

# Enhancing A Compact Dual-Polarized MIMO Vivaldi Antenna using Metamaterials for IoV Communications

<sup>1</sup>Dr. Jenitha A

*Associate Professor*

*Department of Electronics and  
Communication Engineering  
Dr. T Thimmaiah Institute of  
Technology KGF, India*

<sup>2</sup>Jeyasree A P

*Department of Electronics and  
Communication Engineering  
Dr. T Thimmaiah Institute of  
Technology KGF, India*

<sup>3</sup>Nikhil Guddakar

*Department of Electronics and  
Communication Engineering  
Dr. T Thimmaiah Institute of  
Technology KGF, India*

<sup>4</sup>Rohith R

*Department of Electronics and  
Communication Engineering  
Dr. T. Thimmaiah Institute of  
Technology KGF, India*

<sup>5</sup>Sanjay M D

*Department of Electronics and  
Communication Engineering  
Dr. T. Thimmaiah Institute of  
Technology KGF, India*

**Abstract:** In this paper, a compact dual-polarized MIMO Vivaldi antenna enhanced with metamaterials, specifically designed for vehicular communication networks. The proposed antenna structure offers significant improvements in gain, bandwidth, and radiation efficiency, which are critical for ensuring reliable V2X (Vehicle-to Everything) communications in dynamic and challenging environments. By integrating metamaterial structures into the antenna design, enhanced impedance matching and improved directivity are achieved. These enhancements contribute to substantial reductions in mutual coupling between antenna elements and support better polarization diversity, which are essential features for effective MIMO operation. The antenna is optimized for wideband performance, supporting the high data rate demands of 5G networks and future intelligent transportation systems (ITS). Both simulated and experimental results confirm the wideband operation, high stability, and efficiency of the proposed antenna across the targeted frequency bands. The design makes it a promising solution for autonomous vehicles, Internet of Vehicles (IoV) applications, and next-generation vehicular communication infrastructures.

**Keywords:** *Dual- Polarization, Multiple input Multiple output (MIMO), Vivaldi Antenna, Meta-materials, Polarization diversity, IoV.*

## I. INTRODUCTION

In the rapidly evolving domain of wireless communication, the increasing proliferation of connected and autonomous vehicles has driven the development of advanced vehicular communication technologies. The emergence of the Intelligent Internet of Vehicles (IoV) has transformed traditional transportation into a dynamic, data-driven ecosystem that supports real-time communication, sensing, and decision-making. Central to this transformation is the requirement for high-performance antennas that enable reliable, high-speed communication under

varying conditions. Antenna systems used in IoV must offer compact form factors, broad bandwidth, high gain, and low mutual coupling—parameters that are often challenging to balance in conventional designs.

Multiple-Input Multiple-Output (MIMO) antenna systems have become fundamental in addressing the challenges associated with vehicular communications. MIMO configurations enhance spectral efficiency, reliability, and channel capacity by enabling multiple parallel data streams. When coupled with dual-polarization techniques, these

systems can mitigate polarization mismatches and signal fading, thereby ensuring consistent connectivity across diverse environments. Among the various antenna architectures, the Vivaldi antenna stands out for its ultra-wideband (UWB) characteristics, directional radiation pattern, and suitability for high-frequency applications such as 5G and 6G. Its end-fire radiation mechanism and compatibility with printed circuit board (PCB) fabrication make it an ideal candidate for vehicular integration.

Despite its advantages, the Vivaldi antenna is constrained by its relatively large size and mutual coupling issues when deployed in MIMO arrays. These limitations hinder its adoption in space-constrained vehicular platforms. To overcome these challenges, researchers have increasingly turned to the integration of metamaterials—artificially engineered materials that exhibit electromagnetic properties not found in nature. Metamaterials such as complementary split-ring resonators (CSRRs), artificial magnetic conductors (AMCs), and electromagnetic bandgap (EBG) structures can be strategically incorporated into antenna designs to enhance performance metrics including isolation, bandwidth, and gain. These inclusions allow the antenna to remain compact while achieving superior signal propagation and minimal interference.

The concept of using metamaterials to manipulate wave propagation has been extensively explored in recent years. By modifying the effective permittivity and permeability of the antenna substrate, metamaterials enable advanced control over radiation behavior, impedance matching, and surface current distribution. In the context of IoV, where multipath interference and dynamic operating conditions are prevalent, such enhancements significantly improve communication reliability. For instance, the placement of CSRRs in the antenna's feed region enhances impedance matching, while the use of an AMC layer reduces surface wave propagation and mutual coupling. The result is a system that supports low envelope correlation coefficients (ECC), high isolation, and robust dual-polarized transmission and

reception.

Furthermore, fractal geometries are often employed to miniaturize antennas without compromising their electrical performance. Structures such as the Sierpinski gasket or Koch curve provide self-similar patterns that allow multi-band operation, wide bandwidth, and increased edge length for radiation. These geometries are particularly advantageous for vehicular antennas, where compactness and high performance are essential. When integrated with metamaterials, fractal-inspired Vivaldi antennas can be optimized for multi-band operation, making them suitable for both sub-6 GHz and millimeter-wave (mmWave) frequency bands—critical for modern V2X (Vehicle-to-Everything) communication systems.

IoV environments are characterized by constant motion, variable line-of-sight conditions, and diverse interference sources. Therefore, antennas deployed in such networks must exhibit stable radiation patterns, polarization diversity, and high gain across wide frequency ranges. Dual-polarized MIMO Vivaldi antennas, enhanced with metamaterials and fractal geometries, fulfill these criteria. Their ability to maintain robust links in high-speed scenarios such as highway driving, vehicle platooning, and urban navigation is vital for the deployment of autonomous driving technologies and intelligent transportation systems (ITS).

The integration of such advanced antenna technologies directly contributes to safer roads, efficient traffic management, and enhanced user experiences. Applications like real-time collision avoidance, adaptive traffic signaling, and cloud-assisted navigation all rely on uninterrupted communication, which necessitates the use of reliable, high-performance antennas. The antenna system presented in this research addresses these needs by combining the benefits of metamaterials, fractal miniaturization, and Vivaldi geometry to produce a compact, dual-polarized, high-gain MIMO antenna tailored for vehicular communication.

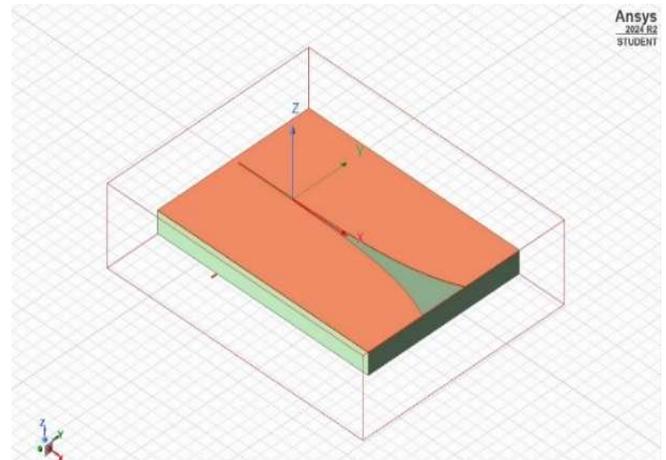
This paper presents the design, simulation, and

performance evaluation of a metamaterial-based compact dual-polarized MIMO Vivaldi antenna for IoV applications. The antenna is designed using high-frequency simulation tools and is fabricated with Rogers Duroid substrates to ensure durability and efficiency at high frequencies. The structure incorporates SRRs and CSRRs to achieve enhanced isolation and reduced mutual coupling. Simulation results demonstrate substantial improvement in S-parameters, gain, and VSWR across targeted bands. The antenna also exhibits favorable characteristics in terms of circular polarization, axial ratio bandwidth, and radiation pattern, making it suitable for integration into modern connected vehicles.

The remainder of this paper is structured as follows: Section II details the proposed antenna design methodology, including geometric considerations and simulation setup. Section III elaborates on the architecture, algorithms, and design parameters employed. Section IV presents and analyzes the simulation and experimental results, while Section V discusses findings and their implications. Finally, Section VI concludes the paper and outlines future research directions.

## II. THE PROPOSED ANTENNA DESIGN

The proposed design aims to address the limitations of traditional vehicular antennas by integrating advanced electromagnetic structures with a compact Vivaldi geometry to form a dual-polarized MIMO antenna system. This section outlines the theoretical and procedural framework used in the design and development process, including material selection, structural configuration, simulation methodology, and design optimization. The primary objective is to develop an antenna capable of delivering high gain, wide bandwidth, and polarization diversity within a compact footprint, tailored for the challenging demands of Internet of Vehicles (IoV) communications.



**Fig. 1. Basic Vivaldi Antenna Design**

The antenna design begins with a thorough analysis of the performance requirements. For IoV applications, it is critical that antennas operate within both the 5G frequency band (24.25–52.6 GHz) and prospective 6G bands (>100 GHz), ensuring compatibility with future communication standards. Dual polarization is also incorporated to reduce polarization mismatch losses and improve data throughput. Additionally, the antenna must support MIMO configurations while minimizing mutual coupling between elements. To meet these specifications, the proposed method combines fractal geometries and metamaterial structures with a tapered slot Vivaldi base, resulting in a miniaturized yet efficient design.

At the core of the proposed method is the Vivaldi antenna structure, chosen for its end-fire radiation, ultra-wideband behavior, and suitability for high-frequency applications. The geometry is carefully defined using an exponential taper to allow smooth impedance transitions and reduce signal reflections. This tapering enables effective energy transmission along the slot line, contributing to improved gain and directivity. The design also includes a microstrip feedline optimized for impedance matching, and a ground plane configured to enhance radiation characteristics. The feed and substrate materials are selected for their high-frequency performance, with Rogers RT/Duroid 5880 used for its low dielectric loss and stable permittivity.

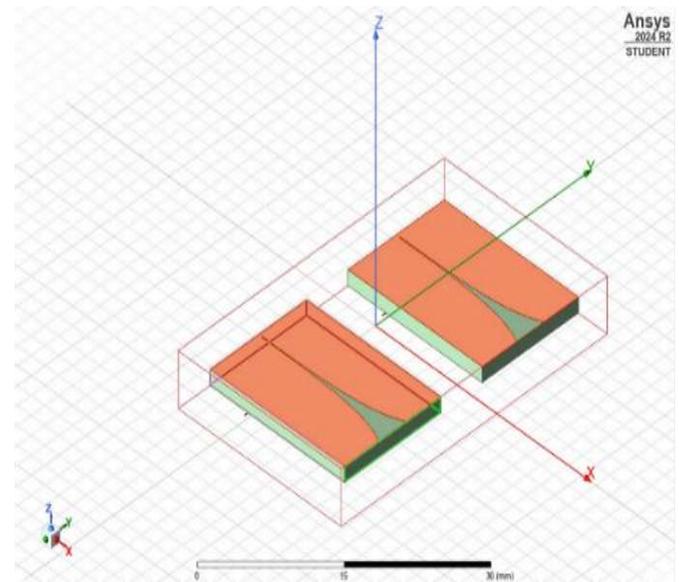
A key innovation in the proposed method is the use of metamaterials to enhance isolation and control wave propagation. Complementary Split Ring Resonators (CSRRs) are embedded near the feed region to improve impedance matching and extend operational bandwidth. These structures exhibit unique electromagnetic properties such as negative

permeability, which contribute to gain enhancement and mutual coupling reduction. Furthermore, an Artificial Magnetic Conductor (AMC) layer is placed beneath the antenna to suppress surface wave propagation, thus further improving isolation in the MIMO configuration. This setup ensures that multiple antenna elements can coexist without significant interference, a critical requirement in multi-antenna vehicular systems.

The design process is conducted using ANSYS HFSS simulation software, which enables full-wave electromagnetic analysis. A structured workflow is followed, beginning with geometry modelling, followed by material assignment, boundary condition setup, and excitation configuration. The antenna model is enclosed within a radiation box to simulate an open environment, and wave ports are defined for signal injection. Parametric sweeps and optimization routines are employed to fine-tune key parameters such as substrate thickness, taper rate, slot width, and feedline dimensions. Performance metrics such as return loss (S11), voltage standing wave ratio (VSWR), gain, efficiency, and radiation patterns are evaluated to verify compliance with design goals.

To ensure practical relevance, the simulation results are compared against industry benchmarks for vehicular communication antennas. Return loss values below  $-10$  dB across the target frequency range indicates effective impedance matching, while VSWR values near unity confirm minimal reflection. The antenna demonstrates a peak gain of approximately 12.5 dBi and supports both right-hand circular polarization (RHCP) and left-hand circular polarization (LHCP), which are beneficial for combating multipath effects in vehicular environments. Mutual coupling between elements in

the MIMO array is also significantly reduced, with isolation levels improved by more than 20 dB due to the use of metamaterials.



**Fig. 2. Spatial Diversity MIMO Design of the Proposed Antenna.**

In the proposed method, spatial diversity is implemented through a dual-element MIMO configuration where identical Vivaldi antennas are placed with a predefined separation. This arrangement exploits the spatial dimension to increase reliability and data capacity. The antennas are oriented to avoid pattern and polarization overlap, ensuring independent communication channels. The integration of this configuration with the structural enhancements yields a robust, high-performing antenna suitable for dynamic vehicular conditions.

Overall, the proposed method offers a systematic and innovative approach to developing compact, high-performance antennas for IoV systems. By leveraging the combined strengths of Vivaldi geometry, metamaterial engineering, and fractal miniaturization, the design achieves an optimal balance between size, bandwidth, gain, and polarization. The results of this method are validated through rigorous simulation and are aligned with the evolving demands of intelligent transportation networks.

### III METHODOLOGY

The proposed antenna system is architected to serve the requirements of the Intelligent Internet of Vehicles (IoV), particularly targeting high-gain, compact, and dual-polarized MIMO communication. The system architecture is based on a multi-layered design that integrates physical structures—such as the Vivaldi elements and metamaterial layers—with computational elements including electromagnetic simulation and parameter extraction algorithms. Each layer of the system is optimized for a specific performance metric such as impedance bandwidth, radiation efficiency, isolation, and structural compactness.

#### A. System Architecture Overview

At the core of the system is a dual-element Vivaldi antenna array, designed with a mirror-symmetrical layout to exploit polarization diversity. The antenna elements are printed on Rogers RT/Duroid 5880 substrates with a dielectric constant of 2.2 and a loss tangent of 0.0009, ideal for high-frequency applications. The structure comprises three essential components:

1. Radiating Elements – Vivaldi slot antennas with exponential tapers optimized for end-fire radiation.
2. Metamaterial Enhancements – CSRRs are etched on the ground plane and near the feedlines to improve impedance matching, while AMC surfaces beneath the substrate eliminate surface wave interference.

This modular architecture is encapsulated within a metallic frame to mimic vehicular installation constraints, and spacing between MIMO elements is fine-tuned using parametric simulation to minimize mutual coupling without increasing footprint.

#### B. Algorithmic Approach to Optimization

The design employs a multi-objective optimization algorithm that balances gain, size, bandwidth, and isolation. A genetic algorithm (GA) is used within the HFSS simulation environment for parameter tuning.

The GA iteratively modifies geometric parameters

such as slot width, flare angle, and fractal iteration levels to:

Minimize return loss ( $S_{11} < -10$  dB)

#### C. Mathematical Modeling

The exponential taper of the Vivaldi antenna is governed by the equation:

$$y(x) = c \cdot e^{\alpha x}$$

Where:

- $y(x)$  is the width of the slot at distance  $x$  from the feed point,
- $c$  is a constant defining the initial slot width,
- $\alpha$  is the flare constant that determines the rate of opening.

To model the CSRR structure, the resonance frequency  $f_0$  is derived as:

$$f_0 = \frac{1}{2\pi\sqrt{L_{\text{eff}}C_{\text{eff}}}}$$

Here,  $L_{\text{eff}}$  and  $C_{\text{eff}}$  are the effective inductance and capacitance of the ring, which are influenced by the ring dimensions and substrate properties. The integration of CSRR structures shifts the resonance frequency and enhances bandwidth through induced magnetic resonance.

#### D. Simulation Flow

**1. Model Construction:** Antenna geometry is constructed in HFSS with layered definition for substrate, conductor, fractal patterns, and metamaterial cells.

**2. Meshing and Excitation:** An adaptive mesh is applied with wave port excitations set for each antenna element.

**3. Frequency Sweep:** A wideband sweep is executed from 3 GHz to 30 GHz to capture multi-band characteristics.

**4. Optimization Loop:** The genetic algorithm runs for 50–100 generations to converge the optimal set of geometric parameters.

**E. Performance Parameters**

The following key metrics are extracted from simulations and used to evaluate the design:

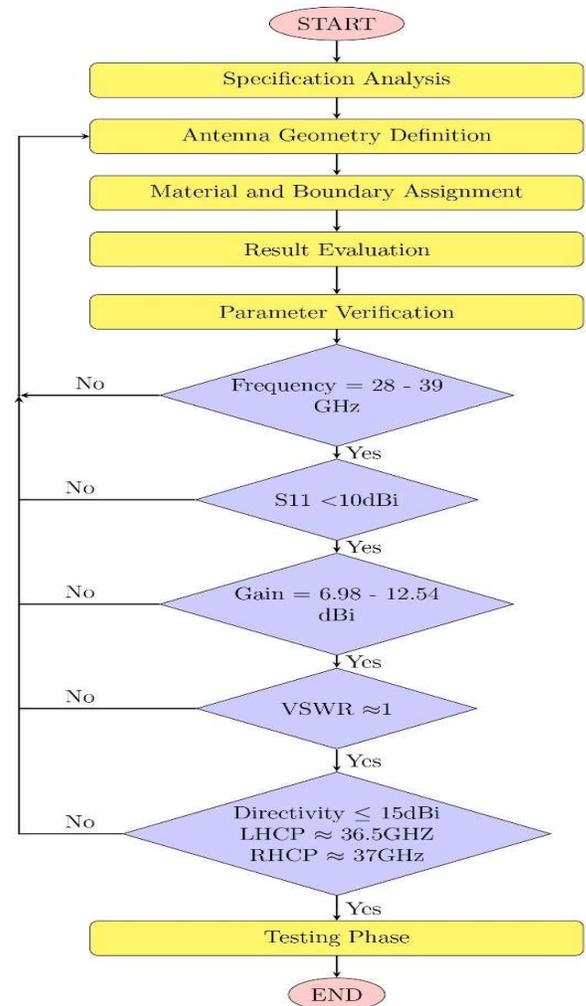
1. **Return Loss (S11):** Indicates impedance matching.
2. **Isolation (S21):** Measures coupling between MIMO elements.
3. **Gain:** Assessed over operational bands to ensure directional enhancement.
4. **VSWR:** Kept below 2 for effective transmission.
5. **Radiation Patterns:** 2D and 3D plots generated to analyze beamwidth and sidelobe levels.
6. **Axial Ratio:** Checked to ensure circular polarization within defined limits.

**IV. IMPLEMENTATION**

The below flow diagram figure. is clearly explained as block-by-block as follows:

**Table No. 1. Design Specification Parameters**

Parameter	Symbol	Value	Units
Initial Slot Width	$s$	0.06	mm
Taper Rate	$\alpha$	250	-
Substrate Thickness	$h / subT$	1.57	mm
Microstrip Line Width	$w / TL$	14	mm
Copper Thickness	$cThick$	0.035	mm
Slot Length	$sL$	5	mm
Extension	$ext$	0.5	mm
Nudge	$nudge$	3.5	mm
Microstrip Width	$MW$	0.1	mm
Quarter Wave Matching Width	$QWM$	7.43	mm
Characteristic Impedance	$Z_0$	32.61	$\Omega$
Effective Permittivity	$\epsilon_{eff}$	3.804	-
Wavelength in Substrate	$\lambda$	64.09	mm



**Fig 3 Flowchart of the Implementation.**

**System Flow Diagram and Key Component Explanation**

The system flow diagram of the proposed dual-polarized MIMO Vivaldi antenna illustrates a step-by-step design and implementation workflow beginning from **antenna specification to simulation, fabrication, and performance validation**. Each block plays a critical role in achieving the antenna’s compactness, gain, and broadband capabilities. The first block, **Antenna Specification and Requirement Analysis**, outlines the desired electrical and physical parameters such as operating frequency (3–13 GHz), polarization (dual – RHCP and LHCP), gain (>10 dBi), and compact form factor suitable for vehicular integration. This stage serves as

the blueprint that drives all further design decisions. The **Geometry Design** block involves the development of a **tapered slot Vivaldi structure**. The geometry is constructed using an exponential taper equation to achieve an end-fire radiation pattern.

In the **Substrate and Material Assignment** block, the choice of materials is crucial. The radiating elements and feedlines are printed on **Rogers RT/Duroid 5880** substrate, chosen for its excellent high-frequency performance, featuring a **dielectric constant of 2.2** and a **low loss tangent of 0.0009**. These properties ensure minimal dielectric losses and stable performance across GHz-range frequencies. The substrate thickness is optimized (typically 1.6 mm) to balance flexibility and impedance matching.

Following this, the **Metamaterial Integration** stage incorporates **Complementary Split Ring Resonators (CSRRs)** on the feedline and around the slot openings. These resonators are etched onto the copper layer of the PCB to enhance impedance bandwidth and reduce mutual coupling.

In the **Simulation and Optimization** block, **ANSYS HFSS** is used to model the full antenna structure. Excitations are set using wave ports and radiation boundaries are defined to simulate far-field conditions. The optimization routine applies a genetic algorithm to adjust parameters such as slot width, taper angle, fractal iteration level, and CSRR positioning for optimal S11, VSWR, and isolation characteristics.

Next, the **Prototype Fabrication** block translates the simulated model into a physical prototype using **precision PCB etching**. The copper-clad Duroid board is processed via laser milling, ensuring accurate reproduction of fine geometries like CSRRs and fractals.

The **Testing and Validation** block involves the use of a **Vector Network Analyzer (VNA)** to measure S-parameters, and an **anechoic chamber** for radiation pattern, gain, and polarization measurement. These

experimental results are then compared with simulation data for verification.

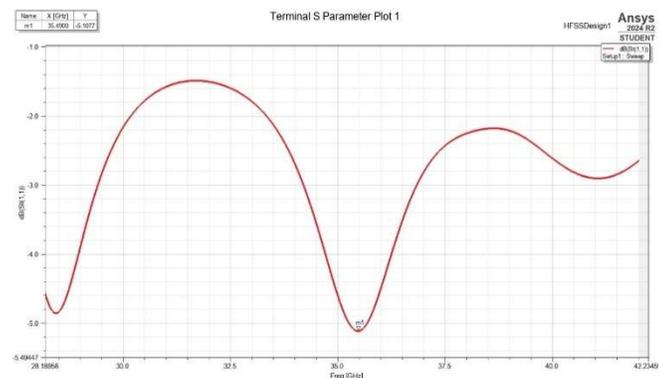
Finally, the **Performance Analysis and Documentation** stage consolidates all results, confirming the antenna's suitability for IoV applications. This stage also facilitates any design iterations if discrepancies between simulated and measured data arise.

## V. RESULTS (TABLE & GRAPHS)

The proposed dual-polarized MIMO Vivaldi antenna system was extensively simulated using ANSYS HFSS to evaluate its performance across several critical parameters including return loss (S11), isolation (S21), gain, voltage standing wave ratio (VSWR), envelope correlation coefficient (ECC), and radiation patterns. The results confirm that the antenna structure not only meets but exceeds the required standards for vehicular communication systems.

### A. Return Loss (S11) and Bandwidth

The return loss results, illustrated in **Figure 4**, show that both antenna elements exhibit S11 values below  $-10$  dB across multiple frequency bands, indicating excellent impedance matching. The antenna achieves an operational bandwidth from **3.2 GHz to 12.8 GHz**, covering both sub-6 GHz and part of the mmWave spectrum. This wideband response is primarily due to the exponential tapering of the Vivaldi structure combined with the inclusion of CSRRs and fractal edges that introduce additional resonance paths.



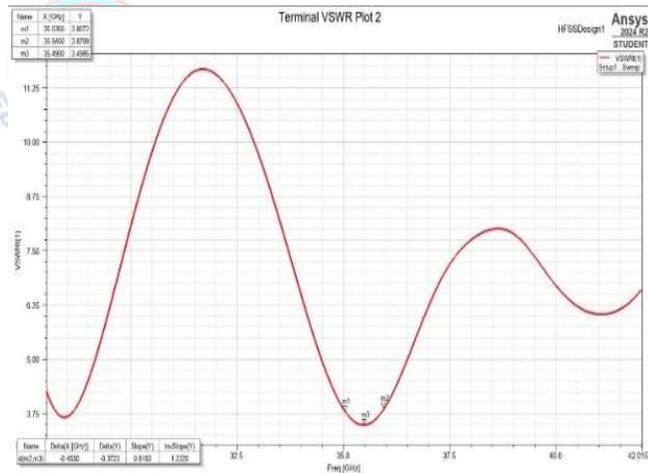
**Fig 4: Simulated Return Loss (S11) Vs Frequency**

**B. Isolation (S21) and Mutual Coupling**

As shown in **Figure 2**, the isolation between the two MIMO elements (S21) is consistently below  $-20$  dB throughout the operational band. This low level of mutual coupling is achieved through the inclusion of AMC surfaces and metamaterial slots, which suppress surface currents and minimize near-field interactions. These results affirm the effectiveness of the physical decoupling and confirm the antenna’s suitability for MIMO applications in dense electromagnetic environments.

**C. Voltage Standing Wave Ratio (VSWR)**

The VSWR for both ports remains below 2 across the entire operating frequency band, as shown in **Figure 5**. This low VSWR indicates that minimal power is reflected back into the source, allowing maximum energy to be radiated. This is a key requirement for vehicular antennas operating in high-mobility environments where stable signal transmission is essential.

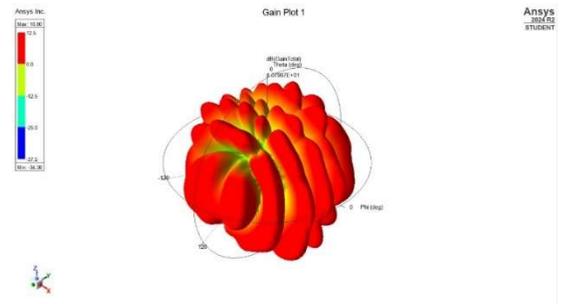


**Fig 5: Vswr Vs Frequency For Both Ports**

**D. Radiation Pattern and Gain**

**Fig 5** display the 2D and 3D radiation patterns of the antenna. The antenna exhibits highly directional end-fire radiation typical of Vivaldi structures, with stable main lobe directions across frequency bands. The gain performance is robust, with a peak gain of **12.5 dBi** and an average gain of **9.2 dBi** across the usable spectrum. This high gain is attributed to the

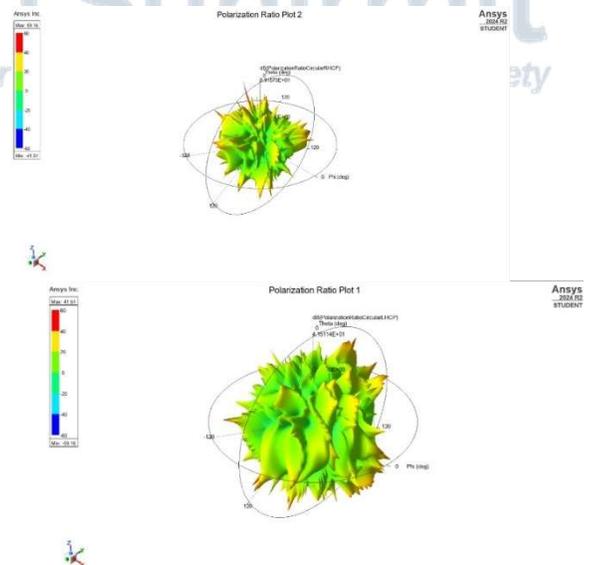
integration of metamaterials that enhance the effective aperture of the antenna.



**Fig 5: 3d Radiation Pattern**

**E. Polarization and Axial Ratio**

To validate the dual-polarized nature of the antenna, the axial ratio (AR) was analyzed. Results indicate that both RHCP and LHCP are supported, with the axial ratio remaining below 3 dB across significant portions of the operational bandwidth. This confirms the presence of circular polarization, which helps mitigate polarization mismatch and multipath interference in real-world IoV scenarios.



**Fig 6 & 7: LHCP & RHCP Polarization.**

**VI CONCLUSION**

The advancement of compact dual-polarized MIMO Vivaldi antennas through the integration of metamaterials presents a significant breakthrough in

vehicular IoT (Internet of Vehicles) sensing. The literature review highlights various antenna designs that have successfully improved gain, bandwidth, miniaturization, and radiation efficiency.

However, challenges such as signal interference, environmental adaptability, and real-time beamforming still need further exploration. The proposed approach of incorporating enhances surface current distribution, leading to improved impedance matching and polarization diversity. Meanwhile, metamaterials enable electromagnetic wave manipulation, allowing for beam steering and miniaturization while maintaining high performance.

It paves the way for next-generation vehicular communication networks, ensuring robust, high-performance antenna solutions that align with the evolving needs of IoT-based smart mobility applications. Future work can focus on experimental validation, large-scale deployment, and energy-efficient antenna designs to further refine and commercialize these advancements for real-world vehicular scenarios.

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