E-ISSN 2586-9027
Homepage : *https://tci-thaijo.org/index.php/SciTechAsia* Science & Technology Asia
Vol.30 No.2 April - June 2025 Page: [176-192]
Original research article

Design, Simulation and Analysis of a Microstrip Rampart Line Antenna (MRLA) for a MIMO-OFDM Transceiver Module in UAV Applications

Jeba Kumar RJS*, G.P. Ramesh

Department of Electronics and Communication Engineering, St. Peter's Institute of Higher Education and Research, Chennai 600077, India

Received 3 May 2024; Received in revised form 16 April 2025
Accepted 30 April 2025; Available online 18 June 2025

ABSTRACT

An Unmanned Aerial Vehicle (UAV) is a swarm of Mobile Sensor Networks that operates in the recommended standard of 802.11g, which needs a miniaturized Microstrip Rampart Line Antenna (MRLA) to establish full duplex Multiple-Input Multiple-Output (MIMO) Radio Frequency Communication. Hence, a MIMO Orthogonal Frequency-Division Multiplexing (OFDM) transceiver module which operates in 432.5 MHz for UAV application is in need for compact size antenna. The innovative aspect of this research paper is to showcase the novel rampart design, i.e., Microstrip Rampart Line Antenna (MRLA) and its practical evaluation, specifically operating within the Ultra-High-Frequency (UHF), i.e., 432.5 MHz. The novelty of the recommended design is to enhance performance in terms of both bandwidth and overall radiation properties. To attest the correctness of the proposed MRLA design, the simulation findings are compared with the state-of-art research design for size reduction comparison, fabricated results were observed, and thereby measured test results via fabrication were found in line with simulated results. The observed fabricated test results of the proposed MRLA antenna for MIMO-OFDM module, constructed for the Operating-Range-of-Frequency (f0) of 432.5 MHz, yields a Reflection-Coefficient (S11) value of -47 dB, an acceptable VSWR numerical value of 1.5, and an Axial Ratio (AR) of 1.8; hence it is ideally suited to establish medium-to-long range UAV RF communication. This proposed antenna will pave the way for futuristic AI based Reconfigurable Antennas for advanced UAV applications.

Keywords: Antenna; MIMO; OFDM; Radio frequency; Radiation pattern

***Corresponding author:** jebakumarrjs@gmail.com **doi:** 10.14456/scitechasia.2025.34

1. Introduction

In Unmanned Aeriall Vehicle (UAV) applications, MIMO-OFDM transceiver modules operating at 432.5 MHz Ultra High Frequency (UHF) are essential for providing dependable and effective communication between the mobile sensor nodes. They also make data collecting, monitoring, and analysis easier for a variety of real-world applications. The MIMO-OFDM module makes distant communication frameworks adequate and allows for higher data flow, especially in Sensor Web of Things applications. Originating from telemetry technology, Machine-to-Machine (M2M) conversation refers to the exchange of statistics between several conversation nodes, without requiring human interaction.

UHF signals ranging from 300 MHz to 3 GHz exhibit relatively good propagation characteristics, allowing them to penetrate obstacles such as buildings, foliage, and atmospheric conditions better than higher frequency bands like microwave frequencies. This makes UHF suitable for various communication applications, including urban and indoor environments. 432.5 MHz falls within the UHF spectrum, typically ranging from 300 MHz to 3 GHz. This frequency range is commonly used for various applications, including television broadcasting, two-way radio communication, satellite communication, and amateur radio operations. At UHF frequencies, antennas tend to be smaller compared to lower frequency bands like VHF (Very High Frequency).

A Microstrip Rampart Line Antenna (MRLA) is a type of antenna design that consists of a conductive trace arranged in a serpentine or zigzag pattern on a substrate. This configuration allows the antenna to achieve a longer physical length within a compact area, thereby increasing its effective radiating length. Microstrip Rampart Line Antennas are commonly used in numerous applications, which involve Wireless Communication Systems (WCS), Radar Systems (RS), and Radio-Frequency-Identification (RFID) devices. One of the key advantages of MRLA Antennas is their compact size, which makes them suitable for integration into small electronic devices and systems where space is limited. [1]. An antenna is an RF electromagnetic transducing entity which transmits and acquires EM, i.e., electromagnetic fields, together with microwave, radio waves, thermal energy, and visually realized photons, i.e., light, through changing electric cutting-edge into EMW and vice versa. A circularly diverged, i.e., polarized electrically powered discipline consists of equivalent-amplitude orthogonal discipline additives which are out of segment through ninety stages and the axial ratio of the sphere is in the direction of zero dB [2, 3].

This novel research paper on Microstrip Rampart Line Antenna (MRLA) is structured meticulously to provide a thorough investigation into the proposed 432.5 MHz Proportionate Microstrip Rampart Line Antenna design. It commences with an Introduction to Microstrip Rampart Line Antenna (MRLA), setting the stage by outlining the significance and applications of MRLA technology. Following this, the Study on Literature Review section critically examines existing literature, emphasizing the research motivations and contributions that lay the groundwork for the proposed study. In the subsequent section, Geometry and Analysis of Proposed 432.5 MHz Symmetric Microstrip Rampart Line Antenna (MRLA), the focus shifts to the technical details of the antenna's structure and design considerations, providing insights into its geometric configuration and analytical framework. The Simulated & Measured Outcomes and Discussion of 432.5 MHz Symmetric Microstrip Rampart Line Antenna section serves as the core of the paper, offering a comprehensive analysis of both simulated and measured performance metrics. This includes a detailed examination of various parameters such as the proposed antenna design, 3-D radiation pattern, S1,1-Parameter, Voltage Standing Wave Ratio (VSWR), Axial Ratio, and Azimuthal Gain (Far-Field), alongside a comparative analysis with existing antenna designs. The Conclusion section summarizes the key findings and implications derived from the study, highlighting the significance of the proposed antenna design and potential avenues for future research.

2. Literature Overview on Current State of Art Research

Chaudhary et al. [4] introduced a log periodic proportionate rampart antenna designed for applications in RF and Sensor Web of Things (S-WoT). The primary objective of the research was antenna miniaturization, aiming to create a compact design suitable for modern wireless communication systems. However, while the antenna succeeded in reducing size, it fell short in achieving optimal spectral efficiency. The antenna was fabricated on a printed circuit board (PCB), which is a common practice in antenna design for ease of fabrication and integration into electronic devices. However, the inclusion of the PCB substrate and associated components led to a reduction in the antenna's gain. This limitation highlights the trade-off between miniaturization and antenna performance. Furthermore, the study identified that small deviations in the frequency band occurred when variations in the rampart structure were introduced. These deviations towards higher frequencies could potentially impact the antenna's performance and suitability for specific frequency bands.

Silue et al. [5] devised an S-band Rampart Line Antenna tailored for implantable telemetry applications. Their study primarily concentrated on altering the time slots between various S-band frequencies to synchronize with the L-band frequency. However, despite this effort, the research did not achieve optimal spectral efficiency. This shortfall can be attributed to the frequency characteristics overlapping as a consequence of the repeated frequency changes implemented through the use of the asymmetric rampart structure. While the study represents a significant advancement in adapting Rampart Line Antennas for implantable telemetry applications, further work is warranted to refine the antenna design and address the spectral efficiency challenges posed by the repeated frequency changes.

Yao et al. [6] introduced a standardized RFID Rampart Line Antenna constructed for short-range RF applications within the UHF frequency band. The primary aim of the research was to develop an antenna that could be seamlessly integrated with a Multiple Input Multiple Output (MIMO) based adaptable electronic antenna system for S-WoT applications. However, despite its intended purpose, the proposed antenna fell short in achieving effective back-reflection loss, thereby adversely affecting the reflection coefficient. The inability to mitigate back-reflections can lead to decreased antenna performance, including issues with impedance matching and signal transmission efficiency. While this work made notable strides in developing a standardized RFID Rampart Line

Antenna for S-WoT applications, further research is necessary to address the challenges associated with back-reflection loss and enhance the antenna's overall performance and suitability for practical deployment in short-range RF applications. This includes investigating alternative antenna designs or optimization techniques to improve back-reflection characteristics and maximize Reflection Coefficient (S11) efficiency.

Das et al. [7] introduced a slotted ground coil antenna engineered to operate in broadband range of radiation. Their research aimed to develop an antenna capable of transmitting and receiving signals across a wide frequency spectrum. However, despite their efforts, the antenna design fell short of achieving the desired antenna efficiency and reflection coefficient below -10 dB.

2.1 Research inspiration and novelty contribution towards envisioned mrla antenna

Microstrip Rampart Line Antennas offer a practical solution for achieving reliable wireless communication in constrained environments while maintaining good performance characteristics. Real-time application requires MRLA radio wire in a size that is compact and can be used for portable applications less than 10 × 10 cm [8-12]. Different side flaps, i.e., side lobes are existing in the 3-Dimensional (3D) radiation reenactment of contemporary state-of-the art ask due to the proximity of the topsy-turvy wander design. Due to pivot impact of MRLA design within the present work there's massive probability of radiation concealment around the fundamental operation recurrence of frequency (f_0), i.e., side groups. The S1,1 antenna constraints of the present work yield the low reflection coefficient esteem of -12 dB [13-15]. The ponder on the current state-of-the-art inquire about, cemented the way for an envisioned research proposal to devise a compacted geometry of 7.5 × 8 cm Microstrip Rampart Line Antenna (MRLA) working at UHF Recurrence of 432.5 MHz for S-WoT Domestic Application in WSN Spectra.

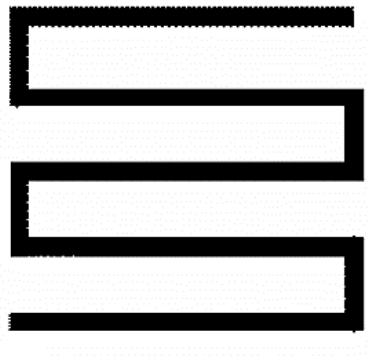

Fig. 1. Zig-zag pattern of symmetric rampart line structure.

3. Geometry and Analysis of Envisioned 432.5 MHz UHF Proportionate Microstrip Rampart Line Antenna (MRLA)

A zigzag-shaped conductive element with multiple segregations is the building block of Rampart Line Antenna, a radio frequency (RF) antenna. The inverted antenna design allows for a very compacted antenna layout and shortens the antenna length (L) while keeping the antenna radiation efficiency ($\dot{\eta}$) very high. Rampart geometry is the term used to describe an antenna with a small electrical diameter. In antenna design, the curved line consists of rows that run horizontally (parallel to the rampart unit) and vertically (perpendicular to the rampart unit). Likewise, the construction of the Rampart Line structure is a symmetrical and asymmetrical design pattern, depending on the application requirements.

The amalgamation of vertical & horizontal lines form turns, i.e., the curvy geometry edifice is as shown in Fig. 1. Turns are necessary to increase the antenna's effectiveness. The resonance frequency (f_0) of the antenna is reduced when the rampart interval increases.

In order to overcome the demand for size restrictions, folded Rampart Line Antennas can be designed to repeat the same shape in a limited number of measurements, which increases the antenna and its overall length by at least half the wavelength of the required frequency. Mobile devices like smartphones and tablets frequently use Rampart Line Antennas due to their small size, and broad bandwidth is a popular choice. In addition, they are utilized in wireless communication systems & RFID [16-18], When space is limited, a Rampart Line Antenna can be both cost-effective and efficient. The antenna and its structure are exactly standardized using Advanced Electro-Magnetic-Simulation (EMS) using the CAD software i.e. FEKO tool, a moment technique platform utilized to compute radiating antenna properties and optimization techniques to ensure optimum Impedance-Matching (IM) and radiation power in the UHF frequency bands. Antenna performance can be influenced by factors such as rampart length, patch length, slot length to slot width. Design execution of the envisioned symmetrical 432.5 MHz Microstrip Rampart Line Antenna (MRLA).

Rampart lines have the same radio signal radiation efficiency as traditional half and quarter lengths. The Rampart Line Antenna size reduction parameter (β) is mainly calculated by the numerical figure and placing of the rectangular meshes of the rampart line element, which is mainly an amalgamation of vertical and horizontal lines. The antenna's polarization is determined by the Rampart line radiation. The proximity of two curves is a crucial factor, as it can cause more cross-linking and affect the polarization rate of the radiation pattern [19].

The construction of the MRLA Microstrip Rampart Line Patch antenna unit typically consists of the following entities:

- Substrate: The substrate is usually a dielectric cloth with low loss and high permittivity, consisting of fiberglass epoxy (FR-4), Rogers Duroid, or Teflon. The substrate provides a mechanical assist and determines the antenna's electric residences, along with impedance matching and bandwidth.
- Patch: The patch is a conductive detail usually made of copper or aluminum that is positioned on one side of the substrate. It is generally in the form of a rectangle, square, circle, or different geometries. The patch radiates electromagnetic waves while excited via an RF signal.
- Ground Plane: The floor aircraft is a conductive layer on the opposite aspect of the substrate from the patch. It serves as a reflective surface for the electromagnetic waves radiated by the patch, improving antenna performance and directing radiation inside the favored route.

The R-L-C (Resistor-Inductor-Capacitor) equal circuit version is a simplified illustration used to describe the electrical conduct of an antenna. Basic RLC Representation represents an antenna's electrical houses the use of fundamental passive electrical additives inclusive of resistors, inductors, and capacitors as depicted in Fig. 2.

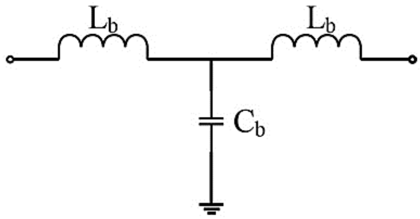

Fig. 2. Equivalent Prototype of Envisioned Microstrip Rampart Line Antenna (MRLA).

- Resistor (R): Represents the radiation resistance of the antenna. This component debts for the strength dissipated as electromagnetic waves radiate from the antenna structure into unfastened area.
- Inductor (L): Represents the antenna's inductive element, normally associated with the bodily duration and shape of the antenna.
- Capacitor (C): Represents the antenna's capacitive element, which arise from the spatial distribution of fee within the antenna shape.

The RLC model helps in understanding impedance matching techniques for antennas. By adjusting the values of R, L, and C, it is possible to optimize the antenna's impedance to match that of the transmission line or the connected electronics, thereby maximizing power transfer efficiency. While the RLC equivalent circuit provides a useful conceptual framework, it is a simplified model that may not capture all aspects of antenna behavior accurately, especially for complex antenna designs or at very high frequencies. More sophisticated modeling techniques, such as electromagnetic simulation software, are often employed for detailed analysis and design validation. The horizontal lines are found along the patch's linear length (l) of the printed circuit board (PCB), whereas the vertical lines are placed along the patch length. The geometrical alignment of the MRLA antenna warrants for a smaller footprint of less than 0.1 λ, as it is equivalent to repeating folded dipole antenna [20]. The arithmetic representation of accumulated inductance (L) and capacitance (C) is computed as stated in arithmetic Eqs. (2.1)-(2.4).

$$Inductance\ of\ MRLA\ (L) = \frac{L \times l}{2}, \tag{3.1}$$

$$Capacitance\ of\ MRLA\ (C) = C \times l, \tag{3.2}$$

where, L is Inductance per unit length, C is Capacitance per unit length & l is linear length of the MRLA rampart segment. The definite impedance of unit section of rampart line is scientifically expressed in terms of spacing & thickness as,

$$Impedance\ MRLA = 276 \times log[\frac{s}{t}], \tag{3.3}$$

where, s is the distance between ramparts and t is the thickness of the rampart line. The effective length of the Microstrip Rampart Line Antenna is expressed as,

$$S \times N = \frac{\lambda}{10}. \tag{3.4}$$

Here N is the empirical number of turns (Rampart Unit), λ is the wavelength and S is the space between the two rampart lines. In the far-field model, where the magnetic fields are removed, the Rampart Line Antenna and its transmission lines do not emit fields. The vertical parts of the MRLA emit radiation fields.

3.1 Geometric structure of envisioned proportionate 432.5 MHz microstrip rampart line antenna (MRLA)

Microstrip Rampart Line Antenna (MRLA) fabricated on an FR4 substrate

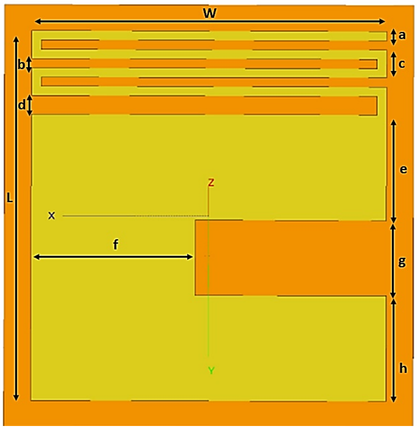

Fig. 3. MRLA 432.5 MHz rampart line antenna geometry & design label.

typically consists of a thin conducting trace patterned on the FR4 material. The structure resembles a series of interconnected "ramparts" or zigzag-shaped lines, hence the name "rampart line." These ramparts effectively increase the length of the antenna within the limited physical space of the substrate, enabling resonance at the desired operating frequency. The conducting trace is usually made of copper, etched onto the FR4 substrate using standard printed circuit board (PCB) fabrication techniques. The width, spacing, and number of ramparts are carefully designed to achieve the desired electrical characteristics, such as impedance matching, radiation pattern, and bandwidth. Additionally, the FR4 substrate provides mechanical support and insulation for the antenna, ensuring stability and electrical isolation. Overall, the structure of an MRLA on an FR4 substrate is designed to optimize performance while maintaining a compact and cost-effective design that is perfectly apt for numerous radiocommunication applications. In the rampart configuration, the antenna element takes up less space in each dimension within 85 × 70 mm. FR4 substratum is used with a

Table 1. Geometric Dimensions of 432.5 MHz Microstrip Rampart Line Antenna (MRLA).

Label	Measurement (mm)
a	1.75
b	1.75
c	5.25
d	3.50
e	20
f	30
g	14.25
h	20
L	70
W	65
Rampart Patch Measurement	70 × 65
Ground Plane Measurement	75 × 80
Substrate (FR4) Measurement	75 × 80 × 0.8

dielectric-constant (ε) of 3.7-3.8. The element of the rampart line consists of planar (zero degree) and linear (perpendicular) lines, which results in a sequence of right-angled curves as shown in Fig. 3. The radiation emitted from the curves is responsible for determining the antenna's polarization. In other possibilities, the distance is restrained by the available rampart lattice space and the polarization of the radiation field depends on the distance between the bend over microstrip rampart lines. Table 1, describes geometric scalar measure for the envisioned UHF 432.5 MHz Proportional Microstrip Rampart Line Antenna (MRLA).

Table 2 presents the essential data about Simulation Assumptions, Numerical Methods and Material Parameters for the proposed MRLA Design.

4. Simulated vs. Fabricated Result Analysis of 432.5 MHz UHF Proportionate Microstrip Rampart Line Antenna (MRLA)

The Microstrip Rampart Line Antenna's (MRLA) structure has a model of perpendicular and horizontal lines. By combining horizontal lines and perpendicular linear lines, complete rotations are made

Table 2. Simulation assumptions, numerical methods, and material parameters for MRLA design.

Parameter	Value / Data	Source
Dielectric Constant (Er)	4.3	FR4 datasheet (average)
Loss Tangent (δ)	0.02	Assumed from Literature [1]
Patch & Ground Plane Electrical Conductivity of Copper (σ)	5.8×10^7 S/m	Standard Material Property
Substrate Thickness of FR4 Dielectric Material	0.8 mm	PCB Fabrication Specification
Simulation Tool	CAD Feko 2022	EM Software Suite
Solution Technique	Method of Moments	CAD FEKO Solver
Operating Frequency	432.5 MHz	Design Target
Feeding Technique	Edge Feed	Edge Feed at the bottom center edge of Patch via SMA Connector

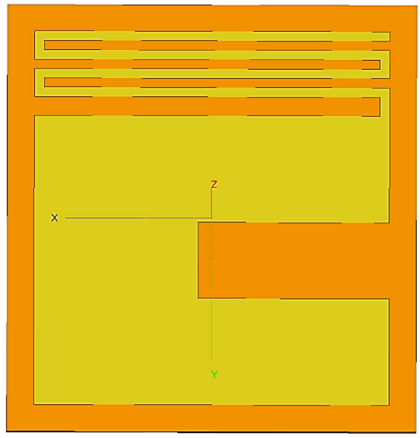

Fig. 4. Simulated proportionate patch of a UHF 432.5 MHz microstrip rampart line antenna (MRLA) - top view.

into turns, i.e., repeating patterns known as ramparts.

4.1 Proposed antenna design of UHF 432.5 MHz symmetric microstrip rampart line antenna (MRLA)

In the proposed MRLA antenna, the number of turns upgrades the RF power of the antenna. A standard linear monopole antenna (MPA) can be bent, which is necessary for UHF applications where it's even possible to use Microstrip Rampart Line Antenna designs. The 65 × 70 mm flex mark on the upper portion of the antenna unit is a metallic piece of repeated rampart in a symmetrical pattern that transmits an RF signal at 432.5 MHz frequency. The patch of the Rampart Line Antenna (Top View) is as illustrated in Fig. 4.

The proposed work employs a dielectric substrate and the interlayer that connects the Rampart Patch area to the ground plane, i.e., FR4. To improvise the gain factor and RF radiation effectiveness of the antenna's performance, a 75 × 80 mm metal ground plate (GP) is placed on the underside of the antenna. The GPS application reduces electrical noise and backscatter, i.e., an adjacent rampart unit interferes within the structure. The rampart patch unit in the MRLA Antenna serves as the radiating element responsible for transmitting and receiving electromagnetic waves. It is typically a metallic structure, often made of copper, printed on a dielectric substrate such as FR4. The patch's dimensions, shape, and configuration determine the antenna's operating frequency, radiation pattern, and impedance characteristics. By applying an alternating current to the feed point of the patch, electromagnetic waves are generated and propagated into free space. The patch's geometry and dimensions are carefully designed to achieve desired performance parameters such as gain, bandwidth, and polarization. Overall, the patch is the essential component of the patch antenna, responsible for its functionality in wireless communication systems. The ground plane in a patch antenna serves several important purposes. It acts as a reflector, directing the radiated energy away from the antenna's feed point and towards the desired direction of radiation. This helps in shaping the antenna's radiation pattern and increasing its direc-

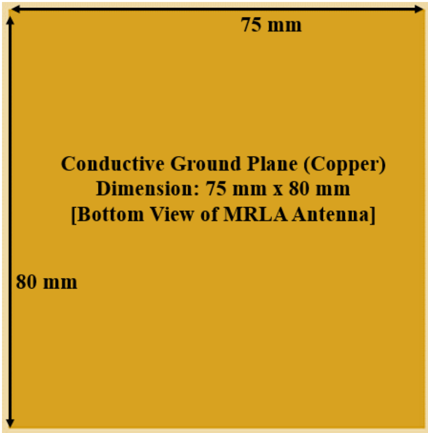

Fig. 5. Simulated ground plane for UHF 432.5 MHz microstrip rampart line antenna (MRLA) - bottom view.

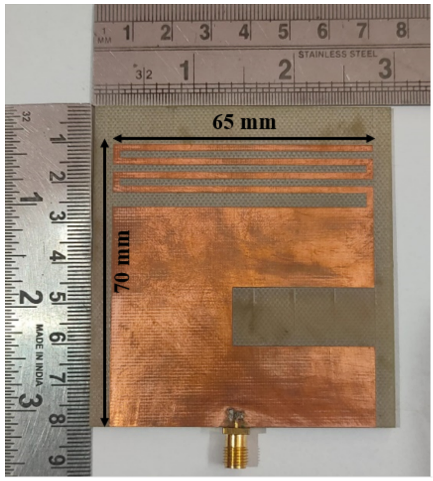

Fig. 6. Fabricated proportionate patch of a UHF 432.5 MHz microstrip rampart line antenna (front side i.e. top view).

tivity. It provides a stable reference for the antenna's electrical field, enhancing its impedance matching and efficiency. Overall, the ground plane plays a critical role in enhancing the performance of patch antennas by providing structural support, enhancing radiation characteristics, and improving overall antenna efficiency. The ground plane (bottom view) of the 432.5 MHz Microstrip Rampart Line Antenna is as shown in Fig. 5; it is a full surface Ground Plane of 75 mm × 80 mm.

Antenna simulation is the process of using computer programs to model how antennas will behave. Antenna fabrication involves constructing antennas based on these simulated designs, using techniques like circuit board manufacturing and metal shaping. The design of 432.5 MHz MRLA antenna is done by CAD-FEKO software by implementing proper meshing of various rampart strip lines, i.e., Vertical & Horizontal. The hardware unit of MRLA consist of Patch (Top), Ground Plane (Bottom) and Substrate (Dielectric Sandwich). FR4 Substrate is made of flame-resistant epoxy resin, i.e., glass fabric composite; moreover, it is an easily available material and cost effective. The simulated MRLA design input file is fed as a reference model into a CNC machine, and is properly milled to form the desired structure precisely. The input, i.e., excitation feed, is soldered using an SMA (Sub-Miniature version A) Connector which has an impedance of 50 ohm. The copper clad lamination serves as the base material for the antenna. The fabricated MRLA patch of the Rampart Line Antenna (Top View) is as shown in Fig. 6. The Fabricated Ground Plane (Bottom View) of the 432.5 MHz Microstrip Rampart Line Antenna is as shown in Fig. 7.

Testing antennas is vital to verify the simulation and fabrication results. This provides real-world data on the antenna's performance and ensures it meets the design goals. Testing also enables quality control during mass production, ensuring consistency and reliability across batches of antennas. The process of creating effective antennas involves simulation, fabrication, and testing. The spectrum analyzer scans a radio frequency signal across the entire

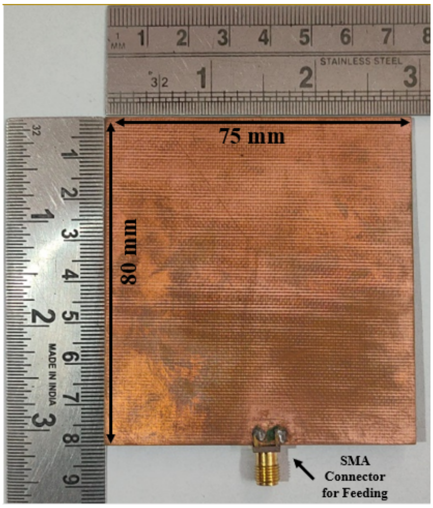

Fig. 7. Fabricated ground plane of UHF 432.5 MHz microstrip rampart line antenna (back side).

antenna and displays the spectral content, helping to tune the antenna for optimal performance. This essential instrument measures and displays the amplitude of signals across a specified frequency range. Modern spectrum analyzers offer a wide range of features, including frequency domain analysis, signal demodulation, and various measurement capabilities, making them crucial for the development of effective antennas. The Antenna Being Tested (AUT) is connected to the spectrum analyzer. This allows the measurement of the antenna's radiation characteristics, such as its radiation pattern, gain, and impedance matching. The AUT could be a prototype or a commercial antenna. The testing environment needs careful control to minimize external interference and reflections. Shielded anechoic chambers or controlled outdoor test ranges are commonly used to simulate real-world conditions while reducing external influences on the measurements. Calibrating the setup is crucial for accurate measurements. This involves calibrat-

Fig. 8. Experimental setup of the UHF 432.5 MHz microstrip rampart line antenna measured by antenna testing spectrum analyzer.

ing the spectrum analyzer, antenna connections, cables, and other components. Calibration standards such as calibration kits or reference antennas are used to establish accurate measurement reference points.

A spectrum analyzer measures electrical signal spectral content. Test an antenna by connecting it to the analyzer and transmitting a signal. Analyzer displays spectral content within expected range for proper antenna function. Experimental setup for the proposed antenna 432.5 MHz Microstrip Rampart Line Antenna measured by Antenna Testing Spectrum Analyzer is as depicted in Fig. 8, to obtain the hardware outputs.

4.2 Proportionate 432.5 MHz microstrip rampart line antenna (MRLA)'s 3D-radiation pattern (RP)

An antenna emits or receives radiation to determine the wavefront's strength. In all figures, the pattern describing the RF emission from the antenna unit is called the radiation pattern (RP). A 3-D radiation pattern illustrates the radiation intensity or power density of an antenna in all three spatial dimensions: azimuth (horizontal plane), elevation (vertical plane), and radial (distance from the antenna). The 3-D radiation pattern comprises main lobes, side lobes, and nulls. The main lobes are the primary directions where most of the radiation en-

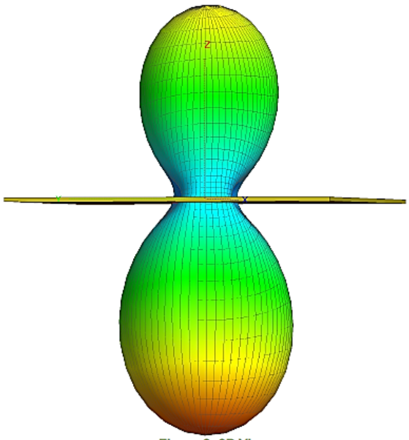

Fig. 9. 432.5 MHz rampart line antenna 3D radiation pattern (RP) of MRLA

ergy is focused. The side lobes are smaller radiation lobes in directions away from the main lobe. Observing 3D radiation pattern is vital for designing, deploying, and optimizing antennas for applications like wireless communications, radar, satellite communications, and broadcasting. The Radio Frequency (RF) energy radiated by the antenna is called the radiation pattern (RP) as shown in Fig. 9.

4.3 Proportionate 432.5 MHz microstrip rampart line antenna (MRLA)'s $S_{[1,1]}$ parameter

The RF Reflection Coefficient (RC), also known as S_{11}, is a fundamental parameter used to evaluate the performance of an antenna or other RF components. It measures how much of the incoming electromagnetic energy gets reflected back from the load or antenna system. A low S_{11} magnitude indicates good impedance matching between the transmission line and the load, meaning minimal energy is lost due to reflection. Conversely, a high S_{11} magnitude suggests poor impedance matching, leading to significant energy reflections and potentially reduced system performance. An-

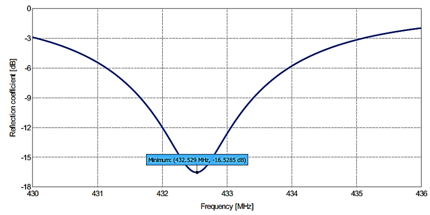

Fig. 10. 432.5 MHz rampart line antenna's reflection coefficient $S_{[1,1]}$ parameter.

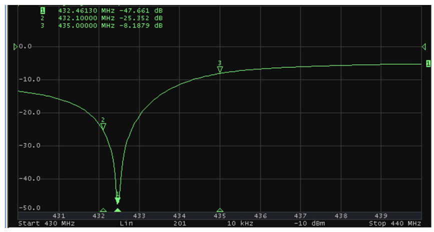

Fig. 11. S_{11} parameter of 432.5 MHz microstrip rampart line antenna measured by antenna testing spectrum analyzer.

alyzing S_{11} measurements helps optimize impedance matching, assess antenna performance, and ensure efficient power transfer in RF systems. The amount of RF power transmitted and received due to a change in impedance is denoted by S_{11} and the proposed 432.5 MHz Microstrip Rampart Line Antenna (MRLA) with symmetrical bandwidth was found to be -6.5 dB. Simulated S_{11} represents a proportional share of the incident RF energy is as depicted in Fig. 10. The fabricated 432.5 MHz Microstrip Rampart Line Antenna is being tested to yield the Reflection Co-efficient value by Antenna Testing Spectrum Analyzer is as illustrated in Fig. 11. The X and Y axis of the graph are adjusted in Fig. 10 and Fig. 11 to enable better visibility for result comparison between simulated and fabricated outcomes.

The proportionate fraction of incident RF signal strength to echoed RF signal strength from the system is represented by return loss (RL), is stated in decibels (dB) unit as in Eq. (4.1). Elevated Return Loss (L) leads to low reflected power in a system. Hence, it is advantageous to use a high-performance loss system.

$$Return\ Loss\ (L) = -20Log(S_{1,1})[dB] \tag{4.1}$$

Return Loss (L) is a key constraint used to compute the impedance (Z) matching of an antenna & it is stated in decibels (dB). It is estimated as the ratio of the power of the incident signal to the power of the echoed signal, i.e., reflected back to the source. A higher return loss implies better impedance matching, indicating that most of the incident signal is absorbed or transmitted through the component, and less is reflected back towards the source. On the other hand, a lower return loss implies poor impedance matching, leading to in higher levels of signal reflection.

4.4 Proportionate 432.5 MHz microstrip rampart line antenna (MRLA)'s voltage standing wave ratio (VSWR)

The Voltage Standing Wave Ratio (VSWR) is a radiation parameter used to assess the impedance (Z) matching and efficiency of an antenna system. It quantifies the ratio of the maximum voltage (Vmax) of the standing wave pattern along a transmission line to the minimum voltage (Vmin) VSWR indicates how well the antenna system is matched to the transmission line and source or load impedance. A VSWR of 1 indicates perfect impedance matching, meaning all power is delivered to the antenna without any reflection. As VSWR increases above 1, it signifies greater mismatch and increased power loss due to reflections. Typically, a VSWR below 2 is considered acceptable for most applications, indicating efficient power transfer and minimal signal loss.

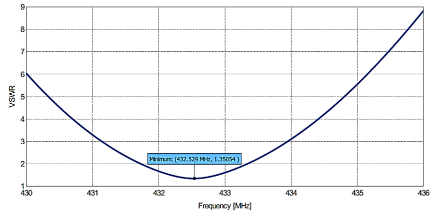

Fig. 12. VSWR value of proportionate 432.5 MHz rampart line antenna (MRLA).

VSWR measurements are used to optimize antenna designs, ensure proper impedance matching, and maximize the performance of RF systems. They measure efficacy of RF power that is being transferred from the RF power source to the final load as shown in Fig. 12, and the design of a proportionate 432.5 MHz Microstrip Rampart Line Antenna (MRLA) obtained the value 1.3. Excessive VSWR results in poor transmission line efficiency, and the transmitter's own efficiency can be compromised by the reflected energy loss (RF loss). The voltage remains constant in a faultless system, for instance. The Microstrip Rampart Line Antenna's Acceptable VSWR is less than 2, or more often considered as 1:1.5 (appropriate accepted value). A representation of the VSWR in terms of reflection-coefficient (τ) is shown as Eq. (4.2). The fabricated 432.5 MHz Microstrip Rampart Line Antenna is being tested to yield the VSWR value by Antenna Testing Spectrum Analyzer is as depicted in Fig. 13. The X and Y axis of the graph are adjusted in Figs. 12-13 to enable better visibility for result comparison between simulated and fabricated outcomes

$$VSWR = \frac{1+\tau}{1-\tau}. \tag{4.2}$$

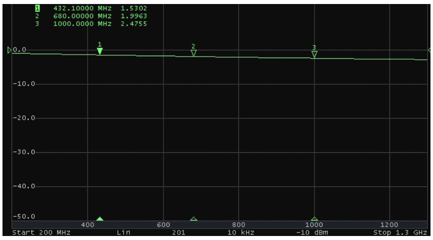

Fig. 13. VSWR of 432.5 MHz microstrip rampart line antenna (MRLA) measured by antenna testing spectrum analyzer.

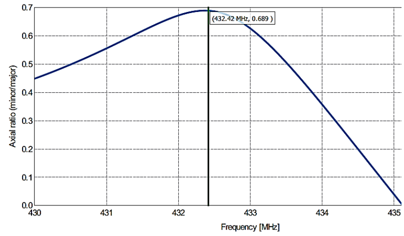

Fig. 14. Axial ratio value of 432.5 MHz microstrip rampart line antenna (MRLA).

4.5 Proportionate 432.5 MHz microstrip rampart line antenna (MRLA)'s axial ratio (AR)

The Axial Ratio (AR) of an RF antenna is a measure used to analyze the performing ability of the antenna, as shown in the Fig. 14. AR is a parameter used to characterize the polarization of an antenna. A low AR indicates circular polarization, where the EF vector rotates uniformly around the direction of propagation. In contrast, a higher axial ratio implies elliptical polarization. The Amax (Major Axis) and Amin (Minor Axis), which are the ratios of an antenna sample, are referred to as Circularly-oriented-axial-Polarized (CP) or Elliptically-oriented-axial-Polarized (EP) are shown in Eq. (4.3). AR is equal to numerical one (0 dB) when the RF antenna is circularly polarized, while the ratio is greater than one (> 0 dB) when the antenna is elliptical. The radiation emitted by the proposed 432.5 MHz Microstrip Rampart Line Antenna (MRLA) is elliptically polarized due to its close proximity of AR is 0.6. The AR represents the deviation from the antenna's standard circularly oriented polarization within a specific angular range. It represents the ratio of the Major Axis (Max-A) to the Minor Axis (Min-A) of the polarization ellipse, which describes the orientation and ellipticity of the electric field (EF) vector of the radiated electro-magnetic waves (EMW). Axial ratios are commonly used to describe circular polarity antennas. This means that the deviation from the circularly oriented polarization will be much less than 3dB in the explicit angular scope. The fabricated 432.5 MHz Microstrip Rampart Line Antenna is being tested to yield the Axial Ratio value by Antenna Testing Spectrum Analyzer as depicted in Fig. 15. The Simulated value of 0.6 (Rounded to 1) is exactly matches with the fabricated antenna's test result of greater than 1, depicts the Circular Polarization of the Proposed MRLA antenna. This property makes its best suited for 360-degree RF Scanning ability in UAV applications. The X and Y axis of the graph are adjusted in Figs. 14-15 to enable better visibility for result comparison between simulated and fabricated outcomes.

$$Axial\ Ratio = \frac{A_{max}}{A_{min}}. \qquad (4.3)$$

4.6 Far-field gain (Azimuthal) visualization of proportionate 432.5 MHz microstrip rampart line antenna (MRLA)

Azimuthal gain, in the far-field region, refers to the directive characteristics of an antenna in the horizontal plane. It represents the variation in signal strength or radiation intensity of the antenna as a function of azimuth angle. A high azimuthal gain in-

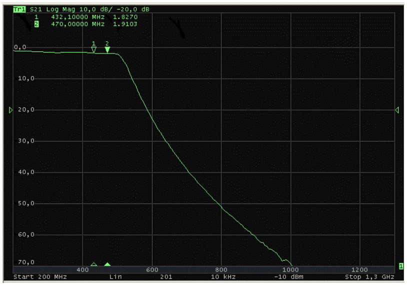

Fig. 15. Axial ratio of 432.5 MHz microstrip rampart line antenna (MRLA) measured by antenna testing spectrum analyzer.

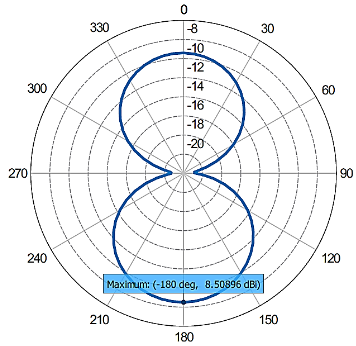

Fig. 16. Proportionate 432.5 MHz microstrip rampart line antenna (MRLA) far-field azimuthal chart planar interpretation.

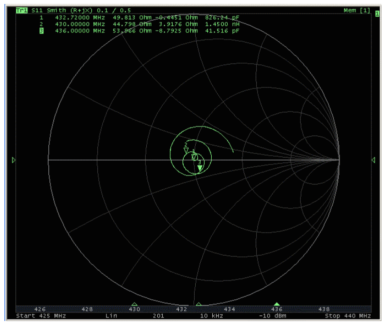

Fig. 17. Smith chart far-field representation of the microstrip rampart line antenna measured by antenna testing spectrum analyzer.

dicates that the antenna is more directive in the azimuthal plane, focusing its radiation pattern on specific directions. Conversely, a lower azimuthal gain implies a broader radiation pattern with less directionality. Azimuthal Gain (AG) measurements evaluate antenna performance, optimize antenna placement for desired coverage areas, and mitigate interference in wireless communication systems. The far-field is the dominion where the field is determined by a generic electromagnetic wave. This region is dominated by oblique energetic EM fields associated with energetic dipole properties. As described in the remote field depiction as shown in Fig. 16, as 8 dB Gain (G) value, for the suggested 432.5 MHz Proportional Microstrip Rampart Line Antenna. The azimuth plane model is created by cutting the 3D radio model of the RF antenna in a horizontal plane, i.e., the XY-Plane. Since the azimuth planar pattern is omnidirectional, the receiver distributes the RF energy across the Azimuthal (Az) Plane to better resolve 3D antennas than the 2D plane. The long range 432.5 MHz Microstrip Rampart Line Antenna (MRLA) is shown in Eq. (4.4). D is the MRLA's span of RF & λ is the wavelength of the radio wave. The fabricated 432.5 MHz Microstrip Rampart Line Antenna is being tested to yield the Far-Field Gain through Smith chart representation by Antenna Testing Spectrum Analyzer is as depicted in Fig. 17.

$$dF(\text{Far Field Distance}) = \frac{2 \times D^2}{\lambda}. \quad (4.4)$$

4.7 Performance analysis of proportionate 432.5 MHz rampart line antenna with current state-of-the-art mrla research works

A study related to the current research using a symmetrical 432.5 MHz Microstrip Rampart Line Antenna (MRLA) is proposed in Table 3. The study shows that our new proportioned 432.5 MHz Microstrip Rampart Line Antenna (MRLA) has better antenna performance and also smaller size of up to 75 × 80 mm than the current research using a symmetrical rampart line model. Noticeably, a high Reflection-Coefficient (S1,1) of -16.5 dB, is significant than state-of-the-art i.e., current-research holds a middling value of S1,1 which is less than -15dB. The appreciable value of 1.35 i.e., <1.5 (exact value) is the most acceptable VSWR range; that is better compared to all surveyed current research. The elliptically oriented axial ratio of 0.6 and the highest FF-Gain of 8 dB depicts a surge in the current-research observations.

4.8 Comparative result analysis of simulated vs fabricated 432.5 MHz microstrip rampart line antenna

The simulation results and fabricated antenna test results for the proposed proportionate 432.5 MHz Microstrip Rampart Line Antenna (MRLA) are analytically compared in Table 4. In the simulation, the reflection coefficient (S_{11}) is found to be -16.50 dB, while in the actual tests, it is noted as -47.6 dB. This observation shows that the fabricated antenna performs significantly better in terms of reflection coefficient ($S_{1,1}$). The VSWR value is numerically observed as 1.35 in the simulation, and it slightly increased to 1.5 in the hardware test observation. The axial ratio also differed, with the simulation yielding 0.68 and the fabricated test resulting to the value of 1.8. The Far Field Gain (FF-G) remained relatively consistent between the simulation (8.50 dB) and the tests (8.10 dB). However, the directivity in the far field was slightly higher in the tests (13.6 dB) compared to the simulation (12.12 dB). Overall, the fabricated antenna proves to be favorable OFDM in UAV application & antenna performance is better which proclaims to be well suited for real-time implementation.

5. Conclusion

The symmetrical Microstrip Rampart Line Antenna (MRLA) operates at 432.5 MHz within the UHF frequency band and boasts compact dimensions of 75 x 80 mm, making it notably smaller than contemporary designs. Notably, it exhibits a successful reflection coefficient (τ of -47.6 dB, surpassing all the rampart antenna current state-of-the-art investigation. The return loss (RL) of -24 dB is determined by converting the RC magnitude to decibels. Likewise, the Voltage Standing Wave Ratio (VSWR) for the 432.5 MHz MRLA stands at 1.5, indicating favorable impedance matching suitable for real-time applications. With an Axial Ratio (AR) range of 1.8, the antenna achieves elliptical polarization characterized by a high-intensity orthogonal electric field, ideal for medium-range UAV applications. Future research endeavors will focus on utilizing various optimization methods to further reduce the MRLA's symmetrical proportionate rampart line model, aiming to achieve a more streamlined design structure while enhancing antenna efficiency. Hence, the development of the proportionate 432.5 MHz Microstrip Rampart Line Antenna represents a significant advancement in UHF antenna technology, offering a compact and highly efficient RF antenna in UHF frequency range. The proposed fabricated antenna displays an impressive reflection coefficient, return loss, VSWR, and axial ratio which makes it feasible for real-time implementation, particularly in UAV MIMO-OFDM module unlocking new possibilities for UAV communication systems. Also, this work paves the way forward to futuristic AI Antennas for advanced UAV applications.

Table 3. Comparative Analysis of Simulated Proportionate 432.5 MHz Rampart Line Antenna with current state-of-the-art research.

Parameter	Proposed	Ref. [6]	Ref. [5]	Ref. [4]
Antenna Geometry in mm	75 × 80	400 × 200	180 × 100	85 × 30.5
Reflection Coefficient (S1,1)	-16.50 dB	- 16 dB	-12 dB	-15.2 dB
Voltage Standing Wave Ratio (VSWR)	1.35	1.6	1.4	1.1
Gain Far-Field (G-FF)	8.50 dB	6.3 dB	9.4 dB	7.6 dB
Directivity Far-Field (D-FF)	12.12 dB	14.7 dB	11.3 dB	10.3 dB
Axial Ratio (AR)	0.68	Not Reported	Not Reported	Not Reported

Table 4. Simulation vs Fabricated Antenna comparative result analysis on the Proportionate 432.5 MHz MRLA Antenna.

Parameter	Simulation Result of MRLA Antenna	Fabricated Testing Result of MRLA Antenna
Reflection Co-efficient (S_{11})	-16.50 dB	-47.6 dB
VSWR	1.35	1.5
Axial Ratio	0.68	1.8
Gain (Far Field)	8.50 dB	8.10 dB
Directivity (Far Field)	12.12 dB	10.6 dB

Acknowledgement

The corresponding author of this research paper would like to thank the RF Communication Research Lab at the Department of Electronics and Communication in St. Peter's Institute of Higher Education and Research, India.

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