

T-Truncated Fractal Slot UWB Antenna for Wide Band Scanning in RF Sensor Network

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ABSTRACT- The emergence of wireless communication networks (WCNs) introduces new opportunities for efficient spectrum utilization through wide scanning of the network. Leveraging Software Defined Radios (SDRs), users can conduct wide spectrum sensing and adjust transmission properties dynamically. The concept of opportunistic use of available spectrum requires adaptable antennas with ultra-wide band scanning capabilities. Dynamic Spectrum Access (DSA) emerges as a promising solution to congestion within densely populated networks. In this study, we introduce an innovative compact antenna specifically crafted for wide spectrum sensing. Circular polarization property enhances the antenna's ability for orientation-free spectrum scanning, facilitated by corner truncation. The antenna design incorporates novel T-fractal slots and electromagnetic band gap structures on a small FR4 substrate measuring 12x18x1.6 mm². The aim is to identify unused channel opportunities within radio frequency sensor networks (RFSN) through wideband scanning. The impact of insertion of band gap and fractal slots provide a matching of wide range of impedance bandwidth. With an average gain of 2.5 dBi across its operational frequency range, the antenna meets FCC standards, affirming its suitability for spectrum sensing in RFSN. Experimental findings reveal a wide bandwidth from a range of 0.79 to 12.0 GHz in terms of return loss characteristics relative to the feed port.

Keywords: WSN, fractal, band gap, SDR, DSA.

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1. INTRODUCTION

Dynamic Spectrum Allocation (DSA) emerges as a critical technology to identify vacant Channels within Wireless Sensor Networks (WSNs) [1], [2] and [3]. Contemporary wireless communication systems demand opportunistic spectrum utilization and effective spectrum management as illustrated in Figure 1. Primary users, holding licenses, enjoy all infrastructure privileges and network priorities as per the allotted spectrum. While licensed free spectrum is available to all as listed below [4]. Scanning antenna represents core features of self-oriented wireless sensing network for embedded systems. It supports SDR to operate for various applications including wideband scanning and used in cognitive radio networks. A wideband antenna design using ground structure modification approaches to improve radiation characteristics and impedance bandwidth is presented in the referenced study. The study shows that antenna performance for wideband wireless applications is greatly enhanced by structural optimization. However, the stated design primarily concentrates

on improving bandwidth, leaving room for additional advancements in RF scanning capabilities and polarization variety [5].

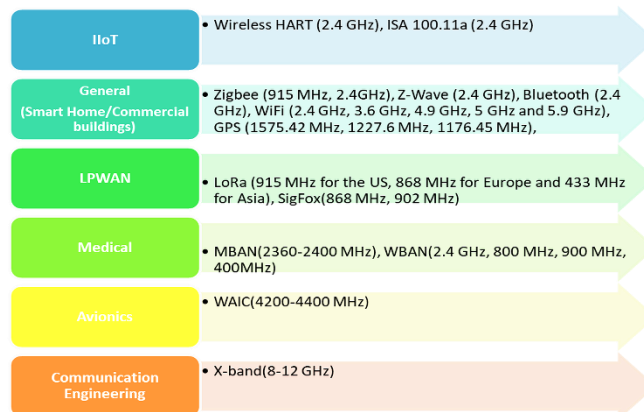


Figure 1. Spectrum analysis for advanced communication system

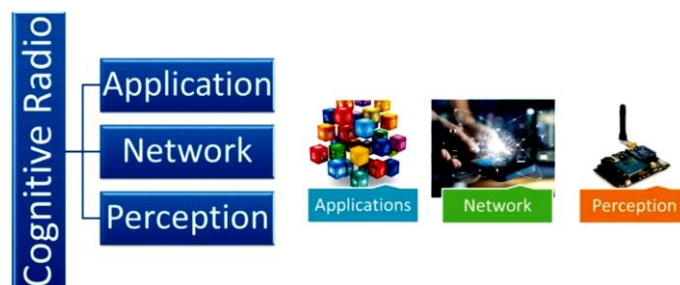


Figure 2. Wireless sensor network model

As per FCC standard frequency spectrums used for communication technologies are listed in *figure 1*, it shows the necessity for wide-scanning radiation devices. The model delineates unique functionality with procedural effect of WSNs, and physical sensing layers with a band of operating frequencies as main operating parameters, shown in *figure 2*. This illustration emphasizes the utility of the need of one antenna to cater to a greater number of applications [6], [7] and [8]. The primary function of any Wireless Sensor Network (WSN) involves continuously scanning unused spectrum, known as white space [9]. This task entails intricate hardware and software complexities, particularly in processing low bandwidth network sensing and high bandwidth of the spectrum sensing. Narrow band sensing (NBS) technology demands precise hardware design and soft computing capabilities. Discriminating between unwanted random noise and truly utilized spectrum remains a significant challenge across both scanning modules [10].

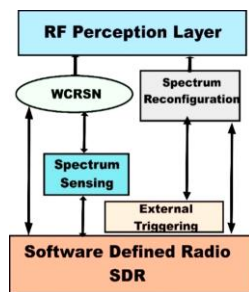


Figure 3. Process flow for RF scanning through SDR

This study [11] describes an octagonal fractal-based triband and ultra-wideband antenna that is fed by a 50 microstrip line and is built on a FR4 substrate. WLAN, WiMAX, LTE, Bluetooth, Wi-Fi, and C/X-band applications are just a few of the wireless technologies that the antenna supports with its wide impedance bandwidth and strong gain. The design's suitability for multiband wireless communication systems is demonstrated by simulations employing HFSS and CST. Addressing this challenge involves considering Signal-to-Noise Ratio (SNR) improvement for Software Defined Radio in WSN. *Table 1* shows the RF network components and their functionality with respect to communication systems [2], [12] and [13].

It facilitates supervisory control and as an interface for various network RF protocols and service interfaces, allowing for reconfiguration of embedded system parametric properties [14]. The complex hardware need can be eliminated through effective implementation of wireless sensor networks for both type of sensing narrow band and wideband sensing applications. To elicit the process flow between software protocol and physical perception layer, *Figure 3* shows the importance of the RF perception layer in software-defined radios. The iterative process of perception of RF interface persists until spectrum response is detected, thereby pioneering a novel technology known as software-defined antenna (SDA) that revolutionizes actions in the RF environment [15]. *Figure 3* explains how SDR can be more effective by using the association of Software Defined Antennas (SDA), ensuring effective management of Wireless Sensor Networks (WSN). Wireless sensor network

demands high data rates to scan and respond immediately over the RF network. The ability to adapt to bandwidth changes or maintain consistently large bandwidths are a valuable feature of SDAs. The SDR can easily manipulate the properties of SDA through RF excitation and similarly, the RF excitation via spectrum sensing excites the SDA. As we explore the perception layer, which is actually the interface of the sensor network, *figure 4* illustrates the persistence of RF interface for supervisory management of WSN.

Table 1. RF networks Functional Description

Component	Sub Components / features	Functions/Description
Sensor Nodes	Sensors	For data acquisition or signal acquisition from the medium
	Microcontroller / Processor	Process sensor data, control node operations
	Transceiver	Enable wireless communication between nodes
	Power Source	Typically, batteries or energy-harvesting devices Sensing, data processing, communication
Sink Node / Base Station		Collect data from sensor nodes, gateway to external networks
Communication Architecture	Network Topologies	Star, tree, mesh topologies
	Mac Layer Protocols	Manage access to communication medium (e.g., TDMA, CSMA)
	Routing Protocols	Determine data paths (e.g., LEACH, AODV)
Data Aggregation and Processing	In Network Processing	Data aggregation and fusion within the network to save energy
	Edge Computing	Perform processing at the edge for faster response times
Power Management	Energy-Efficient Protocols	Minimize energy consumption, extend battery life
	Sleep Modes	Low-power modes when nodes are inactive
Security Mechanisms	Data Encryption	Ensure data privacy during transmission
	Authentication Protocols	Verify node identities
	Intrusion Detection Systems	Monitor for suspicious activities
Middle ware and Application Layer	Middleware	Abstraction and common services for application development
	Application Layer	Interface with end-user applications
	Applications	Environmental monitoring, health care, industrial automation, etc.

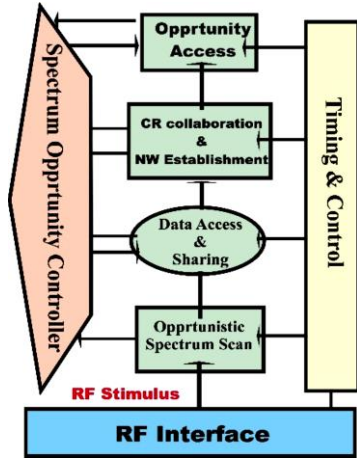


Figure 4. RF scanning and associative module

The perception layer of the RF spectrum is the primary interface to SDA is the exposed RF spectrum; it collects RF stimuli and processes signal to detect actual transmissions along with random noise. The bidirectional communication can be ensured through an effective scan of RF vacancy and signal transmission over the channel. Timings and synchronizations are the essential parameters for the minimization of delay in authorized transmissions. This depends completely upon throughput of RF interface for sensing every opportunity in the environment. Therefore, a wideband compact antenna with optimized parameters is a crucial component of RF interface for efficient signal transmissions. This paper focuses on the designing of a versatile antenna for RF scanning with ultra-wide band capabilities.

2. ANTENNA DESIGN FOR WSN

This section explains the designing of a UWB antenna for wireless sensor network. The major objectives behind the antenna designing are the ultra-wideband and an orientation free surface [16]. The wide application domain of the antenna is wireless scanning network. The primary function of the antenna design is to detect available vacancy and then allow bilateral communication over the RF network. Model realization leads mathematical modelling of the antenna, the design parameters areas.

$$D = \frac{V_0}{f_{low} \sqrt{\epsilon_{reff}}} - 2(L + 2\Delta L - w) \quad (1)$$

$$f_L = \frac{c}{L_1 + W_1}; \quad f_H = \frac{c}{L_2 + W_2} \quad (2)$$

$$l_1 = 2(L_2 - w) + W_2 + \frac{0.2l}{\sqrt{\epsilon_{reff}}} \quad (3)$$

Surface waves (SW) generated by these distributed networks correspond to specific frequency bands, each influenced by the unique characteristics of the radiating surface. These bands delineate distinct regions where electromagnetic waves propagate efficiently, presenting opportunities for diverse applications and functionalities within the antenna system.

$$f_s = \frac{c}{2L} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (4)$$

$$l_e = 1 + \frac{0.4l}{\sqrt{\epsilon_{reff}}} \quad (5)$$

Effective dielectric constant (ϵ_{reff}) is offered by the slot length

$$f_{calc} = \frac{c}{4l_e \sqrt{\epsilon_{reff}}} \quad (6)$$

By incorporating cross-correlation effects and lumped networks of inserted slots, the antenna's feasibility is enhanced for an extended frequency range. Equations (1) to (6) offer a detailed depiction of the radiating characteristics of the proposed antenna structure, along with the corresponding modeling of the wideband sensing device. Instead of using multiple antenna sets to scan a wide frequency spectrum, employing a single, extra-wideband antenna is more effective for opportunistic spectrum scans. For radiating surface fractal slots are developed, whereas the ground surface is designed to control the impedance width of the antenna with the help of EBG structure. Therefore, an antenna is proposed on a compact 12x18x1.6 mm³ substrate with a dielectric constant of 4.4. From the significant literature on UWB antennas, the initial structure is taken as a shape of a U patch on antenna. The modifications have led to optimization of ground structure through DGS and electromagnetic band gaps (EBG) are used for the same. Through successive iterations a 12x11 mm² rectangular patch is reshaped on the top of radiating surface. At the ground side the EBG patterns are optimized for bandwidth variation in the ground plane. figure 5 shows the schematic design and analytical modelling of the proposed model and iterative simulations. Initially, iterations concentrate on the antenna, yielding results within the desired domains.

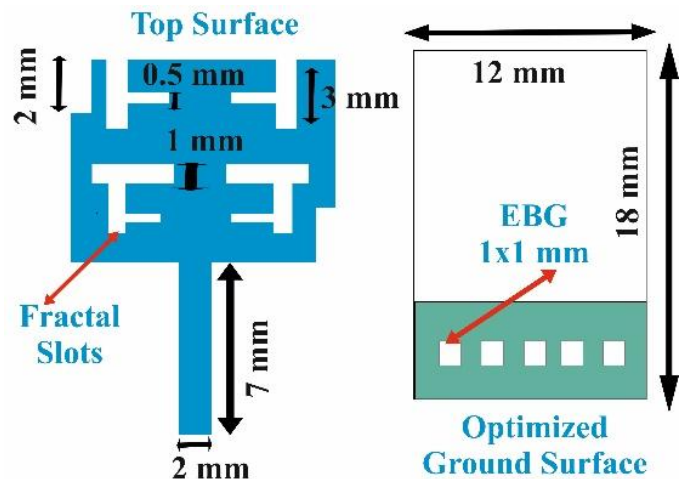


Figure 5. Patch design of proposed antenna

The main structure consists of a rectangular 12x18x1.6 mm³ substrate intended to resonate at a central frequency of 7.5 GHz. The slot insertions exhibit prominent features such as variable impedance, path difference, radiating characteristics, and current distribution. The optimized square-shaped 1x1 mm²

Electromagnetic Band Gap (EBG) pattern minimizes spurious feed radiations and extends critical cut-off frequency boundaries. The corner truncation generates path difference and led to a 90 -degree phase shift. The overall impact of the fractal, corner truncation, and EBG enables the antenna for desired performance in the field of ultra-wideband scanning. *Figure 6* elaborates the electrical equivalence of the patch impedance of the radiating surface of the proposed antenna. The diagram offers insight into how the antenna elements interact and contribute to the overall electromagnetic behavior, enabling a deeper understanding of its performance characteristics.

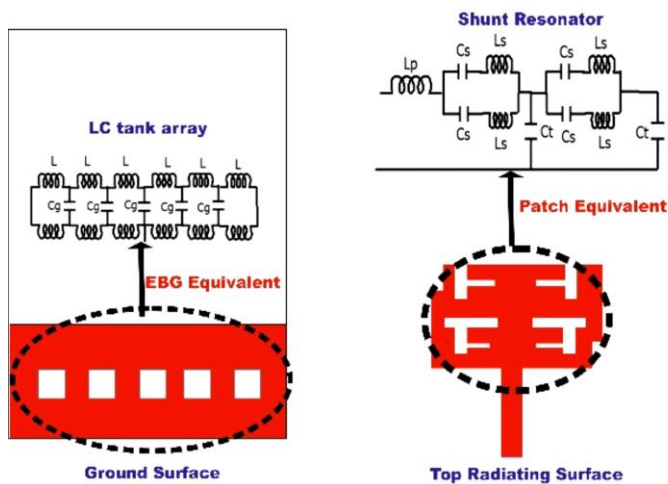


Figure 6. Electrical equivalence of EBG structure

3. RESULTS AND DISCUSSION

The proposed antenna's performance is primarily assessed by its bandwidth, gain, efficiency, and radiation characteristics. An iterative methodology is employed to ensure the antenna design adheres to the stringent compatibility requirements of Wireless Sensor Networks while optimizing its overall performance across multiple metrics. Within the antenna's electrical representation, an L-C tank circuit is strategically distributed as a network. Through effective antenna tuning, both dimensional and performance optimization are achieved. Notably, Antenna 5 was identified as the most suitable model for WSN applications among various iterations, showcasing a wide frequency span from 0.69 to 11.9 GHz under high frequency structural analysis. The analysis highlights the critical role of Electromagnetic Band Gap (EBG) patterns in optimizing antenna performance, particularly in achieving enhanced impedance matching and wideband characteristics. These improvements are essential for antenna designs intended to operate in dynamic and challenging RF environments, such as those encountered in Wireless Sensor Networks (WSNs) and Radio Frequency Sensor Networks (RFSNs). Corner truncation is employed to excite two orthogonal modes with a 90° phase difference, enabling orientation-independent antenna operation during RF spectrum scanning. Without this feature, antenna orientation could significantly limit the effective utilization of available spectrum opportunities within the Primary User (PU) band. The proposed antenna structure achieves circular polarization (CP), ensuring compatibility across the entire

operational frequency range. Inductance L and capacitance C for proposed structure are determined as

$$L = \mu_0 h \quad (7)$$

$$C = \frac{W\epsilon_0}{\pi} (1 + \epsilon_r) \cosh\left(\frac{2W+g}{g}\right) \quad (8)$$

$$\omega = \frac{1}{\sqrt{LC}} \quad (9)$$

$$BW = \frac{\Delta\omega}{\omega} = \frac{1}{\eta} \sqrt{\frac{L}{C}} \quad (10)$$

The incorporation of EBG patterns in the ground plane significantly enhances impedance matching, resulting in a notable broadening of bandwidth. *Equations (7)–(10)* quantify the parameters influencing the effective bandwidth, thereby demonstrating the importance of EBG integration in the overall radiating structure. The corresponding performance improvement is clearly depicted in *figure 8*.

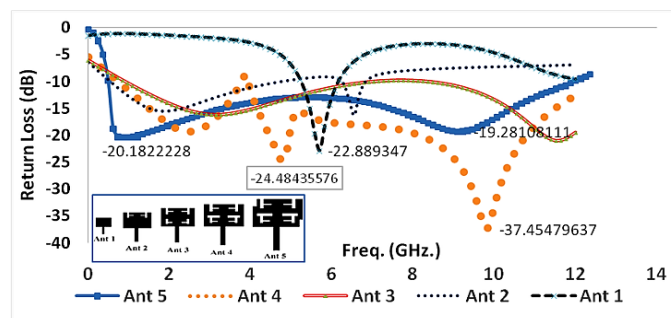


Figure 7. Design evolution of antenna through iterative process

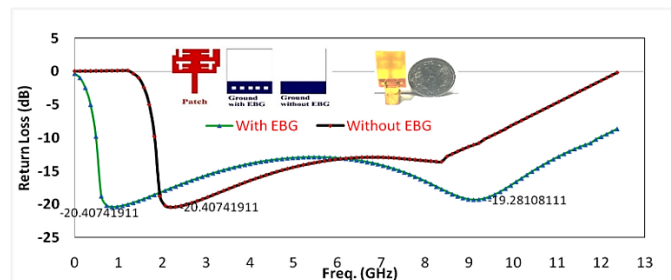


Figure 8. Effect of EBG on antenna performance

Furthermore, the proposed antenna maintains circular polarization across the complete operational bandwidth, as confirmed by axial ratio analysis. The 3 dB axial ratio over the full frequency range is shown in *figure 9*, indicating effective CP performance. The corner truncations generate two orthogonally phase-shifted radiation modes, which are essential for achieving circular polarization. Based on simulation results, the antenna is fabricated on an FR4 substrate with a dielectric constant of 4.4, chosen for its commercial availability and cost-effectiveness. Although FR4 introduces dielectric losses that may cause minor deviations between simulated and measured results, it remains a practical choice for real-world applications. The fabricated antenna prototype is shown in *figure 10*.

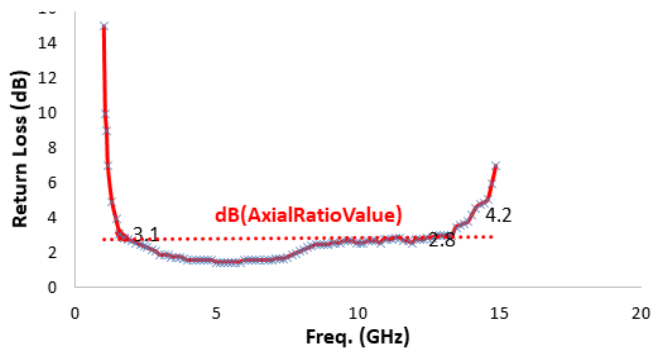


Figure 9. Axial ratio for frequency range

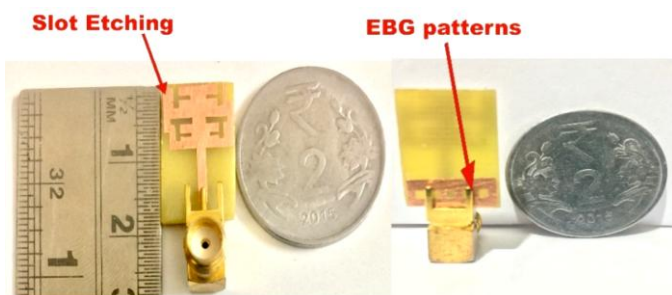


Figure 10. Antenna Prototype

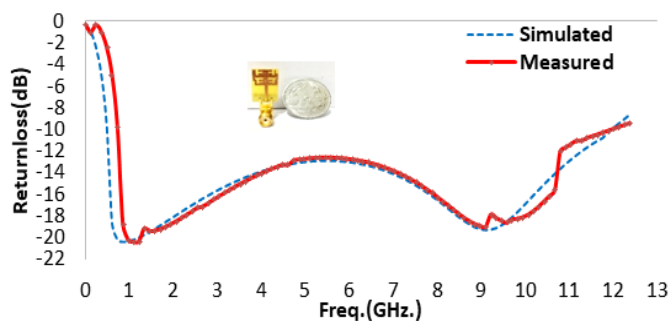


Figure 11. Return loss measurement

Experimental measurements were conducted using a Rohde and Schwarz ZVA 40 Vector Network Analyzer (VNA) and in anechoic chamber as shown in *figure 12*. A comparison of simulated and measured return loss characteristics is presented in *figure 11*. The observation of the relative S11 characteristics indicates that the measured operating bandwidth extends from 0.78 to 12.0 GHz, while the corresponding simulated bandwidth ranges from 0.72 to 12.1 GHz for the 10 dB return loss criterion, confirming the antenna's suitability for wideband RF scanning applications. The antenna exhibits stable gain characteristics across the operating frequency range, making it suitable for both near-field and far-field RF sensing. This gain stability enhances reliability in communication and sensing applications. *Figure 13* presents a comparison of measured and simulated total realized gain relative to an isotropic radiator, showing a close agreement with an average gain of 2.59 dBi. The gain varies from a minimum of 1.51 dBi at 700 MHz to a maximum of 3.12 dBi at 7.2 GHz. These consistent gain characteristics make the

antenna well suited for frequency scanning in both far-field and near-field radiation domains. This stability in gain performance enhances the antenna's utility and reliability in various applications, ensuring effective communication and sensing capabilities within Wireless Radio Frequency Sensor Networks (RFSN).

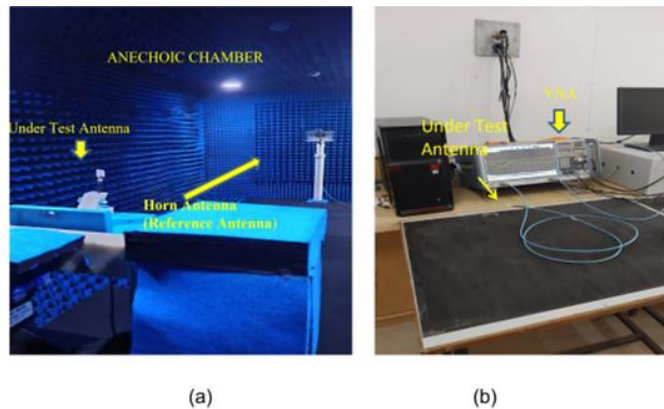


Figure 12. Measurement set up. (a) anechoic chamber (b) Rohde and Schwarz ZVA 40 Vector Network Analyzer (VNA)

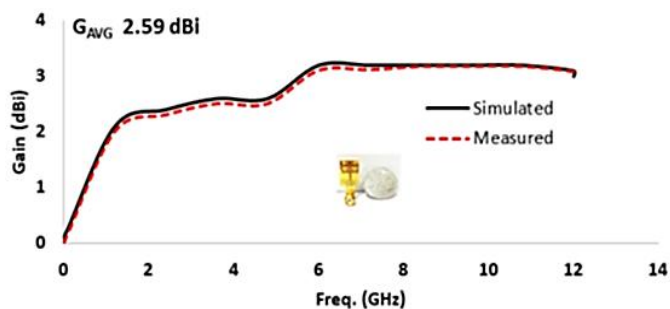


Figure 13. Total gain analysis

Figure 12 provides a comparison between the measured and simulated total realized gain of the antenna relative to an isotropic radiating source showing a close match of an average gain of 2.59 dBi, with the gain varying from a minimum of 1.51 dBi at 700 MHz to a maximum of 3.12 dBi at 7.2 GHz. *Figures 14* and *15* depict the measured and simulated radiation patterns in the H-plane and E-plane, respectively, at multiple frequency points. The consistent radiation behavior across frequencies ensures dependable performance for RF sensing and communication in RFSNs. The outcome of this work demonstrates the successful development and experimental validation of a compact wideband circularly polarized antenna incorporating Electromagnetic Band Gap (EBG) structures and corner truncation techniques. The proposed antenna achieves a measured 10 dB impedance bandwidth of 0.78–12.0 GHz, closely matching the simulated bandwidth of 0.72–12.1 GHz, thereby confirming reliable wideband operation. The integration of EBG patterns significantly improves impedance matching and bandwidth, while corner truncation enables the excitation of orthogonal modes required for stable circular polarization across the entire operating frequency range.

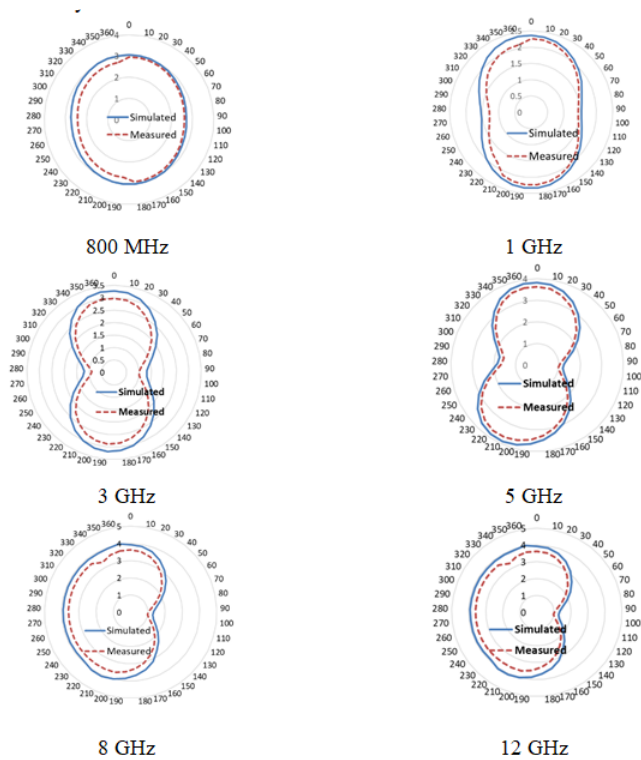


Figure 14. H plane radiation characteristics

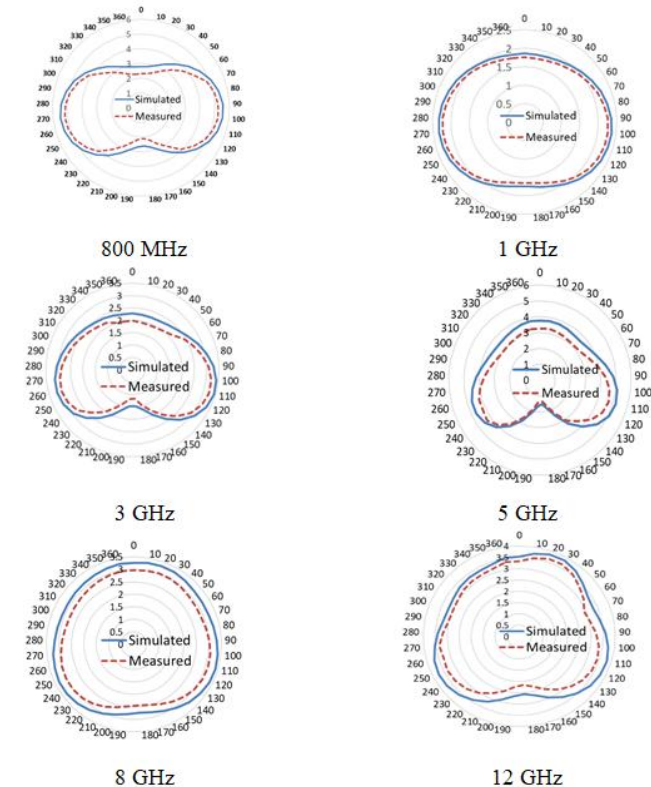


Figure 15. E plane radiation characteristics

Ref.	Band (GHz.)	Material (ϵ, t)	Dim. (mm)	Methodology	Remarks in Reference design frame
[9]	2.97-22.46	4.4, 1.6 mm	25x17	Slot spanner type, cuts in ground	Large dimensions, lower edge of frequency on higher side, return loss are high.
[10]	2.5-12	4.4, 1.6 mm	48x48	Resonator Split ring	High return loss, notching, large dimension
[11]	3.04-10.87	4.4, 1.6 mm	20x20	Slots like rectangle	Impedance bandwidth is comparatively low
[12]	2.45-10.65	4.4, 1.6 mm	19x24	Strips with thin slots	Large dimensions, tri-band rejection
[13]	3.6-11.6	4.4, 1.6 mm	30x34	Dual slot rectangular	Lower edge frequency high, complete UWB
[14]	5-15	4.4, 1.6 mm	11x15	Shape of wings	Low impedance bandwidth, large lower edge frequency
[15]	3.1-16	4.4, 1.6 mm	22x26	Rings of circular shape	UWB feature without band lower edge frequency extension
[16]	3.3-9.6	2.2, 1.6 mm	46x36	Fractal	Large dimensions, lower edge frequency high
[17]	2.5-10	4.4, 1.6 mm	27x28	Fractal square slots	Lower edge frequency high
[18]	3-11	4.4, 6.5 mm	65x40	DRA	Lower edge frequency high, large dimension, large size and thickness
Proposed	0.75-12.00	4.4, 1.6 mm	12x18	Corner truncation with EBG in fractal antenna	Reduced size, UWB with 0.75 GHz lower edge, circular polarization, extended scanning bandwidth

The antenna exhibits consistent gain, stable radiation patterns, and orientation-independent performance, validating its effectiveness in practical RF environments. These outcomes establish the proposed design as a feasible and efficient solution for wideband RF spectrum scanning and sensing, particularly in Radio Frequency Sensor Networks (RFSNs), cognitive radio systems, and other emerging wireless applications requiring compact, low-cost, and broadband antenna structures. In summary, the proposed antenna provides a robust and compact

Table 2. Comparison of antenna designs from literature with proposed work

solution for modern RF applications operating in dynamic spectral environments. Comprehensive analysis of key performance parameters—including orthogonal mode excitation, impedance bandwidth, radiation efficiency, gain stability, and radiation patterns—confirms the antenna's suitability for Radio Frequency Sensor Networks. Compared with existing antenna designs, the proposed structure offers wideband operation extending to lower frequency ranges without increasing physical dimensions. The comparative performance metrics presented in *table 2* demonstrate the novelty of the design and its compliance with FCC standards, making it highly compatible with emerging RF technologies.

The novelty of this work lies in the synergistic utilization of fractal slotting, corner truncation, EBG integration, and ground plane deformation to simultaneously achieve wide bandwidth, extended low frequency operation, and reliable radiation performance without increasing antenna dimensions.

4. CONCLUSION AND FUTURE SCOPE

This paper presents a compact and efficient antenna solution for Radio Frequency Scanning Networks (RFSNs) by integrating fractal-shaped slot structures, patch corner truncation, a deformed ground plane, and Electromagnetic Band Gap (EBG) elements. The combined design approach enables ultrawideband impedance bandwidth from 3.1 to 10.5 GHz, along with an extended lower-frequency operating range of 0.8 to 3.1 GHz, thereby supporting continuous and wideband RF spectrum scanning. The proposed antenna exhibits stable radiation characteristics, orientation-independent circular polarization, an average realized gain of 2.51 dBi, and a radiation efficiency of 79.9%. These characteristics make the proposed antenna highly suitable for applications such as Radio Frequency Sensor Networks, cognitive radio systems, spectrum monitoring, wireless sensor networks, and wideband RF sensing platforms. Additionally, the antenna's compatibility with software-defined radios (SDRs) enables seamless integration with intelligent spectrum sensing frameworks. As future scope, the proposed antenna can be further enhanced by incorporating reconfigurable elements such as PIN diodes or varactors to enable frequency agility and adaptive polarization. Integration with artificial intelligence and machine learning-based spectrum management algorithms can further improve dynamic spectrum access and interference mitigation in next-generation RF systems. Moreover, extending the design to flexible or conformal substrates would enable deployment in wearable, IoT, and unmanned sensing platforms, expanding its applicability in emerging wireless communication and sensing technologies.

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