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Design and Implementation of Multiband Elliptical Ring Patch Antenna for Wireless Communication Systems

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Abstract

The paper discuss proposed multiband elliptical ring microstrip patch antenna for wireless communication applications, including ISM, Zigbee, Bluetooth, 4G, 5G, LTE, and UWB. The antenna is designed to operate efficiently across multiple resonance frequencies, including TM_{11}, TM_{21}, TM_{01}, and TM_{31} modes. The antenna is fabricated using an FR4 substrate, and its performance is evaluated through both simulation and measurement. The results show that the antenna exhibits strong performance at its resonant frequencies, with realized gain values of 1.514 dB at 2.4 GHz (TM_{11} mode), 1.835 dB at 4 GHz (TM_{21} mode), 3.496 dB at 5.6 GHz (TM_{01} mode), and 4.804 dB at 8.4 GHz (TM_{31} mode). At 6.4 GHz, the antenna achieves its maximum realized gain of 7.537 dB. The field distribution and radiation pattern measurements, demonstrate excellent agreement between measures and simulated results. These findings confirm that the proposed antenna provides reliable and consistent performance, making it a promising solution for multiband communication applications that require efficient bandwidth and gain across a wide frequency range.

Keywords: Bandwidth Enhancement, Elliptical Patch, Multiband, Multimode, Wireless Communication.

Introduction

With the continuous advancement of wireless communication standards such as ISM, Zigbee, Bluetooth, LTE, 4G, 5G, and UWB, the demand for compact and high-performance antennas has significantly increased. These technologies require antennas capable of operating over multiple frequency bands without compromising gain, efficiency, or physical compactness. In previous research, numerous design methodologies were proposed to enhance antenna characteristics in terms of bandwidth, gain, and radiation behaviour (1). A considerable amount of work has been devoted to bandwidth enhancement. Stacked patch configurations have been employed to produce dual or multiple resonances (2), while grooved ground planes have been utilized to suppress surface waves and extend impedance bandwidth (3). The introduction of slotted radiating patches was found to create additional current paths, thereby supporting wideband performance (4–6). Other approaches have incorporated coplanar waveguide (CPW) feeding structures to simplify fabrication and improve impedance matching (7), whereas parasitic elements combined with slot loading have been used to generate multiple resonant modes (8–10). Additionally, the application of engineered electromagnetic surfaces such as metasurfaces has enabled manipulation of the radiated fields, effectively broadening the operational bandwidth (11). Efforts have also been made to improve antenna gain and radiation efficiency. Techniques involving hybrid or composite substrates were used to enhance radiation efficiency (12), while frequency selective surfaces (FSS) placed above radiating patches demonstrated gain improvement through reflective reinforcement (13). The utilization of meta materials with negative permeability was reported to improve aperture efficiency (14). Moreover, geometric modifications such as lifting or tapering the radiating edges of the patch were shown to minimize surface wave losses, leading to increased efficiency (15). Collectively, these developments illustrate the ongoing attempts to achieve a balance between compact geometry, wide bandwidth, and high radiation performance. Elliptical geometries have recently gained attention due to their inherent capability to support multimode excitation within a compact structure. In several past studies, CPW-fed elliptical slot antennas were demonstrated to offer

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wideband characteristics with simple fabrication processes (16). Further investigations on elliptical patches with modified ground planes have shown wide coverage extending from lower microwave to millimetre-wave frequency ranges (17). Compact elliptical configurations have also been proposed for high-gain applications such as synthetic aperture radar, providing notable gain improvements (18). In addition, cavity-backed elliptical arrays have been reported for millimeter-wave systems, yielding high directional gains (19). Studies involving the integration of elliptical patches with meta material structures have enabled antenna miniaturization and dual-mode excitation (20). Earlier investigations into elliptical annular rings have also provided theoretical and experimental validation of their capability for wideband circular polarization (21).

Hybrid elliptical designs have been explored to address specific performance needs. Elliptical fractal antennas incorporating defected ground structures (DGS) were shown to operate effectively over ultra-wideband ranges (22). Other research demonstrated that DGS configurations can shift resonance frequencies and improve impedance matching (23, 24). Planar monopole antennas with triangular or elliptical geometries were also examined for enhanced radiation uniformity (25), while specific DGS arrangements were used to suppress cross-polarization in elliptical patches (26). Studies involving kite-shaped or slotted elliptical designs achieved super-wideband coverage (27), and advanced analytical models have been employed to improve the accuracy of circular polarization analysis in elliptical microstrip structures. The incorporation of dielectric superstates over elliptical slot antennas has been shown to increase radiation efficiency, particularly in on-chip RF systems.

Unlike conventional geometries, the elliptical ring configuration provides distinct advantages for multiband antenna design. The structure naturally supports multiple resonant modes within a compact footprint, resulting in reduced size without compromising radiation performance. The inclusion of an elliptical slot introduces supplementary current paths that enhance impedance bandwidth and matching compared to other slot-loaded designs. Furthermore, elliptical rings allow better separation of resonant modes and greater flexibility in exciting higher-order modes, improving frequency coverage. Although mathematical modelling using Mathieu functions increases analytical complexity, the demonstrated benefits in multimode operation, compactness, and radiation efficiency strongly justify the use of the elliptical ring geometry in the present study.

In this context, the present work proposes a multiband elliptical ring patch antenna that combines a central elliptical slot with an enclosing elliptical ring. This structure enables the excitation of multiple resonant modes (TM_{11}, TM_{21}, TM_{01}, and TM_{31}) at 2.4 GHz, 4.0 GHz, 5.5 GHz, and 8.4 GHz, respectively. The design has been optimized through simulation and validated experimentally, showing consistent agreement between measured and simulated results. By addressing the limitations of earlier designs, the proposed antenna provides a compact and efficient solution suitable for multiband wireless communication systems.

The novelty of this work lies in the design of a compact multiband elliptical ring patch antenna that exploits multimode excitation (TM_{11}, TM_{21}, TM_{01}, and TM_{31}) within a single structure, achieving wide coverage and high efficiency across four key wireless communication bands, which has not been simultaneously demonstrated in earlier elliptical patch designs.

The structure of the paper is as follows: Section II details the antenna design and parameter optimization, along with the mathematical model of the elliptical patch. Section III covers the simulation and measurement results. Section IV discusses performance evaluation and application relevance, while Section V concludes with a summary of findings.

The paper is organized as follows: Section II outlines the design process of the proposed antenna, including the optimization of key parameters and the mathematical formulation for the elliptical patch. Section III presents the simulation and measurement results, including return loss and radiation pattern comparisons. In Section IV, the performance of the antenna is discussed in detail, and the suitability of the antenna for various wireless communication applications is evaluated. Finally, Section V concludes the paper with a summary of the key findings.

Methodology

Figure 1 illustrates both the schematic layout and the fabricated prototype of the proposed inset-fed multiband elliptical ring patch antenna. The structure incorporates a modified elliptical radiating element featuring a central elliptical slot and an outer elliptical ring, which collectively contribute to supporting multiple resonant modes and improved bandwidth performance. The antenna is modeled using an FR4 substrate, chosen for its wide availability and reasonable electrical performance. It has a relative permittivity (ε_r) of 4.4, a thickness of 62 mils (approximately 1.57 mm), and a loss tangent of 0.02, offering a practical balance between cost and dielectric losses. As an initial step, a single-band inset-fed elliptical patch antenna—referred to as Antenna I—is designed to resonate at 2.45 GHz. The geometric dimensions of the elliptical patch are derived using approximate analytical relations based on Mathieu functions, which provide solutions for the field distribution associated with the TM_{11} mode. This foundational design serves as the basis for further development toward multiband operation through additional structural modifications.

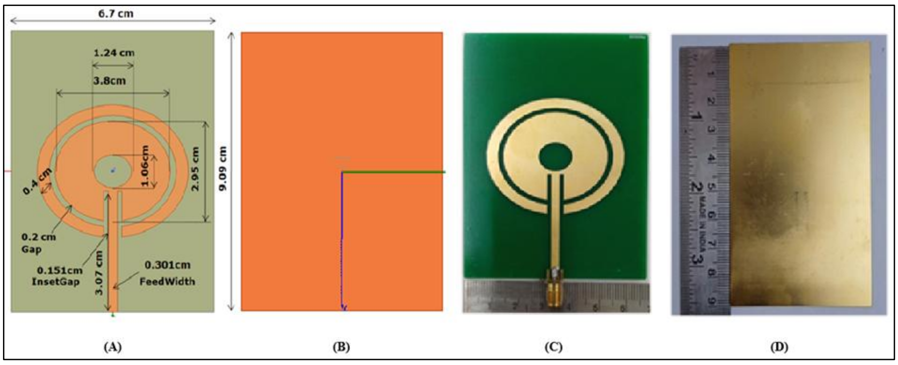

Figure 1: Geometry of Proposed Multiband Elliptical Ring Antenna: **(A), (B):** Simulated Antenna, **(C), (D):** Fabricated Antenna

$$f_r = \frac{k_{mn}C}{2\pi r_e\sqrt{\varepsilon_{eff}}} \quad [1]$$

$$\varepsilon_{eff} = \varepsilon_r - \frac{0.35\varepsilon_r}{2}\left[\frac{h}{x} + \frac{h}{y} + \frac{h^2}{xy}\right] \quad [2]$$

$$r_{ec} = \sqrt{\frac{{x_{eff}}^2 + {y_{eff}}^2}{2}} \quad [3]$$

$$x_{eff} = \left\{x^2 + \frac{2hx}{\pi\varepsilon_{eff}}\left[ln\left(\frac{x}{2h}\right) + (1.41\varepsilon_{eff} + 1.77) + \frac{h}{x}(0.268\varepsilon_{eff} + 1.65)\right]\right\}^{1/2} \quad [4]$$

$$y_{eff} = \left\{y^2 + \frac{2hy}{\pi\varepsilon_{eff}}\left[ln\left(\frac{y}{2h}\right) + (1.41\varepsilon_{eff} + 1.77) + \frac{h}{y}(0.268\varepsilon_{eff} + 1.65)\right]\right\}^{1/2} \quad [5]$$

Here, ε_{eff} represents the effective semi-major axis accounting for the fringing field, as defined in Equation (2).

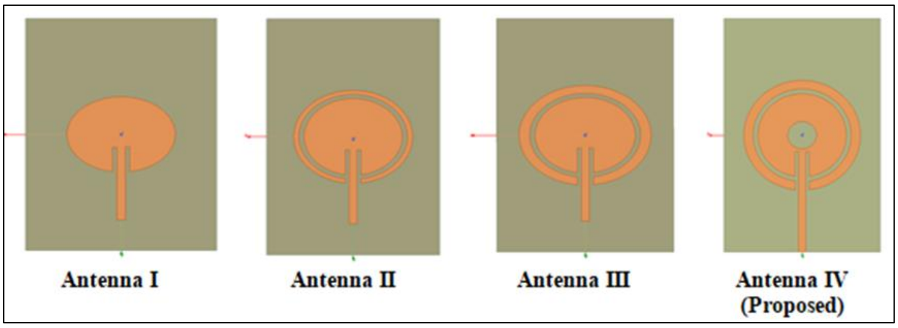

Figure 2: Evaluation of Proposed Multiband Elliptical Ring Antenna

To achieve higher-order modes, a slightly larger size was selected while maintaining a constant eccentricity of the ellipse. This resulted in three resonance frequencies corresponding to three different modes: TM_{11}, TM_{21}, TM_{01}, and TM_{31}.

Figure 2 illustrates the intermediate stages in the evolution of the given antenna. A comparison of return loss (in dB) versus frequency is presented for Antenna I, Antenna II, Antenna III, and the proposed design. Due to its elliptical shape, the simple elliptical patch (Antenna I) resonates at two distinct frequencies. These results are shown in Figure 3. When a ring is introduced around Antenna I, forming Antenna II, the resonant frequency slightly shifts towards a lower frequency, and an additional higher resonance band around 5 to 6 GHz starts to appear. Further optimization of the outer ring thickness in Antenna III results in a reduced S11 value, and a third resonant frequency is observed in the 7 to 8 GHz band. The addition of a central elliptical slot in the patch results in the excitation of a fifth resonant frequency and contributes to enhanced bandwidth performance in the proposed antenna.

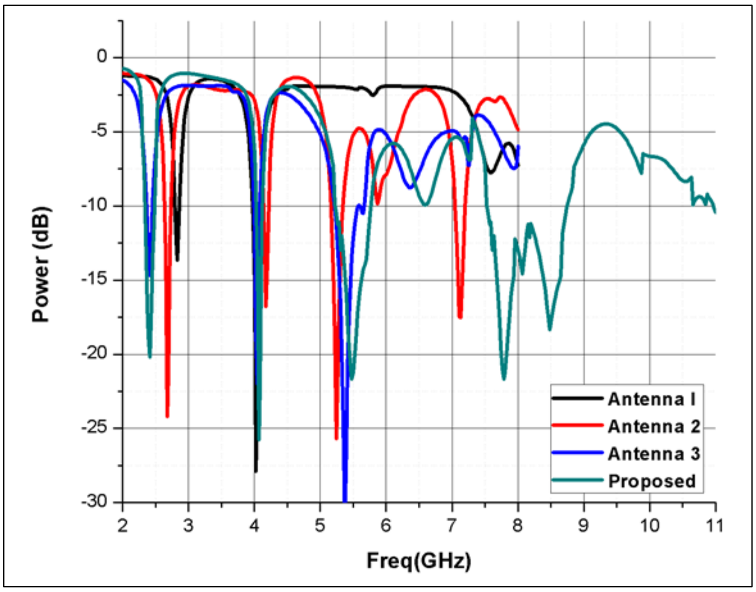

Figure 3: Simulated Return Loss Comparison of the Intermediate Antenna Stages (Antenna I, II, III) with the Proposed Multiband Elliptical Ring Antenna

The optimization process focused on critical antenna parameters, particularly the dimensions of the outer elliptical ring and their influence on overall performance. Through a series of parametric sweeps, the optimal configuration was identified, resulting in an outer ring thickness of 4 mm and a 2 mm spacing from the inner elliptical patch. Although genetic algorithms were initially evaluated as a possible optimization approach, they were not implemented in the final design, as the parametric sweep method provided reliable and efficient convergence. Table 1 provides a summary of the proposed antenna's dimensions following the completion of all optimization steps.

Table 1: Optimized Dimensions of Proposed Multiband Elliptical Ring Patch Antenna

Parameter Name	Value
patchX	3.8cm
patchY	3.25cm
subH	62mil
subX	6.7cm
subY	9.09 cm
InsetDistance	0.978cm
InsetGap	0.151 cm
FeedWidth	0.301cm
FeedLength	3.07cm

Results and Discussion

Return Loss

The fabricated prototype of the proposed antenna is shown in Figure 1. To evaluate the antenna's performance, return loss measurements were carried out using an Anritsu MS46122B Vector Network Analyzer, ensuring precise assessment of resonant frequencies and impedance matching. A comparison between the simulated and measured S_{11} is presented in Figure 4. The antenna exhibits multiband resonance, as summarized in Table 2. The table outlines the resonant frequencies, bandwidths, percentage bandwidths, and potential applications. The detailed percentage bandwidth and diverse applications demonstrate the suitability of this antenna for various wireless communication systems.

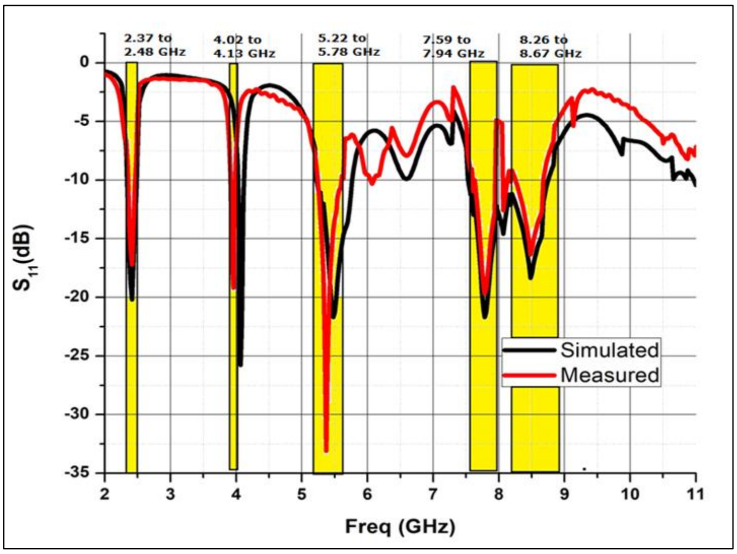

Figure 4: Comparison between the Simulated and Measured S_{11}

Field Distribution

The distribution of the electromagnetic fields at the resonant frequencies of the proposed antenna is presented in Figure 5, highlighting the mode behaviour and current concentration. The observed field distributions confirm that the antenna supports a range of resonant modes, each excited at different frequencies, contributing to its multiband performance.

Table 2: Resonant Frequencies, Bandwidths, Percentage bandwidths of Proposed Antenna with Applications

Freq (GHz)	BW (MHz)	Perc. BW	Application
2.37-2.48	110 MHz	4.54%	ISM band, Zigbee, Bluetooth
4.02-4.13	110 MHz	2.7%	4G, 5G
5.22-5.78	560 MHz	10.2%	ISM, LTE, WiFi
7.59-7.94	350 MHz	4.5%	UWB, C band Radar,
8.26-8.67	410 MHz	4.85%	UWB, C band Radar

At 2.4 GHz, the resonance is due to the fundamental mode, TM_{11}, which exhibits a symmetric field distribution. The next higher mode, TM_{21}, resonates at 4 GHz, displaying a more complex field distribution with two peaks. The third higher-order mode, TM_{01}, has a resonance at 5.5 GHz, with a null at the center of the patch. The final mode, TM_{31}, resonates at 8.4 GHz, characterized by a more intricate field distribution with multiple peaks and nulls.

In summary, the antenna supports the following modes:

- TM_{11} at 2.4 GHz (fundamental mode),
- TM_{21} at 4 GHz (first higher-order mode),
- TM_{01} at 5.5 GHz (second higher-order mode),
- TM_{31} at 8.4 GHz (third higher-order mode).

These results demonstrate the antenna's capability to operate at multiple resonant frequencies, corresponding to different modes, each with distinct field distributions.

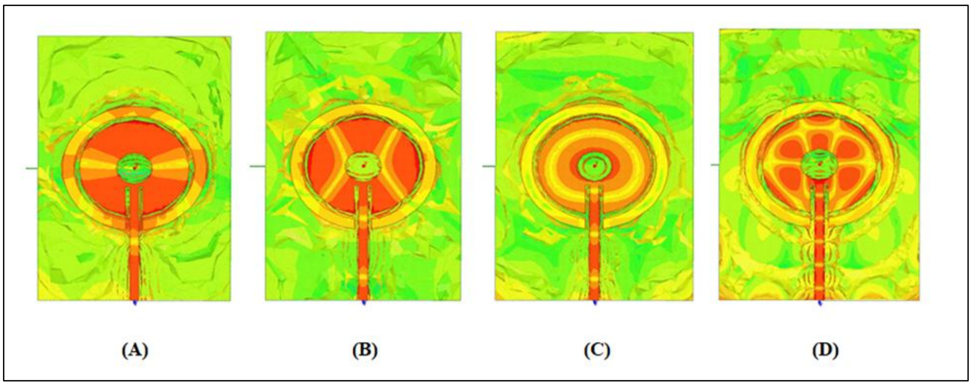

Figure 5: Surface Electric Field Distributions of The Proposed Patch Antenna at Different Resonant Frequencies, Illustrating the Excitation of: (A) TM_{11} mode at 2.4 GHz, (B) TM_{21} mode at 4 GHz, (C) TM_{01} mode at 5.5 GHz, and (D) TM_{31} mode at 8.4 GHz

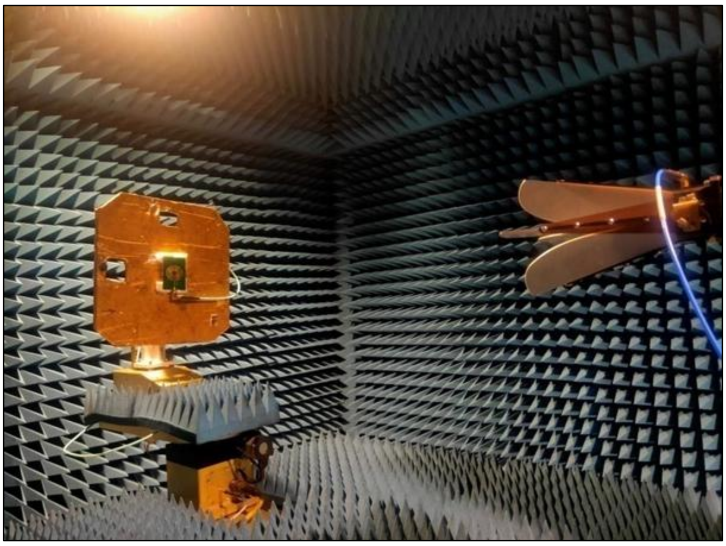

Figure 6: Radiation Pattern Measurement Setup for Proposed Antenna

Evaluation of Radiation Characteristics

The directional and radiation characteristics of the proposed antenna were experimentally analyzed to validate its simulated performance. Measurements were conducted in an anechoic chamber using a standard radiation pattern setup, in which the antenna under test (AUT) was mounted on a precision rotatable mast to capture azimuth and elevation responses, as shown in Figure 6. This configuration ensured accurate far-field measurement while minimizing environmental reflections.

Simulated and measured radiation patterns were compared at the principal resonant frequencies of 2.4 GHz, 4.0 GHz, 5.5 GHz, and 8.4 GHz. The comparative results, illustrated in Figure 7, demonstrate close agreement between the two datasets in terms of main-lobe direction, half-power beamwidth, and cross-polarization levels. Such correlation confirms the reliability of the electromagnetic simulation and validates the structural integrity of the fabricated prototype. At lower frequencies, the radiation patterns exhibit quasi-omnidirectional characteristics, while at higher modes, the patterns become more directive, indicating efficient excitation of higher-order modes. These findings confirm that the antenna maintains stable radiation behavior across multiple frequency bands, meeting the requirements for multiband wireless applications.

Realized Gain Analysis

The realized gain of the proposed antenna was evaluated across a wide frequency range to examine its efficiency under various resonant modes. The frequency-dependent variation of realized gain is presented in Figure 8, which depicts the combined simulated and measured results over the entire operational bandwidth.

At 2.4 GHz, corresponding to the TM_{11} mode, the antenna exhibits a realized gain of 1.514 dB, indicating efficient radiation at the fundamental mode and demonstrating stable operation within the lower frequency band. When the frequency increases to 4.0 GHz, associated with the TM_{21} mode, the realized gain improves to 1.835 dB, signifying enhanced radiation efficiency due to excitation of the first higher-order mode. In the higher frequency region, around 5.5 GHz, attributed to the TM_{01} mode, a further improvement in gain is observed. The antenna records a realized gain of 2.963 dB at 5.2 GHz, reaching a local maximum of 3.496 dB at 5.6 GHz. This enhancement confirms effective radiation characteristics and strong performance in the upper-mid frequency band.

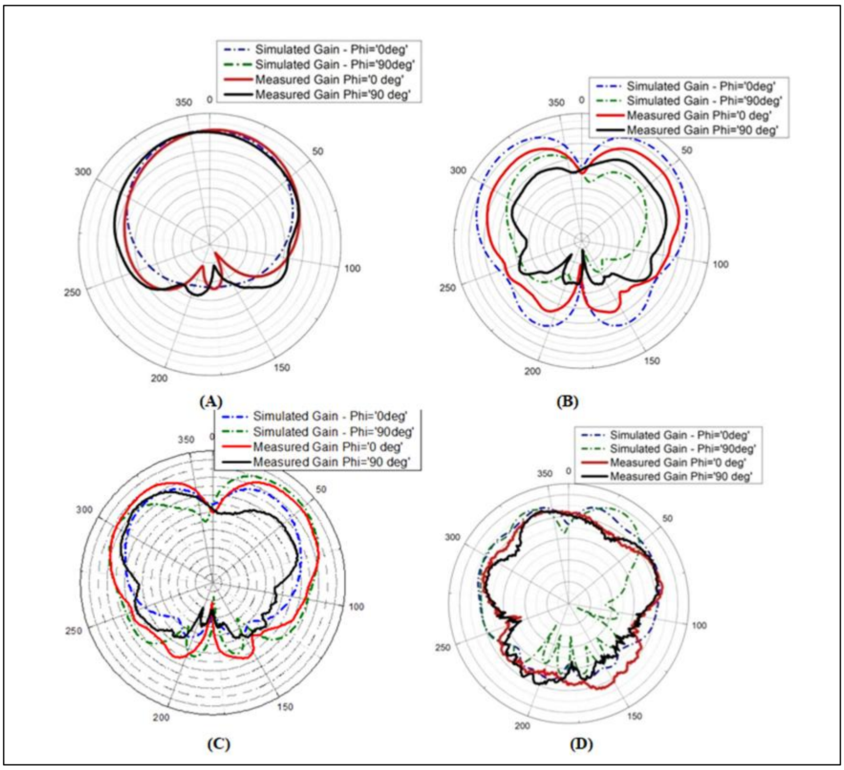

Figure 7: Validation of the Proposed Antenna Design through Comparison Of Simulated and Measured Results at (A) 2.4 GHz, (B) 4 GHz, (C) 5.5 GHz, and (D) 8.4 GHz

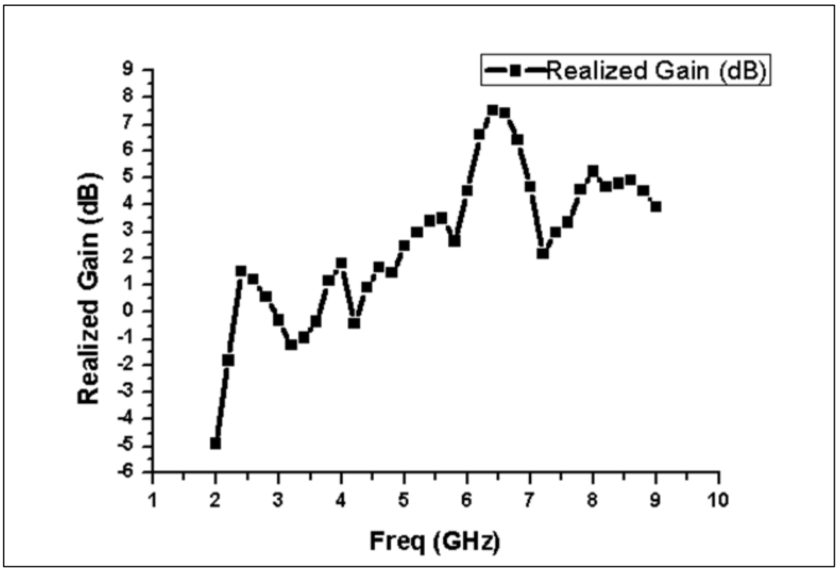

Figure 8: Frequency-Dependent Realized Gain Performance of the Proposed Antenna

At 8.4 GHz, corresponding to the TM_{31} mode, the realized gain increases to 4.804 dB, reflecting high radiation efficiency and stable performance at the third higher-order resonance. A broader observation of the gain behaviour indicates that within the lower-frequency range (2.0–3.6 GHz), the antenna exhibits marginal or slightly positive gain, suggesting limited radiation efficiency in this region. Beyond 4.0 GHz, however, a consistent upward trend in gain is evident, implying improved radiation performance with increasing frequency.

The antenna demonstrates its optimum performance in the 5.5–6.4 GHz frequency range, where a maximum realized gain of 7.537 dB at 6.4 GHz is achieved. This behavior confirms the antenna's optimized radiation characteristics in the mid-to-high-frequency region and emphasizes its suitability for multiband wireless applications.

Sensitivity Analysis and Practicality

The performance of the proposed elliptical ring patch antenna was also examined under variations in conductor width, dielectric constant, and substrate thickness to ensure design robustness. Results indicate that small deviations in conductor width mainly affect impedance matching, while changes in dielectric constant and substrate thickness influence resonant frequencies and bandwidth. However, the antenna maintained stable radiation characteristics and acceptable return loss across these variations, demonstrating good tolerance to fabrication inaccuracies and material inconsistencies. This confirms the design's practicality for real-world implementation.

Suitability for Array Integration

In addition to stand-alone operation, the compact geometry and multimode excitation of the proposed antenna make it a strong candidate for multi-element array configuration. Its symmetrical elliptical structure facilitates easy placement in planar or conformal arrays without significant mutual coupling issues. Therefore, the antenna can be extended for use in array-based systems, supporting applications in advanced wireless communication and radar platforms.

Comparison with Previous Multiband Antennas

The comparative evaluation presented in Table 3 distinctly demonstrates the superior performance of the proposed elliptical ring patch antenna when assessed against previously reported multiband and wideband designs. In earlier investigations, several antennas were primarily developed to achieve broadband or ultra-wideband (UWB) characteristics (14–20). Although wide frequency coverage was successfully realized in many of these studies, the reported gain values were generally moderate, and the overall antenna dimensions were comparatively larger than those of the present design. In some cases, modified ground structures—such as half-circular or slotted configurations—were employed to extend the bandwidth; however, the resulting gain performance typically remained between 2.5 and 5 dBi, indicating limited radiation efficiency in practical operation.

Other reported configurations achieved higher gain levels through the use of cavity-backed or array-based elliptical geometries (16, 17). While these designs offered realized gains exceeding 9 dBi, and in certain instances up to 19 dBi, they required either larger apertures or complex array assemblies, making them less suitable for compact wireless devices. Similarly, antennas employing meta material-based miniaturization techniques achieved size reduction but introduced increased fabrication complexity and reliance on non-standard dielectric materials, which may restrict scalability in conventional fabrication environments (18).

Table 3: Comparison of Proposed Antenna with Previously Reported Multiband Antennas

Reference	Antenna Type / Geometry	Frequency Bands (GHz)	Bandwidth (MHz)	Peak Gain (dBi)	Size (mm^2)	Key Features
Srivastava & Khari (14)	CPW-fed elliptical slot	3.1 – 10.6	~7400	3.5	18.3 × 23	Compact UWB, simple fabrication

Ratnasari *et al.*, (15)	Elliptical patch, half-circular ground	1.8 – 18	~16,200	2.5 – 5	60 × 62	Wideband coverage, chamber testing
Ashong *et al.*, (16)	Elliptical patch for SAR	9.4 – 10.0	640	9.3	45 × 50	High gain for radar applications
Sun & Wong (17)	Elliptical cavity-backed array	28 – 38	~10,000	19 – 21	Array: 32 elements	mmWave CP, array-based high gain
Chen & Alù (18)	Elliptical patch + metamaterial	8.5 – 10.2	~1700	6.0	40 × 45	Miniaturization using μ-negative material
Gupta *et al.*, (20)	Elliptical fractal patch + DGS	3 – 15	~12,000	5.2	36 × 40	UWB with fractal geometry
Bhattacharyya & Shafai (19)	Elliptical annular ring	2.2 – 4.8	~2600	4.8	50 × 55	Wideband CP operation
Proposed Work	Elliptical ring patch with slot	2.4, 4.0, 5.5, 8.4	110 – 560	7.5 (max)	38 × 32.5	Compact size, multiband, high gain

In contrast, the proposed elliptical ring patch antenna exhibits an excellent balance between compactness, gain, and multiband performance. With an overall footprint of only 38 × 32.5 mm^2, it efficiently operates across four distinct resonant bands—2.4, 4.0, 5.5, and 8.4 GHz—effectively covering ISM, LTE, Wi-Fi, and C-band communication systems. A peak realized gain of 7.5 dBi is achieved, representing a significant improvement compared to many earlier compact antenna designs. The integration of an elliptical slot within an outer elliptical ring structure enables multimode resonance and enhanced radiation efficiency, while maintaining a simple and easily manufacturable design compatible with standard FR4 substrates.

Overall, the comparative analysis confirms that the proposed antenna not only matches but, in several aspects, surpasses the performance of existing multiband configurations in terms of size efficiency, gain enhancement, and frequency versatility. Consequently, it can be considered a strong candidate for modern compact wireless communication systems, where both miniaturization and high radiation efficiency are essential requirements.

Conclusion

This work presents a comprehensive evaluation of the proposed elliptical ring patch antenna design through both simulation and experimental measurements. The detailed field distribution analysis across multiple resonant frequencies—including TM_{11}, TM_{21}, TM_{01}, and TM_{31} modes—demonstrated the antenna's capability to support efficient radiation while maintaining compactness. Radiation pattern measurements conducted in an anechoic chamber exhibited excellent agreement with simulated results, thereby confirming the robustness of the design approach. The realized gain performance further validated the antenna's effectiveness across its resonant modes, with measured values of 1.514 dB at 2.4 GHz (TM_{11}), 1.835 dB at 4.0 GHz (TM_{21}), 3.496 dB at 5.6 GHz (TM_{01}), and 4.804 dB at 8.4 GHz (TM_{31}). A maximum realized gain of 7.537 dB was observed at 6.4 GHz, highlighting optimal operation in the mid-to-high frequency range.

A key contribution of this study is the deliberate adoption of the elliptical ring geometry, which provides distinct advantages over conventional circular or rectangular patches. The elliptical structure naturally supports multimode excitation within a reduced footprint, while the central slot introduces additional current paths that enhance impedance bandwidth and improve resonance tuning. Although elliptical structures require more complex mathematical treatment due to Mathieu functions, their benefits in multimode operation, compactness, and efficient radiation make them highly suitable for modern antenna design.

Overall, the results confirm that the proposed antenna delivers stable radiation characteristics, effective field distribution, and enhanced gain across multiple frequency bands. The compact form factor, multimode excitation, and validated high-gain performance establish the antenna as a reliable candidate for a wide range of wireless applications, including ISM, Zigbee, Bluetooth, LTE, 4G, 5G, and UWB systems. The demonstrated novelty—achieving efficient multimode operation (TM_{11}, TM_{21}, TM_{01}, and TM_{31}) within a single elliptical ring structure—sets this work apart from earlier elliptical patch designs and underscores its contribution toward next-generation multiband communication technologies.

Abbreviations

4G: Fourth Generation, 5G: Fifth Generation, CPW: Coplanar Waveguide, dB: Decibel, DGS: Defected Ground Structure, FSS: Frequency Selective Surface, GHz: Gigahertz, ISM: Industrial, Scientific, and Medical, LTE: Long-Term Evolution, RF: Radio Frequency, SAR: Synthetic Aperture Radar.

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Author Contributions

All authors have actively contributed to various stages of this research. Kanani Piyushkumar Dayalji: designing the antenna structure, carrying out the electromagnetic simulations, analysing the simulation data, Vishal Vora: formulating the research idea, overseeing the project, offering technical guidance throughout, Balvant Makwana: handled the antenna's physical fabrication, performed measurements in the anechoic chamber, assisted with interpreting experimental data, drafting the manuscript. Every author has reviewed and approved the final draft of the paper.

Conflict of Interest

The authors affirm that there are no conflicts of interest related to the content or publication of this research work.

Declaration of Artificial Intelligence (AI) Assistance

The authors declare no use of artificial Intelligence (AI) for the write up of the manuscript.

Ethics Approval

As this research did not involve any human or animal subjects, obtaining ethical clearance was not necessary. All procedures followed recognized standards for research integrity and ethical practices in the engineering field.

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