plane length was reduced by 50%, from 39.05mm to 19.525mm. This modification significantly enhanced gain and directivity, improving radiation efficiency from 2.67% to 57.23% (Varshney et al., 2023). The effect of this optimization is shown in Figure 3.

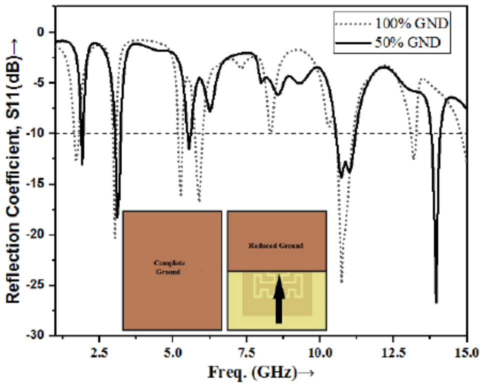

Figure 3. Effect of ground length variation on reflection coefficient (S11).

3.4 Feeding Technique

Inset feeding was adopted for improved impedance matching compared to edge feeding. At 3.1 GHz, the inset-fed antenna achieved an input impedance of “(50.69 – j4.50) Ω, closely matching the 50Ω port (Figure 4).”

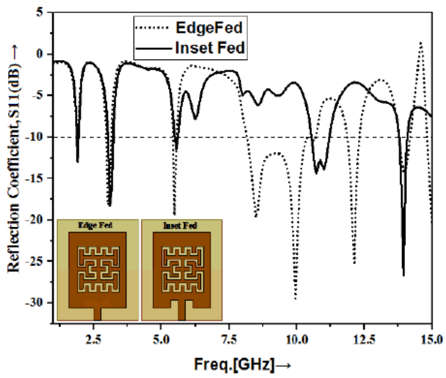

Figure 4. Comparison of edge feed and inset feed reflection coefficients.

3.5. Fabrication and Experimental Setup

The antenna prototype was fabricated using photolithography and chemical etching. Measurements were conducted using an Agilent N5247A Vector Network Analyzer (VNA) and an anechoic chamber for radiation testing. The fabricated design closely aligned with simulation results, with minor discrepancies attributed to connector limitations and soldering inaccuracies (Figure 5).

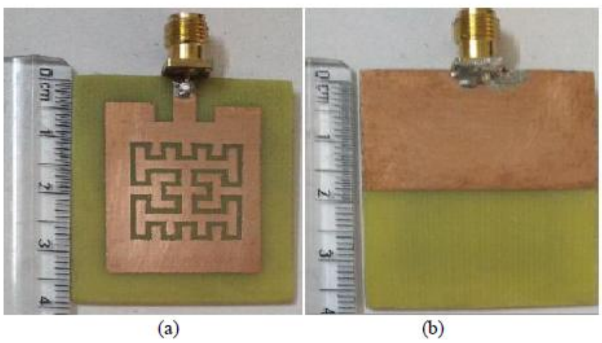

Figure 5. Fabricated prototype of the hybrid βΩ antenna (top (a) and bottom(b) views).

4. "Results And Discussion:"

"The hybrid βΩ fractal antenna" demonstrated strong performance across multiple operating bands, with both simulated and measured data showing good agreement. The reflection coefficient (S11) results confirmed five clear resonant frequencies at 1.91, 3.12, 5.56, 10.75, and 13.94 GHz (Figure 6). These responses validate the antenna's suitability for GSM, WCDMA, WLAN, radar, and satellite communication systems. Radiation pattern analysis revealed stable behavior, with the E-plane showing figure-of-eight characteristics and the H-plane maintaining near-omnidirectional coverage (Figure 7). Such stability ensures reliable signal reception and transmission in practical environments. The gain performance was particularly notable, achieving up to 21.1 dBi at 10.75 GHz, supported by ground plane optimization (Figure 8). The overall efficiency improved substantially, reaching over 57% compared to earlier iterations. Collectively, these results highlight the benefits of the βΩ hybrid geometry, inset feeding, and ground length reduction. Although minor deviations occurred in the measured higher bands, mainly due to fabrication and connector limitations, the antenna consistently delivered compact, high-gain, and multiband characteristics, outperforming many conventional fractal counterparts. The proposed hybrid βΩ fractal antenna holds significant potential for a wide range of wireless technologies. Its multiband operation makes it suitable for GSM and WCDMA systems (1.91–3.12 GHz), WiMAX and WLAN (5.56 GHz), radar and maritime communication (10.75 GHz), and satellite and aerospace communication (13.94 GHz). The compact size, high gain, and stable radiation patterns also ensure adaptability for integration into portable devices, wireless sensor networks, and IoT-based systems where low-profile and reliable antennas are crucial. In addition to these present-day applications, the design provides promising opportunities for future wireless innovations. Incorporating reconfigurable elements such as PIN or varactor diodes could enable dynamic tuning for cognitive radio and adaptive communication platforms. Similarly, adding metamaterial superstrates or Electromagnetic Bandgap (EBG) structures may further improve bandwidth and gain characteristics. Finally, future work can also explore flexible and biocompatible substrates, allowing for wearable and biomedical sensor applications. These directions highlight the versatility of the βΩ fractal approach in shaping next-generation wireless communication systems.

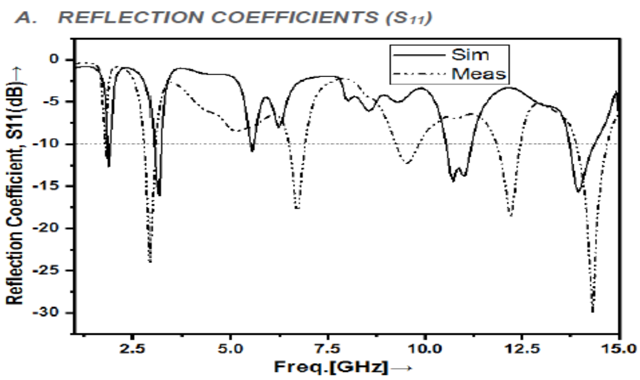

Figure 6. Simulated vs. measured S11 reflection coefficient curves.

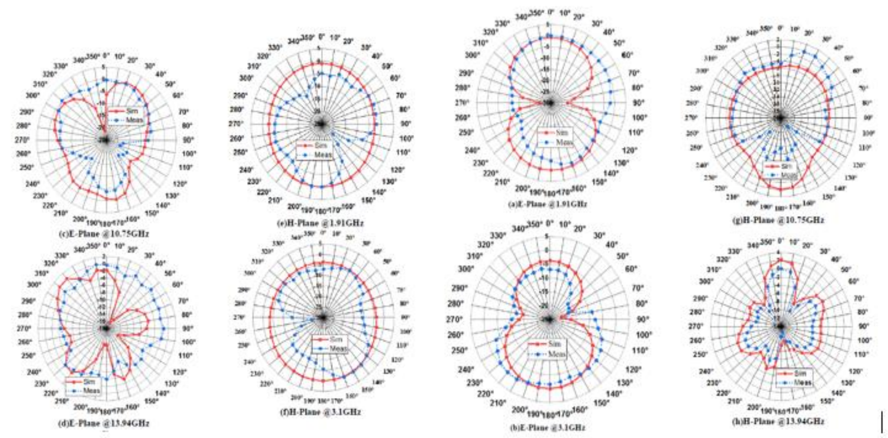

Figure 7. Measured E-plane and H-plane radiation patterns at resonance frequencies.

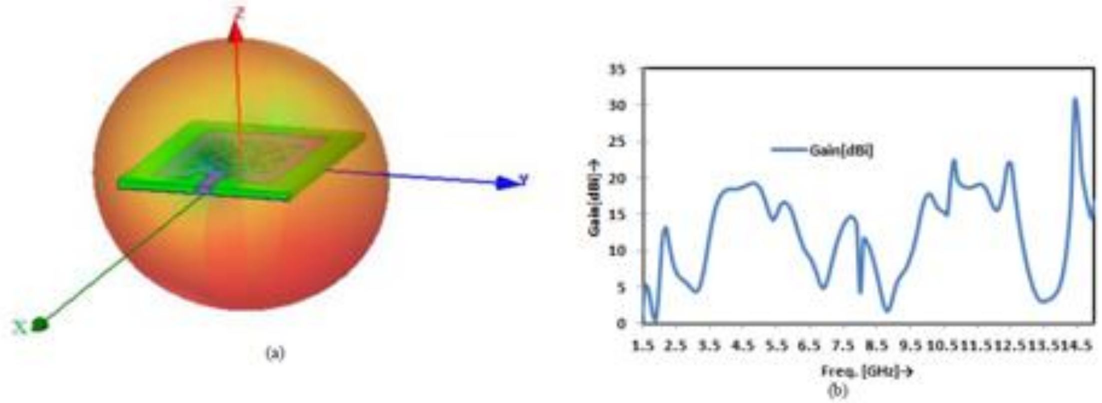

Figure 8. 3D radiation pattern (a) and gain plot across operating frequency bands (b).

9. Conclusion

Hybrid βω-India-idexing fructal slotted antenna displays efficient multiband display in a compact form. By taking advantage of fractal slotting, customized ground reduction and inset feeding, it provides reliable performance for diverse wireless sensors and communication applications. Its compactness, high profit and multiband capacity makes it a strong candidate for the next generation wireless technologies.

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