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Design and Optimization of Dual Band Millimeter Wave MIMO Antenna for Next Generation 5G/6G Wireless Systems

Shiddanagouda.F.B[1], P.S.Aithal[2], A.Srinivasa Reddy[3], Sravanti Thota[4], N.Dinesh Kumar[5]
[1,2]Department of Computer Science and Information Science Srinivas University Mangalore 575001, India
[3,4]Department of ECE Pallavi Engineering College Hyderabad 501505, India
[5]Department of ECE Vignan Institute of Technology and Science Hyderabad 508284, India

Abstract

This research introduces the design and optimization of a dual-band millimeter-wave Multiple Input Multiple Output (MIMO) antenna intended for next generation 5G and 6G wireless systems. Initially, a single antenna operating at 38GHz was designed using RT/duroid 5880LZ substrate material with a dielectric constant of 2.2 and dimensions of 1.7x1.9x0.8mm^3. A MIMO antenna with a four-element array was then developed by positioning each individual antenna a distance of λ/4 apart. To achieve dual-band functionality and improve antenna performance, the ground plane was modified with an outset rectangular split ring slot defected ground structure (ORSRSDGS). The designed millimeter-wave MIMO antenna successfully operates at two frequency bands, 28GHz and 38GHz, exhibiting return losses of -24.8dB and -38.7dB, and providing satisfactory bandwidths of 2GHz and 3.6GHz, respectively. Key parameters of the proposed MIMO antenna design were thoroughly investigated. Characteristics such as overall mutual coupling coefficients (MCC), envelope correlation coefficients (ECC), total peak gain (TPG), diversity gain (DG), size reduction, and radiation pattern performance were all verified. The results indicate that the designed millimeter-wave MIMO antenna is highly suitable for use in 5G and 6G wireless systems.

Keywords: Millimeter wave, MIMO Antenna, ORSRSDGS, Bandwidth, MCC, ECC, TPG, DG

1. Introduction

In the modern era of technological advancement, breakthroughs in artificial intelligence, data science, cyber security, the Internet of Things, and wireless communications are driving a surging demand for compact wireless devices capable of delivering Gigabit data rates. To fulfil these advanced communication requirements, millimeter-wave MIMO antenna systems have emerged as a foremost solution [1]. Nevertheless, deploying millimeter-wave MIMO antennas on a single underlying surface introduces the difficulty of mutual coupling between antenna elements, which can severely impair antenna performance. To address this issue, investigators have explored a numerous innovative strategies to enhance the design of millimeter-wave MIMO antennas [2-3].

In this study, we propose a novel design for a millimeter-wave MIMO antenna that integrates an outset rectangular split ring slot defected ground structure (ORSRSDGS) to suppress mutual coupling issues. This design approach aims to disrupt the pathways for mutual coupling, thereby improving isolation between antenna elements and enhancing overall antenna performance. The subsequent sections of this paper provide a comprehensive discussion on the antenna layout design methodology, detailed results, and the conclusions drawn from our findings.

2. Antenna Design Methodology

In the initial stages, a 38 GHz resonant frequency was chosen as the focus for designing the single millimeter-wave antenna, utilizing the RT/duroid 5880LZ substrate material with its characteristics detailed in Table 1. Further specifics regarding the antenna dimensions were derived from calculations using the provided equations (1), (2), and (3) [4], and these dimensions are succinctly presented in Table 2.

Table.1. Specification of Substrate Material

Material	Relative Permittivity	Loss Factor	Thickness
RT/duroid 5880LZ	2.2	0.0009	0.8mm

$$W_p = \frac{c}{2f_c}\sqrt{\frac{2}{2\varepsilon_e+1}} \qquad (1)$$

$$\varepsilon_{ref} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2\sqrt{1 + 12\frac{h}{W_P}}} \qquad (2)$$

$$L_p = \frac{c}{2 f_c}\sqrt{\frac{2}{\varepsilon_{ref}}} \qquad (3)$$

Table.2. Antenna Dimensions

Variables	Dimensions (mm)
Length of the Substrate (L)	10
Width of the Substrate (W)	10
Length of the Patch (Lp)	2.2
Width of the Patch (Wp)	2.4
Quarter wave Transform Length(L1)	1.1
Quarter wave Transform Width (W1)	0.2
Feed Length (L2)	1.5
Feed Width (W2)	0.6

With the given dimensions, the single millimeter-wave antenna (SMA) designs were precisely engineered using the HFSS Electromagnetic simulator to ensure the highest level of accuracy. The radiator and feed line were constructed on the front side of the substrate, with the ground plane was situated on the backside. These antennas were expertly connected to a 50Ω configuration microstrip transmission conductor, shown in Figure 1.

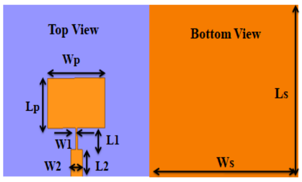


Figure 1. Layout of SMA

A single millimeter wave antenna (SMA) has been developed further into a multi-element MIMO (Multiple Input Multiple Output) configuration. This design incorporates four similar single millimeter-wave antenna elements, each spaced a quarter wavelength (λ/4) apart to mitigate Cross-coupling phenomena and enhance overall performance. To further improve performance, the dimension of the ground plane has been configured to 20mm x 20mm. The layout of this four-element millimeter wave MIMO antenna (FMMA) is illustrated in Figure 2.

Further investigation aimed to boost the effectiveness and compactness of the four-element millimeter wave MIMO antenna (FMMA) structure by decreasing the dimensions of each antenna element in step of 1 mm and integrating a defective ground structure (DGS) approach, specifically utilizing the outset rectangular split ring slot defected ground structure (ORSRSDGS) [5-6]. As shown in Figure 3, the structure of the ORSRSDGS single cell structure, with its optimized dimensions summarized in Table 3.

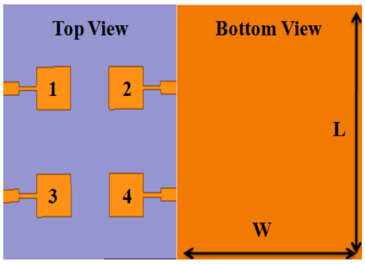


Figure 2. Structure of FMMA

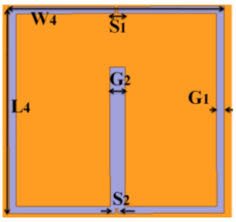


Figure 3. Structure of ORSRSDGS

Table.3. ORSRSDGS Dimensions

Variables	Dimensions (mm)
Substrate Length (L4)	4
Substrate Width (W4)	3.8
S1	0.15
S2	0.1
G1	0.15
G2	0.3

This method involved selectively decreasing the length and width of each antenna element in step of 1 mm, as well as etching the ground plane with two pair ORSRSDGS unit cells positioned 1 mm apart. By strategically implementing ORSRSDGS, the flow of current within the ground layer was effectively disrupted. This approach yielded several advantages. Firstly, it facilitated a reduction in the antenna's physical footprint while preserving or enhancing its operational efficiency. Secondly, ORSRSDGS enabled the antenna to resonate efficiently across two distinct frequency bands, thereby enhancing its versatility without necessitating additional components. Additionally, the implementation of ORSRSDGS contributed to a notable decrease in mutual coupling between the antenna elements. This reduction is pivotal in MIMO systems, preserving signal integrity and minimizes crosstalks. As a result of these advancements, the antenna configuration was renamed the modified compact millimeter wave MIMO antenna (MCMMA), as illustrated as shown in Figure 4, with its optimized dimensions summarized in Table 4.

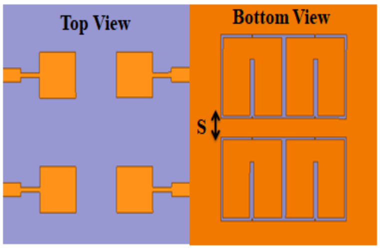


Figure 4. Structure of MCMMA

Table.4. MCMMA Dimensions

Variables	Dimensions (mm)
Length of the Substrate (L)	10
Width of the Substrate (W)	10
Patch Length (Lp)	1.7
Patch Width (Wp)	1.9
Quarter wave Transform Length(L1)	1.1
Quarter wave Transform Width (W1)	0.2
Feed Length (L2)	1.5
Feed Width (W2)	0.6

Selecting the substrate material for the modified compact millimeter wave MIMO antenna (MCMMA) involves choosing a material with low dielectric constant and high thermal stability [6]. The photolithographic process uses light to transfer precise antenna patterns onto the substrate, while the etching process removes excess material to form these patterns. These steps ensure high-performance antenna fabrication by achieving intricate design accuracy and optimal signal transmission properties. Figure 5 illustrates these processes, leading to the final MCMMA prototype shown in Figure 6.

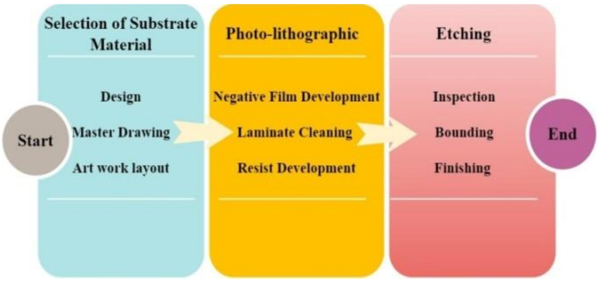


Figure 5. Antenna Fabrication Process

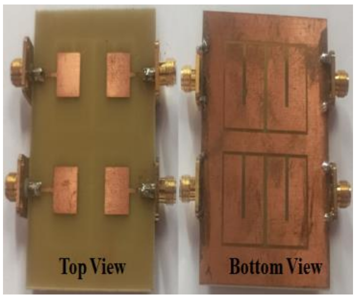


Figure 6. Prototype of MCMMA

3. Results and Discussions

This study investigates the fundamental parameters and operational quality of a millimeter-wave multiple-input multiple-output (MIMO) antenna. In the four-port configuration, when port 2 is turned on, and the rest unused ports are properly matched and closed using a 50Ω load, as depicted in Figure 7.

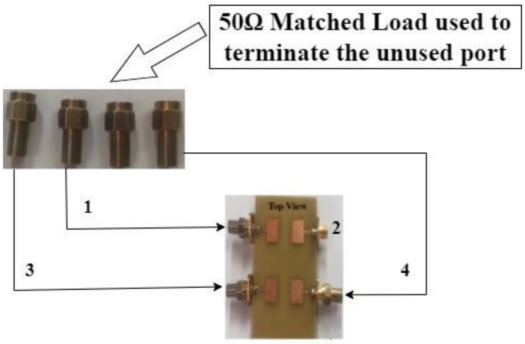


Figure 7. Matched load arrangement for unused ports of MCMMA

This approach ensures that all antenna ports maintain optimal impedance matching and minimize reflections, thereby enhancing overall system performance. By systematically managing the antenna ports in this manner, the design achieves efficient operation and mitigates potential signal interference or degradation. This methodology underscores the importance of meticulous impedance management in maximizing the functionality and reliability of millimeter wave MIMO antenna systems.

Initially, return loss characteristics of the four-element millimeter wave MIMO antenna (FMMA) were analyzed and are depicted in Figure 8. The FMMA resonates at 38 GHz with a return loss of -43 dB, indicative of its strong impedance matching and minimal signal reflection. The antenna supports a bandwidth spanning 4 GHz. highlighting its capability to operate effectively over a broad spectrum of frequencies within the millimeter wave spectrum. This assessment underscores the antenna's efficient capability in terms of signal transmission and reception, crucial for needing extensive data transmission and reliability in millimeter wave communication systems.

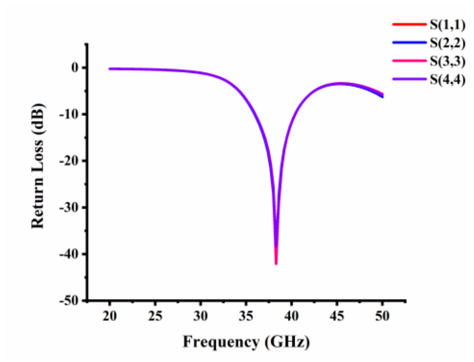


Figure 8. Return Loss Characteristics of FMMA

Figure 9 illustrates the measured return loss characteristics of the modified compact millimeter wave MIMO antenna (MCMMA).

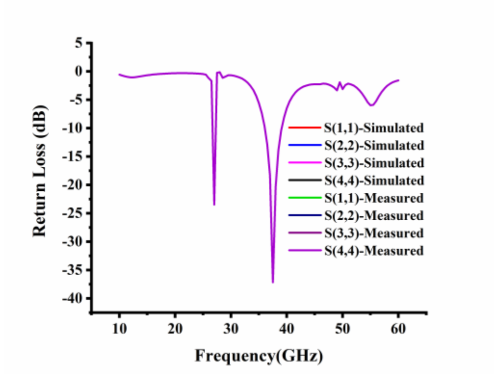


Figure 9. Return Loss Characteristics of MCMMA

The etching of two pairs of ORSRSDGS structures, spaced 1 mm apart on the ground plane, effectively suppressed unwanted surface waves. This resulted in dual resonating points at 28 GHz and 38 GHz. These resonances exhibited return losses of -24.8 dB and -38.7 dB, respectively. The antenna achieved bandwidths of 2 GHz and 3.6 GHz at these particular frequencies. The experimental and simulated antenna results are accurately the same. This careful correlation ensures that both sets of results demonstrate the same resonant frequencies and return loss values. Matching measured and a simulated result offers several benefits. Firstly, it validates the accuracy and reliability of the simulation model, providing confidence in the design process. Secondly, it ensures that the antenna will perform as expected in practical applications, minimizing the need for further adjustments or iterations. Lastly, it facilitates the optimization of the antenna design for improved effectiveness, as the consistent results between measurements and simulations can be used to fine-tune and enhance the antenna's characteristics.

This design not only enhances operational efficiency across multiple frequency bands but also achieves significant virtual size reduction (VSR) and physical size reduction (PSR). These reductions can be calculated using equations (4) and (5) provided below [6-8]. This innovative approach highlights the benefits of advanced ground plane modification techniques in optimizing antenna performance for high-frequency applications.

$$\mathrm{VSR}=\left(\frac{L_1-L_2}{L_1}\right)\mathrm{X}100 \qquad (4)$$

In this scenario, L1 refers to the actual length tied to the lower resonating frequency of the 28 GHz, while L2 denotes the actual length of the higher resonating frequency point 38 GHz. The inclusion of two pairs of ORSRSDGS unit cells enabled the MCMMA to realize a substantial virtual size reduction of 44.11%.

$$\mathrm{PSR}=\left(\frac{A_C-A_M}{A_C}\right)\mathrm{X}100 \qquad (5)$$

In this context, AC denotes the area of the single millimeter-wave antenna (SMA), whereas AM represents the each individual antennas area of the MCMMA. By incorporating two pairs of ORSRSDGS unit cells, the MCMMA achieves a notable physical size reduction (PSR) of 38.82%.

Deploying multiple antennas on a single ground plane can introduce significant coupling effects between the antenna elements. To measure these interactions, the mutual coupling coefficients (MCC) can be determined using the following equation (6) [9]. This calculation is essential for assessing and minimizing coupling, thereby optimizing the overall performance and efficiency of MIMO antennas. By accurately evaluating MCC, engineers can design multi-antenna systems that ensure superior signal integrity and reduced interference, leading to enhanced operational effectiveness.

$$S_{12}=20\log\left(\frac{2Z_{21}-Z_0}{[(Z_{11}+Z_0)^2+(Z_0)^2]}\right) \qquad (6)$$

Assuming Z0 represents the characteristic impedance, set to 50Ω, the values confirm that

Z12 and Z21 are equal, and likewise, Z11 matches Z22. The four-element millimeter wave MIMO antenna (FMMA) exhibits an MCC of -14.64 dB. In contrast, the modified compact millimeter wave MIMO antenna (MCMMA) attains MCC values of -28.67 dB and -43.12 dB at respective frequency points. The observed reduction in MCC for the MCMMA is primarily due to the incorporation of outset rectangular split ring slot defected ground structures (ORSRSDGS). These DGS elements effectively disrupt the current flow at the surface level thereby minimizing the coupling between antenna elements. By strategically etching the ground plane with DGS, unwanted electromagnetic interactions are suppressed, leading to improved isolation and significantly lower mutual coupling coefficients. This innovative approach enhances the performance of MIMO systems, ensuring better signal integrity and reduced interference across 28GHz and 38GHz frequency bands.

The antenna coverage area and link budget are determined by the total peak gain (TPG). The four-element millimeter wave MIMO antenna (FMMA) shows a TPG of 5.32dB, as illustrated in Figure 10. Meanwhile, the modified compact millimeter wave MIMO antenna (MCMMA) achieves TPG measurements of 7.10dB and 7.7dB at corresponding frequency points, as illustrated in Figure 11

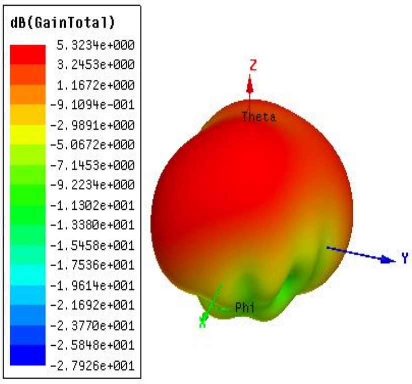
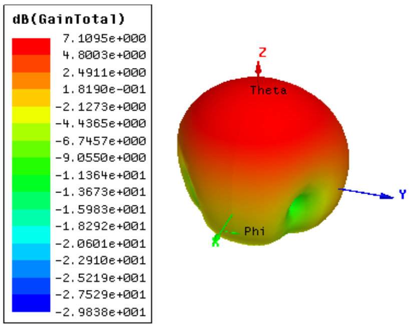
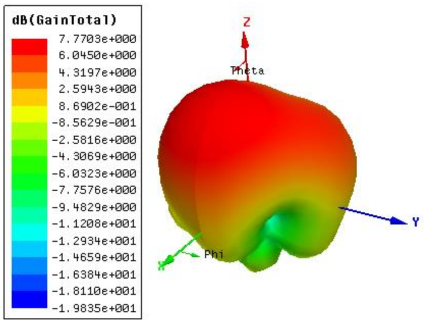


Figure 10. TPG of FMMA

The improvement in gain for the MCMMA can be attributed to the inclusion of outset rectangular split ring slot defected ground structures (ORSRSDGS). These DGS structures enhance the antenna's performance by disrupting surface currents on the ground plane, leading to enhance impedance matching and reduced signal losses. This optimization results in higher radiation efficiency and, consequently, improved total peak gain. By integrating ORSRSDGS, the antenna achieves more effective signal transmission and reception, thereby extending its coverage area and enhancing the overall link budget.



(a) 7.10dB at 28GHz



(b) 7.7dB at 38GHz

Figure 11. TPG of MCMMA

The isolation of the communication channel is measured using envelope correlation coefficients (ECC) [10]. Referring to equation (7), it can be observed that the four-element millimeter-wave MIMO antenna (FMMA) has an ECC value of 0.006, as shown in Figure 12.

$$\rho = \frac{\left|S_{11}^{*}S_{12}+S_{21}^{*}S_{22}\right|^{2}}{\left(1-\left|S_{11}\right|^{2}-\left|S_{21}\right|^{2}\right)\left(1-\left|S_{22}\right|^{2}-\left|S_{12}\right|^{2}\right)} \qquad (7)$$

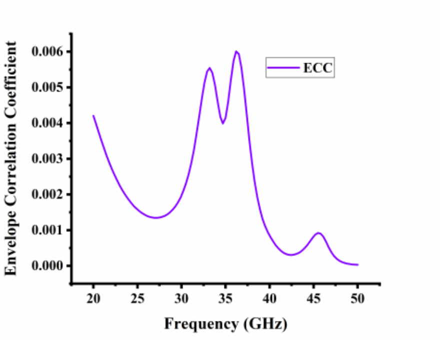


Figure 12. ECC of FMMA

On the other hand, the modified compact millimeter wave MIMO antenna (MCMMA) exhibits an ECC value of 0 at the specified particular frequency points, as highlighted in

Figure 13. This indicates a higher isolation and improved effectiveness of the modified antenna in analysis to the conventional four-element design.

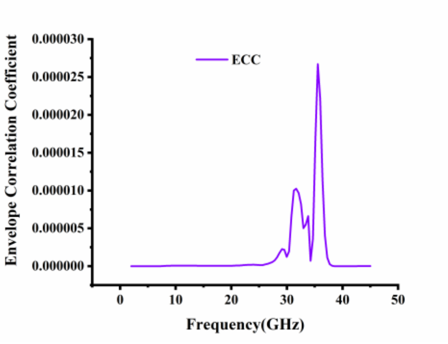


Figure 13. ECC of MCMMA

The performance of the four-element millimeter-wave MIMO antenna involves calculating diversity gain (DG) from the envelope correlation coefficient (ECC) using formula (8).With an ECC measuring 0.06, the antenna exhibits a diversity gain values of 9.9 dB, highlighting its operational efficiency in practical scenarios. This metric reflects the antenna's capability to leverage spatial diversity in signal reception, thereby mitigating fading effects. In contrast, the modified compact millimeter wave MIMO antenna (MCMMA) attains a diversity gain value of 10 dB, corresponding to an value of 0 for ECC at the respective frequency. This enhancement signifies improved spatial diversity, suggesting superior performance in maintaining reliable communication links across various propagation conditions. These diversity gain measurements highlight significant advancements in antenna design, particularly in optimizing signal reception diversity. Such improvements are critical for enhancing overall system efficiency and reliability in millimeter-wave MIMO applications

$$DG = 10\sqrt{\left(1-|\rho|^2\right)} \qquad (8)$$

The radiation pattern shows how electromagnetic waves travel into the far-field region. In Figure 14, the radiation behaviour of the four-element millimeter wave MIMO antenna (FMMA) is depicted, demonstrating broadside radiation characteristics [11-12]. This indicates that the antenna radiates most strongly perpendicular to its surface, ideal for maximizing coverage in that direction.

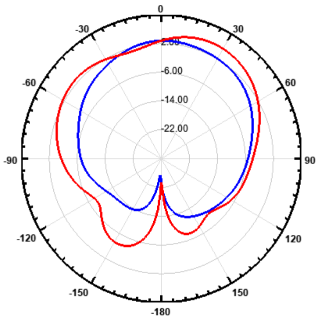
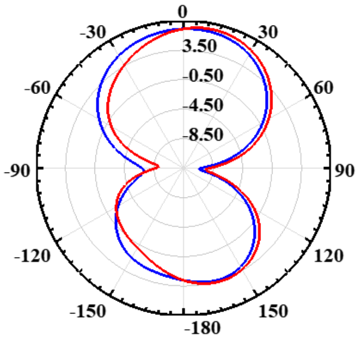
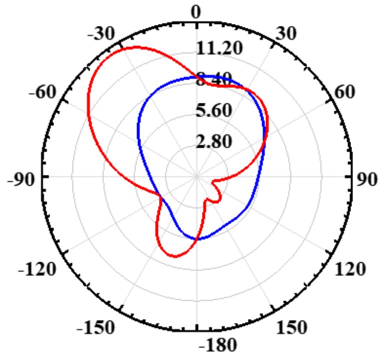


Figure 14. Radiation Pattern of FMMA

In contrast, Figure 15 displays the radiation behaviour associated with the modified compact millimeter wave MIMO antenna (MCMMA), showcasing broadside pattern observed at both points of resonance. This radiation pattern suggests that it maintained consistent directional radiation properties across its operational frequencies, enhancing its suitability for applications requiring stable and predictable coverage patterns. These radiation patterns are crucial for understanding how antennas distribute electromagnetic energy in their surroundings, influencing their effectiveness in communication systems and networks operating in the millimeter-wave spectrum.



(a) 28GHz



(b) 38GHz

Figure 15. Radiation Pattern of MCMMA

The modified compact millimeter wave MIMO antenna (MCMMA), integrating the outset rectangular split ring slot defected ground structure (ORSRSDGS), operates effectively across dual operating bands of 28GHz and 38GHz. It achieves substantial bandwidths of 2GHz and 3.6GHz respectively, highlighting its versatility for a wide range of millimeter-wave applications. The antenna demonstrates impressive total peak gains (TPGs) of 7.10dB at 28GHz and 7.7dB at 38GHz, indicating its efficient radiation and reception capabilities within these frequency ranges. In addition to its frequency characteristics, the MCMMA achieves significant reductions in both physical size (38.28%) and virtual size (44.11%). These reductions are particularly advantageous in applications where constraints on space and weight are critical considerations. Furthermore, the MCMMA exhibits envelope correlation coefficients of 0 and a diversity gain of 10 dB. These metrics underscore its ability to leverage spatial diversity effectively, mitigating signal fading and enhancing communication reliability. This advanced performance sets the MCMMA apart from previous millimeter-wave MIMO antennas, as highlighted in Table 5, where its comprehensive performance metrics are compared with those from existing literature.

Table.5. comprehensive performance

Reference	Fr GHz	BW GHz	TPG dB	PSR	VSR	DG dB
[2]	28	1.23	6.6	-	-	10
	38	1.06	5.86			
[3]	26	1.8	6	-	-	-
[6]	28	2.6	4.3	-	-	-
[7]	28	0.69	5.9	-	-	9.4
	38	0.86	7			
[9]	35	3.5	6	-	-	10
[10]	28	1.4	5.7	-	-	10
	38	0.5	6.9			
[12]	28	2.5	1.27	-	-	9.6
	38	2.1	1.83			
FMMA	38	4	5.32	-	-	9.6
MCMMA	28	2	7.1	38.8%	44.1%	10
	38	3.6	7.7			

Overall, the MCMMA represents a pioneering advancement in millimeter-wave antenna technology, characterized by improvements in efficiency, bandwidth capability, size reduction, and diversity gain. These enhancements position the antenna favourably for enhancing the performance and reliability of millimeter-wave communication systems, particularly in applications related to 5G/6G Wireless communication Systems.

4. Conclusion

The antenna systems were crafted using an electromagnetic analysis simulator HFSS. The modified compact millimeter wave MIMO antenna (MCMMA) integrates an innovative outset rectangular split ring slot defected ground structure (ORSRSDGS) to improve the efficiency of MIMO systems. It efficiently tuned to 28 GHz and 38 GHz, boasting return loss value of -24.8 dB and -38.7 dB correspondingly, showcasing robust impedance matching. The MCMMA offers expansive bandwidths of 2 GHz and 3.6 GHz, catering to diverse millimeter-wave applications. It achieves total peak gains (TPGs) of 7.1 dB and 7.7 dB, ensuring exceptional signal emission and reception. Exhibiting an envelope correlation coefficient of 0 and a 10 dB diversity gain, it guarantees dependable communication. Furthermore, the MCMMA achieves a 38.82% reduction in physical size and a 44.11% decrease in virtual footprint, aligning perfectly with contemporary design parameters. These innovations position the MCMMA as an ideal choice for advanced 5G and 6G wireless systems.

Acknowledgements

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