DESIGN AND IMPLEMENTATION OF ZRO2 BASED CERAMIC MIMO ANTENNA FOR SMART CITIES IN N257 AND N261 BANDS

***Project Reference No.:** 48S_BE_0394*

College : Nagarjuna College Of Engineering And Technology, Bengaluru

Branch : Electronics And Communication Engineering

Guide(S) : Dr. AJAY KUMAR DWIVEDI

Student(S): Ms. MEGHANA H R

Ms. CHAITHRA K A

Ms. ROHINI N

Mr. YASHAS P T

Keywords:

MIMO, ZrO2, n257, Smart Cities, Ceramic Antenna

Introduction:

Dielectric resonators have gained prominence in millimeter-wave frequency applications over the past decade, with rectangular-shaped dielectric resonators (DRAs) offering practical advantages over cylindrical and spherical alternatives. These structures enhance flexibility and adaptability due to their material permittivity, making them well-suited for modern high-frequency systems. As the number of connected devices continues to rise, 5G technology is expected to transform augmented reality and smart cities by improving data reliability, transfer rates, and energy efficiency. Researchers have been exploring millimeter-wave frequency bands to optimize 5G performance, aiming to support the growing demand for advanced communication networks. Circular polarization capabilities in DRAs contribute to their efficiency by rendering them orientation-independent, particularly in environments where signal fading occurs. Various feeding strategies are utilized in millimeter-wave antenna systems to generate circular polarization, ensuring stable operation even in dynamic conditions. Filtering dielectric resonator antennas (DRAs) have been developed to enhance the compactness of communication systems by eliminating the need for an external bandpass filter. These antennas provide better integration while maintaining high radiation efficiency.

This study presents the design and analysis of a two-port circularly polarized dielectric resonator antenna operating at millimeter-wave frequencies. The antenna achieves substantial signal rejection exceeding 15 dB within its frequency range of 28 GHz. Through the implementation of an asymmetrical U-shaped aperture, twin orthogonal modes with a 90-degree phase shift at 27 GHz are generated, enabling circular polarization. Additionally, the strategic alignment of antenna ports minimizes mutual coupling to -20 dB across the operational spectrum.The research is structured into four key sections: the antenna's geometrical configuration, design evaluation, experimental results, and a final summary. These advancements contribute to optimizing millimeter-wave communication for next-generation networks.

Objectives:

The primary objective of this work is to design and develop a circularly polarized ceramic-based MIMO antenna optimized for millimeter-wave communication systems, specifically in the frequency range of 27.5 GHz to 34 GHz. Utilizing ceramic ZrO_2 material enhances the thermal stability and mechanical robustness of the antenna, enabling consistent performance in high-frequency operations. A modified U-shaped radiator is incorporated to achieve improved bandwidth efficiency and impedance matching, ensuring versatile functionality across the operating band. The antiparallel orientation of the antenna elements ensures superior isolation of over 45 dB at 28 GHz, reducing signal interference and optimizing communication reliability. The antenna achieves a positive gain throughout the operating frequency range, with a peak gain of 4 dBi, contributing to stable and robust signal transmission. Additionally, the generation of fundamental $HE_{11\delta}$ modes facilitates diverse radiation patterns, improving spatial signal coverage in dense network environments. The design further enhances crucial diversity parameters such as ECC, DG, and TARC, ensuring high-quality signal propagation essential for multipath environments. By addressing challenges associated with millimeter-wave frequencies, this advanced design positions the antenna as a cutting-edge solution for high-speed, low-latency communication systems, making it particularly suitable for next-generation applications such as 5G IoT sensing. Its innovative approach demonstrates adaptability and effectiveness in meeting the demands of modern wireless communication technologies.

Methodology:

A two-port ceramic-based MIMO antenna is proposed for millimeter-wave applications, particularly targeting 5G-enabled smart city and IoT environments. The design utilizes cylindrical dielectric resonator antennas (DRAs) composed of zirconia (ZrO_2), mounted on a Rogers RT 5880 substrate. Unlike traditional planar patch antennas, DRAs offer high radiation efficiency and support multiple resonant modes, making them favorable for wideband and circularly polarized radiation. To achieve compactness and strong isolation, an antiparallel orientation of the two DR elements is implemented. A microstrip feed is employed from the substrate's bottom layer, with an asymmetrical U-shaped slot etched on the ground plane to excite the dielectric material. This aperture coupling method stimulates hybrid electric modes (HE11δ), which are responsible for circular polarization and improved far-field performance.

The dielectric resonators are carefully dimensioned and positioned to ensure the generation of orthogonal modes with a 90° phase difference. This excitation leads to circular polarization over a broad frequency range (27.8–33 GHz). The U-shaped aperture has undergone iterative optimization: initial configurations started with straight and L-shaped arms, later evolving into the final asymmetric U-slot, which provides more efficient coupling and stable impedance matching across the band.

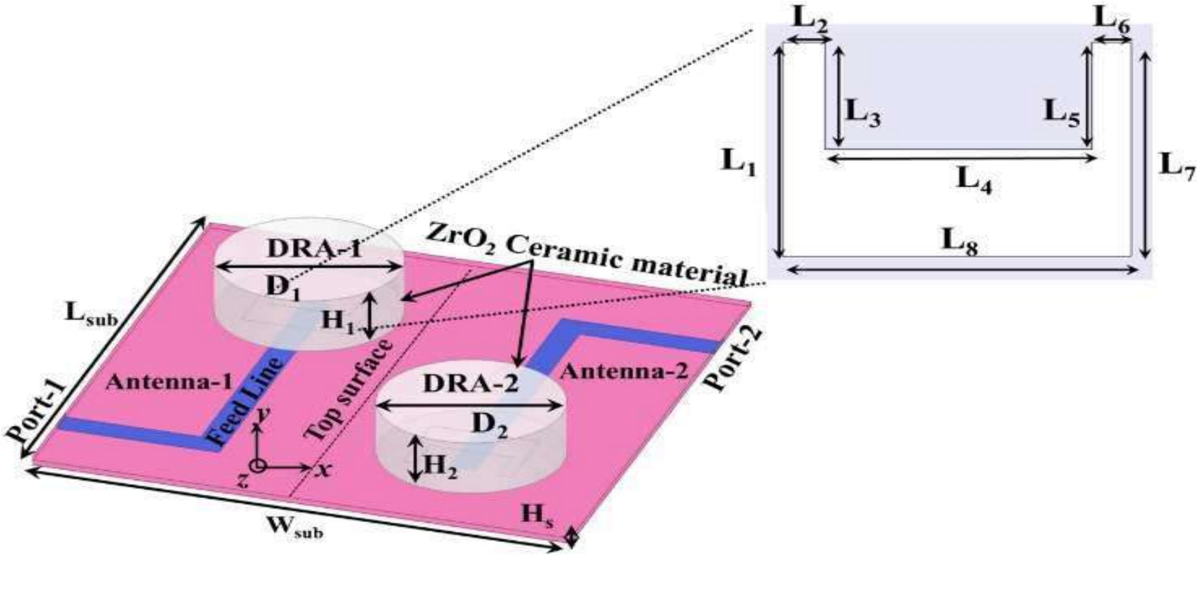


Figure: 3D prospective view of the antennas component

The full antenna structure is modeled and simulated using **ANSYS HFSS**, focusing on key performance metrics such as return loss (|S11|), isolation (|S12|), gain, efficiency, and envelope correlation coefficient (ECC). An isometric 3D model is developed to evaluate the electric field distribution and confirm the excitation of the $HE_{11\delta}$ mode at 28 GHz. Mathematical modeling is also carried out to estimate resonance frequency using known analytical formulations of DRA resonance.

The prototype is fabricated on a 0.254 mm thick Rogers RT 5880 substrate with $\varepsilon_r = 2.2$ and $\tan\delta = 0.0009$. High-precision soldering techniques are used to connect the feed lines, although minor mismatches in measured vs simulated results are observed due to material tolerances and connection inconsistencies. The fabricated prototype is tested using a Keysight E8363C PNA and evaluated in an anechoic chamber for radiation pattern and gain measurements. Measurements show good agreement with simulations: return loss is maintained below −10 dB across the band, and isolation is observed to be better than −40 dB, with a peak gain of approximately 5 dBi.

In addition to standard S-parameter measurements, diversity performance metrics such as ECC and diversity gain (DG) are calculated using both far-field and S-parameter methods. The results confirm a low ECC (~0.003) and near-maximal DG (~9.99 dB), indicating excellent diversity characteristics. Radiation patterns show stable directional behavior with cross-polarization levels suppressed below co-polarization, further validating the design for MIMO operations

Design flow:

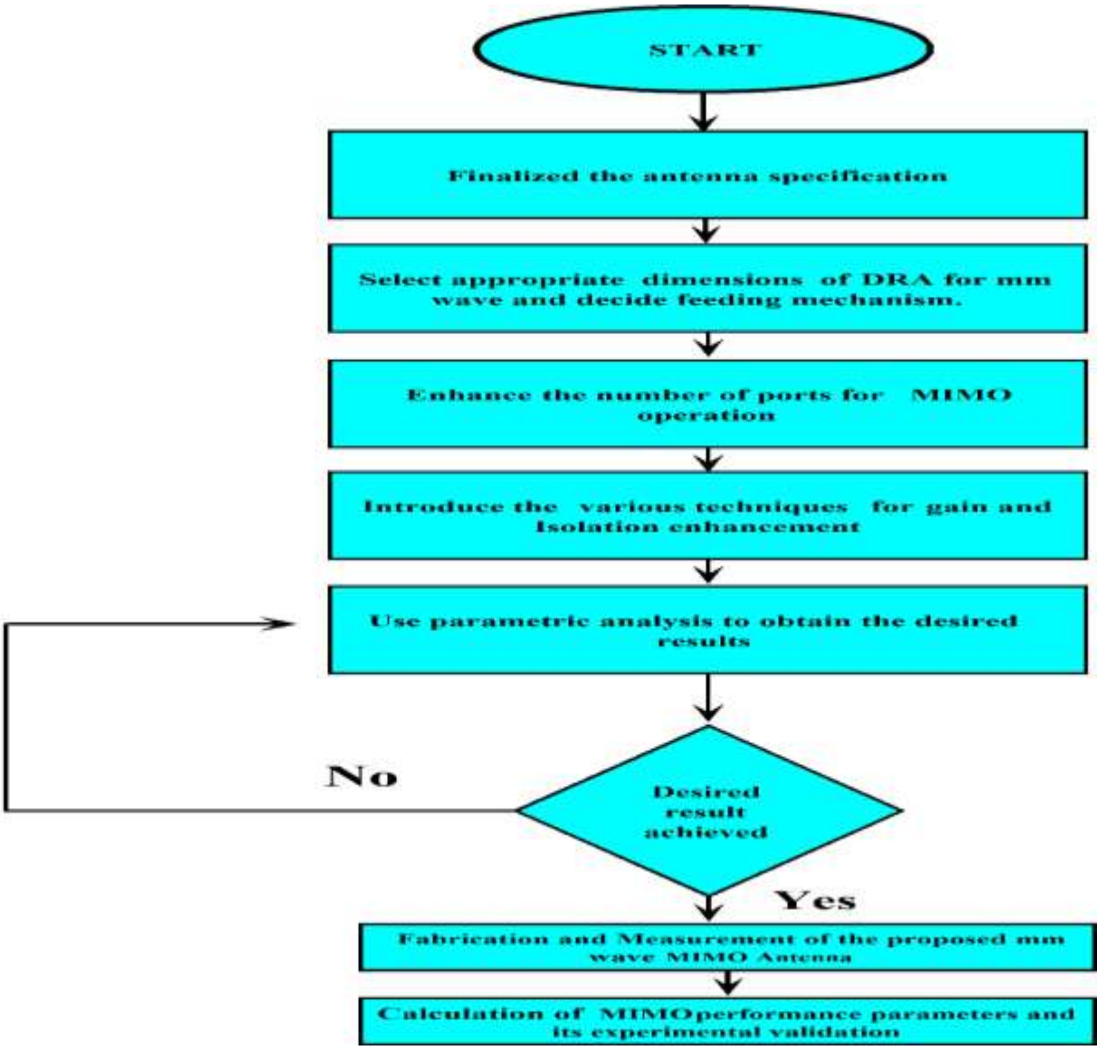


Figure: Flow diagram of the design of the DR based MIMO antenna

Design approach:

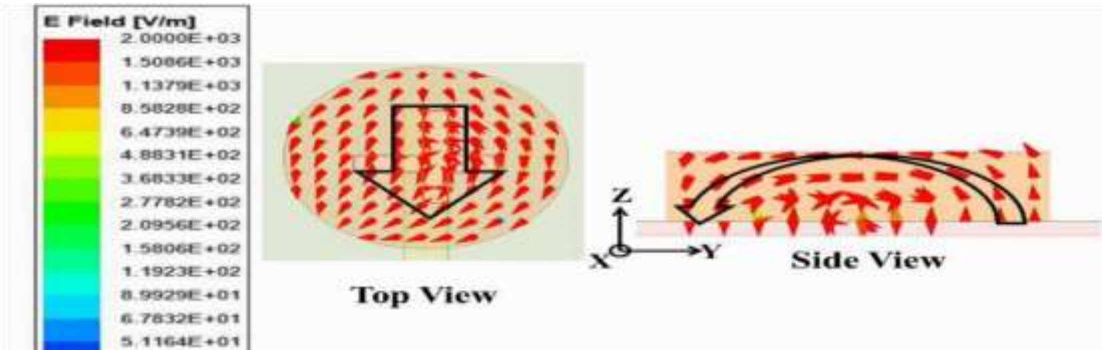
The computational analysis and optimization of the proposed ceramic-based MIMO antenna were performed using a full-wave electromagnetic simulation tool based on the Finite Element Method (FEM). The design process began by defining the antenna's physical structure, which includes the substrate, ground plane, microstrip feed, U-shaped aperture, and cylindrical dielectric resonators.

Aspect	Details
Tool Used	ANSYS HFSS for full-wave EM simulation
Materials	Rogers RT 5880 (εr = 2.2) and ZrO_2 ceram (εr = 9.8)

Simulation & Analysis: Radiation boundaries were applied to simulate an open environment for far-field pattern extraction, while adaptive meshing was used to accurately capture field variations near critical regions. The fundamental HE11δ mode was confirmed at 28 GHz using eigenmode analysis.

Performance Evaluation: S-parameter analysis was carried out over the 25–35 GHz range to assess impedance matching and mutual coupling. Far-field patterns were extracted in principal planes to evaluate the antenna's directivity and polarization characteristics. Additionally, the Envelope Correlation Coefficient (ECC) and Diversity Gain (DG) were calculated to confirm the MIMO performance of the antenna.

Optimization & Validation: A stepwise geometric optimization process was implemented to refine the feed aperture, which enhanced return loss and isolation. After fabrication, the measured results were compared with simulated outcomes, with minor discrepancies attributed to material property deviations and fabrication tolerances.



Movement of the E field lines

$$f_{r,HE_{11\delta}} = \frac{6.321c}{2\pi D\sqrt{\varepsilon_{dra,eff}} + 2}\left\{0.27 + 0.36\left(\frac{D}{2H_{eff}}\right) + 0.02\left(\frac{D}{2H_{eff}}\right)^2\right\}$$

$$\varepsilon_{dra,eff} = \frac{H_{eff}}{\dfrac{H}{\varepsilon_{Al_2O_3}} + \dfrac{H_{sub}}{\varepsilon_{sub(FR-4)}}} \qquad H_{eff} = H + H_{sub}$$

Result and conclusion

Results:

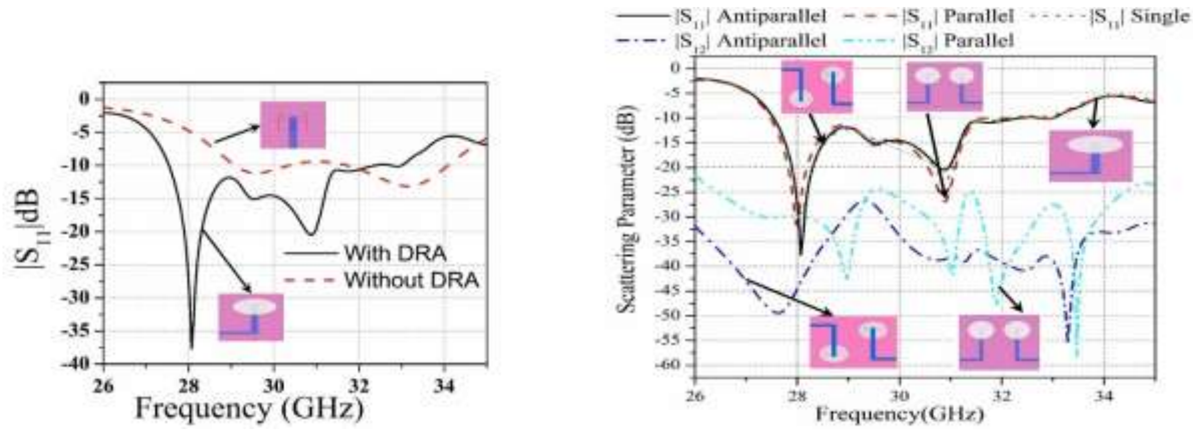


Figure: Plot of Reflection Coefficient with and without the use of DR and Scattering parameters $|S_{11}|$, $|S_{12}|$ Parallel and $|S_{11}|$ $|S_{12}|$ Anti Parallel of the design.

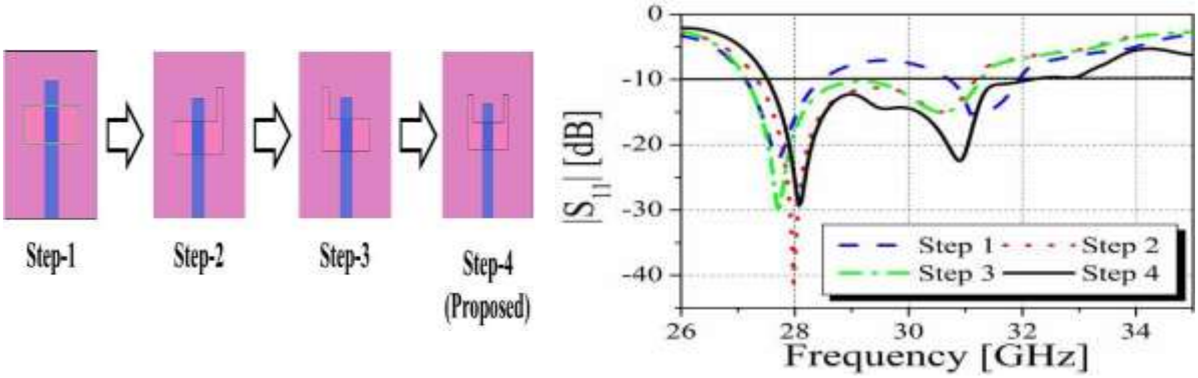
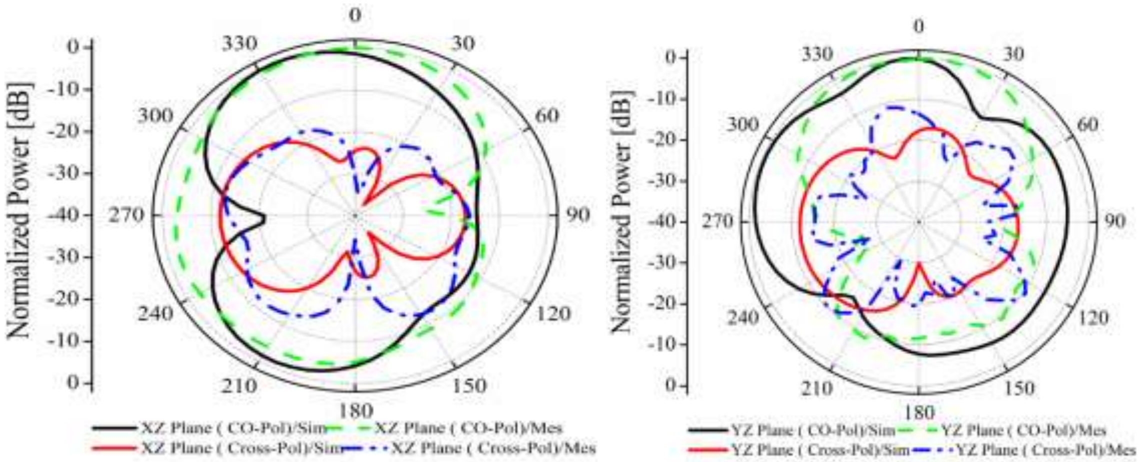


Figure: Stepwise $|S_{11}|$ Curve for different configurations

The proposed ceramic-based MIMO antenna demonstrated excellent performance across the 27.8–33 GHz frequency range. Both simulations and measurements confirmed that the mutual coupling between the ports remained below −40 dB, with an impressive minimum of −50 dB achieved in the antiparallel orientation. In the parallel configuration, mutual coupling was slightly higher, but still well below the acceptable limits. The measured |S11| values exhibited consistent impedance matching throughout the operating band, meeting the bandwidth and isolation objectives. The antenna achieved a peak gain of approximately 5 dBi, maintaining stable performance across the entire frequency range. Radiation pattern measurements revealed good directivity with low cross-polarization levels, validating the circular polarization. The generation of the HE11δ mode was confirmed through field distribution analysis.



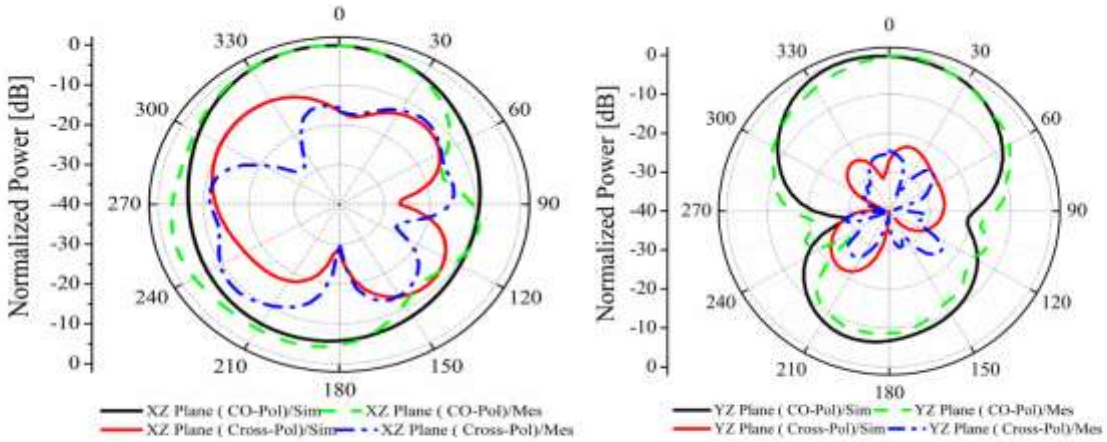


Figure: Port wise 2-dimensional radiation pattern a t 28 GHz in XoZ and YoZ plane

The far-field pattern for port-1 and port-2 in the XoZ and YoZ planes was measured in an anechoic chamber. During the measurement, one port was excited while the other was terminated with a matching load. In the intended direction, the cross-polarization level is significantly lower than the co-polarization level, exceeding 15 dB.

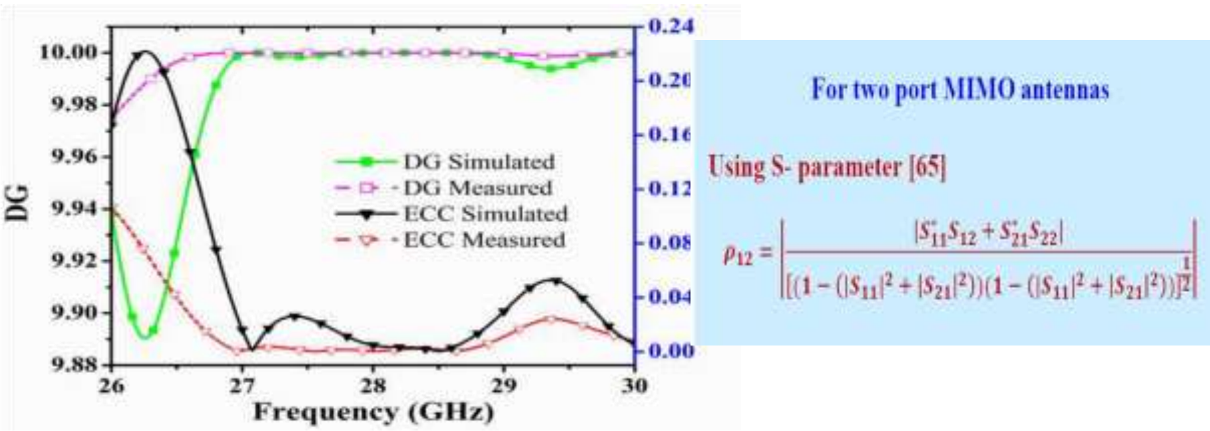


Figure: Diversity Performance of the proposed antenna

Additionally, diversity parameters such as the **Envelope Correlation Coefficient (ECC)** and **Diversity Gain (DG)** were evaluated to assess MIMO performance. ECC, which defines the correlation between the radiation patterns of the antenna when different ports are excited, was found to be approximately **0.003**, well below the acceptable limit of **0.3**, indicating excellent isolation and pattern diversity. Similarly, the DG was measured at around **9.99 dB**, exceeding the standard threshold of **9.95 dB**, ensuring high reliability in multipath environments. These results confirm the antenna's strong diversity performance and demonstrate its viability for applications in **5G-based smart cities and Internet of Things (IoT) systems**.

Conclusion:

The ceramic-based MIMO antenna demonstrates excellent performance across the 27.8–33 GHz range, with low mutual coupling, consistent gain, and reliable circular polarization. The successful excitation of the HE11δ mode and superior diversity metrics (ECC ≈ 0.003, DG ≈ 9.99 dB) highlight its suitability for high-efficiency MIMO operations. Overall, the results confirm the antenna's strong potential for deployment in advanced 5G networks, smart city infrastructures, and IoT-based applications.

Innovation in the project:

The proposed antenna introduces key innovations aimed at enhancing millimeter-wave MIMO performance. High-permittivity, low-loss ceramic material (ZrO_2) is utilized to improve miniaturization and radiation efficiency. An asymmetrical U-shaped slot is implemented to excite orthogonal modes in the dielectric resonator, enabling circular polarization and wider bandwidth. Antiparallel port configuration achieves high isolation (>50 dB at 28 GHz), improving MIMO diversity without extra decoupling structures. Additionally, the design is optimized to excite the fundamental HE11δ mode at 28 GHz, supporting stable radiation patterns and low cross-polarization. These advancements make the antenna well-suited for 5G and IoT applications in smart city environments.

Future scope:

Future developments aim to miniaturize the antenna for compact 5G IoT devices, explore alternative ceramics for enhanced gain and bandwidth, and integrate filtering elements to simplify architecture. Expansion to a 4-port MIMO setup and adaptive features like beam steering using MEMS or varactors will be explored. Improved fabrication will reduce discrepancies. The design will be optimized for n257 band and validated in smart city deployments, with plans for patent filing and further trials.