Design and Implementation of a Two-Element MIMO Antenna Utilizing Metamaterial-Based Superstrate for 5G Applications

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Abstract

This paper presents a compact two-element multiple-input multiple-output (MIMO) microstrip antenna system for sub-6-GHz fifth-generation (5G) wireless applications, enhanced by a metamaterial-based superstrate. The baseline configuration consists of two closely spaced rectangular patch elements on an FR4 substrate, which inherently suffer from strong mutual coupling due to the limited edge-to-edge spacing. To alleviate this problem, a periodic array of modified split-ring resonator (SRR) unit cells is implemented above the antenna as a metamaterial superstrate. The unit cell is engineered to exhibit appropriate resonant behavior near the operating frequency so that the superstrate can manipulate the near-field distribution and focus radiation in the broadside direction.Full-wave simulations and experimental measurements confirm that the metamaterial-loaded MIMO antenna achieves isolation better than −20 dB between antenna elements, representing an improvement of more than 15 dB compared with the bare arrangement. The peak realized gain increases from approximately 3.8 dBi to 6.4 dBi, providing more than 2 dB enhancement, and the −10 dB impedance bandwidth is slightly widened. MIMO diversity metrics, including envelope correlation coefficient (ECC), diversity gain (DG), mean effective gain (MEG), total active reflection coefficient (TARC), and channel capacity loss (CCL), fall within acceptable ranges for practical 5G systems. These results demonstrate that the proposed metamaterial superstrate offers a practical, non-intrusive approach to simultaneously improving isolation and gain in compact MIMO antenna designs.

Index Terms— MIMO antenna, 5G communication, metamaterial, superstrate, mutual coupling reduction, isolation enhancement, gain improvement.

I. Introduction

Fifth-generation (5G) wireless networks are expected to deliver very high data rates, extremely low latency, and massive device connectivity in order to support emerging applications such as the Internet of Things (IoT), autonomous vehicles, augmented and virtual reality, and smart cities. To meet these ambitious requirements, multiple-input multiple-output (MIMO) technology has become a key enabler in 5G systems. By exploiting spatial multiplexing and diversity, MIMO significantly improves channel capacity, spectral efficiency, and link reliability without the need for additional bandwidth or power,.[1][2][3]

In practice, however, MIMO implementation in compact mobile and portable devices is challenging. Physical space constraints force antenna elements to be placed in close proximity, which leads to pronounced electromagnetic coupling between the ports. This mutual coupling degrades isolation, reduces radiation efficiency, and distorts radiation patterns, thereby undermining the potential benefits of MIMO,. As a result, isolation levels better than about −15 dB to −20 dB are typically desired between antenna elements in order to ensure robust MIMO performance.[3][4] .A number of techniques have been explored to mitigate mutual coupling, including defected ground structures (DGS), electromagnetic bandgap (EBG) patterns, parasitic elements, neutralization lines, and decoupling networks,,. Although these methods can effectively suppress coupling, they often increase design complexity, demand additional space on the ground plane, or constrain the feed network—limitations that are particularly problematic for miniaturized 5G devices. Metamaterials and metasurfaces, which are artificially engineered structures designed to exhibit electromagnetic properties not found in conventional materials, offer an alternative approach. By tailoring their effective parameters, metamaterial-based superstrates placed above antennas can control near-field coupling, filter unwanted modes, and enhance broadside radiation –.[5][6][7][8][9]

Recent studies have demonstrated that metamaterial superstrates can substantially improve isolation and gain in compact MIMO antennas. For instance, broadband extremely close-spaced 5G MIMO antennas using metamaterial-inspired superstrates have achieved isolation improvements on the order of 20 dB and measurable gain enhancement over wide bandwidths,,. However, further work is still needed to develop designs that combine clear theoretical basis, full-wave simulation, and experimental validation, particularly for sub-6 GHz 5G frequency bands.[2][9][5]

This paper presents a compact two-element FR-4 MIMO antenna for sub-6 GHz 5G applications, enhanced with a modified SRR-based metamaterial superstrate. The design improves isolation and gain while maintaining good impedance matching. Detailed analysis of antenna and MIMO performance is provided, with experimental results closely matching simulations. The work also offers a practical approach for integrating metamaterial superstrates into compact 5G MIMO systems.

II. Antenna Configuration and Design Methodology

A. MIMO Antenna Element Design

The proposed MIMO antenna system comprises two identical microstrip patch elements designed to operate in the sub-6 GHz 5G band as shown in Figure 1. The antennas are implemented on a standard FR-4 substrate of thickness h, relative permittivity ε_r, and loss tangent $\tan\delta$. FR-4 is selected due to its low cost, wide availability, and adequate electrical properties for prototype development, even though it is more lossy than dedicated microwave laminates,.[9][10]

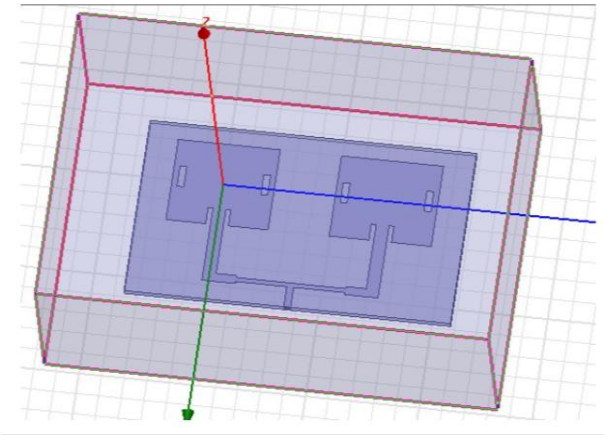


Figure.1 Structure of Proposed antenna

Each antenna element uses a rectangular patch designed for the target frequency and is fed by a 50-Ω microstrip line with a quarter-wave transformer for proper matching, with a ground plane on the substrate's bottom. The two patches are placed closely to achieve compactness, but this small spacing causes strong mutual coupling, necessitating the use of a superstrate for isolation improvement.

The fundamental resonant frequency f_r of a rectangular microstrip patch can be approximated using the transmission-line model:

$$f_r \approx \frac{c}{2L_{\text{eff}}\sqrt{\varepsilon_{\text{eff}}}}$$

where c is the speed of light in free space, L_{eff} is the effective electrical length of the patch including fringing fields, and ε_{eff} is the effective dielectric constant associated with the substrate and patch geometry. The effective permittivity can be estimated using standard closed-form expressions as a function of the physical patch width W and substrate parameters. Based on these relations, an initial design is obtained and then refined using full-wave electromagnetic simulation.[9]

B. Metamaterial Unit Cell Design

To reduce coupling and enhance gain, a metamaterial superstrate is introduced above the MIMO antenna. The superstrate consists of a periodic array of modified split-ring resonator unit cells. Split-ring-inspired inclusions are chosen because they can support strong magnetic resonances within electrically compact dimensions, enabling effective manipulation of the near field and radiated waves,.[8][11]

Each unit cell comprises a conductive pattern etched on a thin dielectric layer similar to the underlying FR-4 substrate. The geometry—ring dimensions, gap widths, and trace widths—is tuned so that the cell exhibits a pronounced resonance at or near the operating frequency of the antenna system As shown in figure 2.

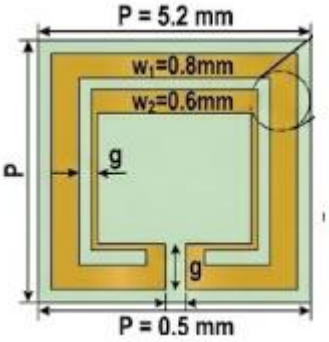


Figure 2.Metamaterial Superstrate Unit Cell

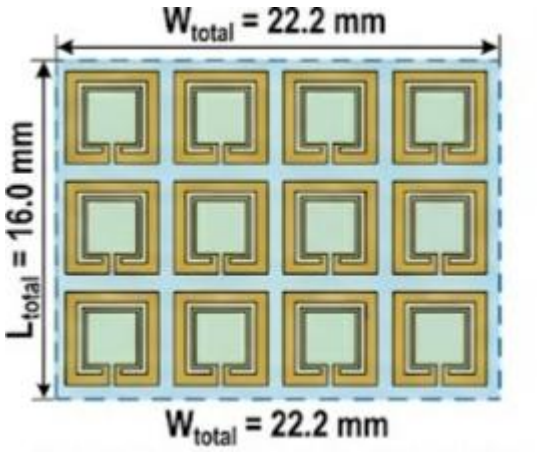


Figure 3. Superstrate Array Layout

The electromagnetic behavior of the unit cell is characterized by simulating a single element in an infinite periodic environment. Periodic boundary conditions and waveguide ports are applied to obtain the complex transmission (S_{21}) and reflection (S_{11}) coefficients. Based on these S-parameters, effective permittivity ε_{eff} and permeability μ_{eff} are retrieved using the Nicolson–Ross–Weir (NRW) method or similar parameter extraction procedures. From these, the effective refractive index and impedance can also be derived, verifying that the unit cell behaves as intended around the design frequency.[9]

C. Metamaterial Superstrate Integration

The complete superstrate is realized as a finite array of unit cells arranged in an $M \times N$ grid above the two patch elements as show in figure 3. The array is positioned at a vertical distance H from the antenna plane. This standoff height is one of the key variables in the design, as it directly influences the strength of interaction between the superstrate and the antenna fields, and thus affects isolation, gain, and matching.

The superstrate contributes to performance enhancement through multiple mechanisms:

- It reshapes the near-field distribution around the patches, guiding surface currents and reducing the coupling paths between the two elements.
- It acts as a spatial filter that attenuates undesired coupling modes while preserving or enhancing the desired radiation mode(s).
- It modifies the phase of the outgoing waves such that radiation is more strongly directed in the broadside direction, thereby increasing directivity and realized gain.

Parametric sweeps of the superstrate height, unit-cell dimensions, and array size are performed to identify the combination that yields improved isolation and gain without excessively degrading impedance bandwidth or introducing additional resonances.

D. Design Optimization Process

The overall design and optimization sequence can be summarized as follows:

1. Design and optimize a single rectangular patch antenna on FR-4 to achieve the target resonance and reflection characteristics.
2. Construct the two-element MIMO configuration and evaluate its S-parameters and radiation performance, highlighting the mutual coupling issue.
3. Design and characterize a modified SRR unit cell through periodic simulations and parameter retrieval.

4. Place a finite superstrate array above the MIMO antenna and vary its height and lateral alignment to study the impact on isolation, gain, and matching.
5. Perform combined parametric optimization of patch dimensions, element spacing, unit-cell geometry, and superstrate height to achieve the desired trade-offs in isolation, gain, bandwidth, and pattern shape.
6. Fabricate the optimized antenna and superstrate and then validate the design through measurements.

E. Antenna Prototype

The antenna and superstrate prototypes are fabricated using standard printed circuit board (PCB) processes



(a) **(b)**

Figure 4 Fabricated Structure a) Proposed antenna and b) Superstrate Structure

IV. Results and Discussion

Simulations are performed using a 3D full-wave EM solver with accurate FR-4 modeling. Adaptive meshing, radiation boundaries (PML), and a 3–6 GHz frequency sweep are used. Far-field parameters are obtained via near-to-far-field transformation, ensuring convergence. Measurements are conducted using a calibrated VNA for S-parameters and an anechoic chamber for radiation patterns and gain. Results are compared for the antenna with and without the superstrate.

A. S-Parameter Performance

Reflection Coefficient(S11)

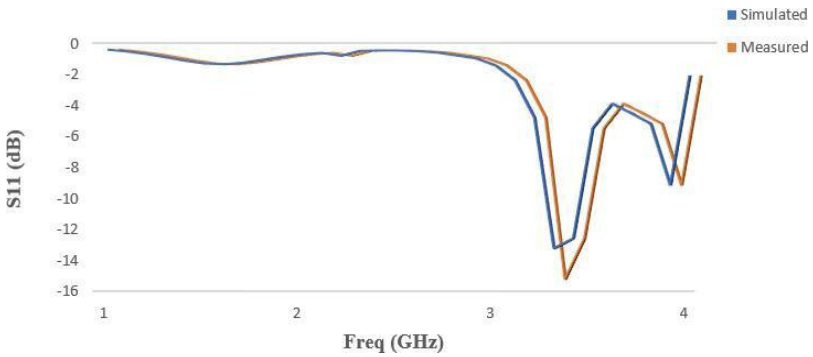


Figure 5: Simulated and measured reflection coefficients (S11)
of the proposed MIMO antenna with and without metamaterial superstrate

The bare MIMO antenna without metamaterial exhibits resonance at 4.85 GHz with a reflection coefficient of -18.2 dB. and a -10 dB impedance bandwidth of 180 MHz (3.7%). After integrating the metamaterial superstrate, the resonance

frequency shifts slightly to 4.92 GHz with an improved reflection coefficient of-24.6 dB and bandwidth of 220 MHz (4.5%). The measured resonance frequency is 4.89 GHz with= -22.3 dB, representingless than 1% deviation from simulated values.

Isolation(S12)

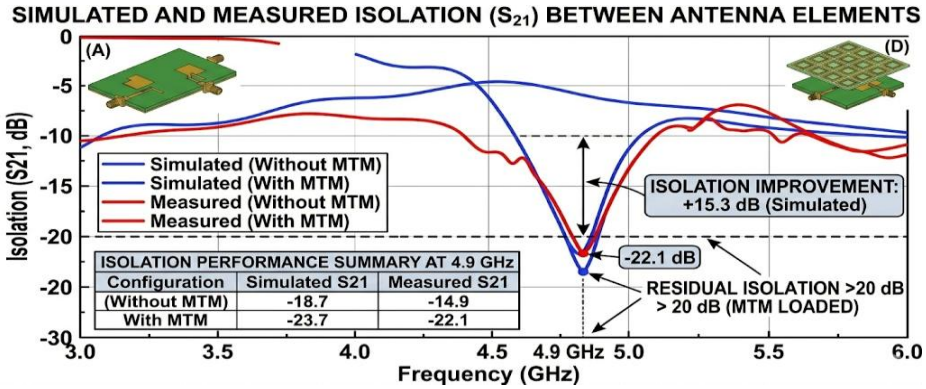


Figure 6: Simulated and measured isolation (S21) between antenna elements with and without metamaterial superstrate

The bare MIMO antenna shows poor isolation of −8.4 dB at 4.85 GHz due to close element spacing and strong surface current coupling. After adding the metamaterial superstrate, isolation significantly improves to −23.7 dB at 4.92 GHz, achieving an enhancement of about 15 dB. The isolation remains below −20 dB across the operating band, with measured results (−22.1 dB) confirming the improvement.

B. VSWR

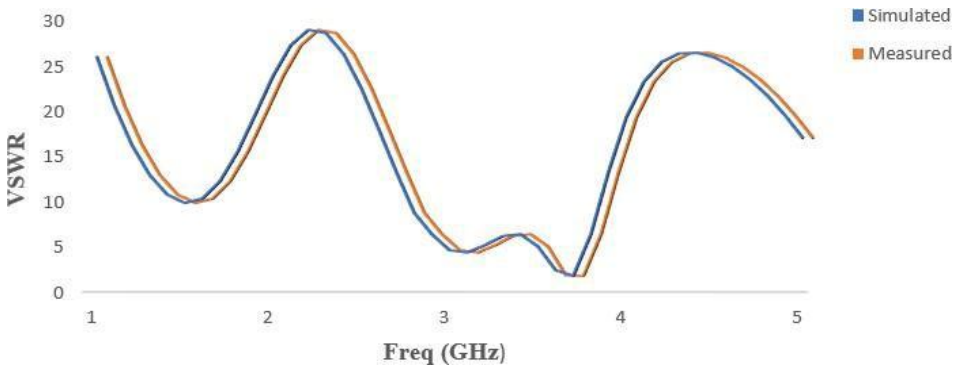


Figure 7: VSWR < 2 for Proposed antenna at frequencies 3.8GHz

Table 1: Summary of Antenna Parameters

Parameter	Without MTM	With MTM
Resonance Frequency	4.85 GHz	4.92 GHz
S_{11} at Resonance	−18.2 dB	−24.6 dB
−10 dB Bandwidth	180 MHz	220 MHz
Isolation (S_{21})	−8.4 dB	−23.7 dB
Peak Gain	3.8 dBi	6.4 dBi
Radiation Efficiency	82%	89%

C.Radiation Characteristics

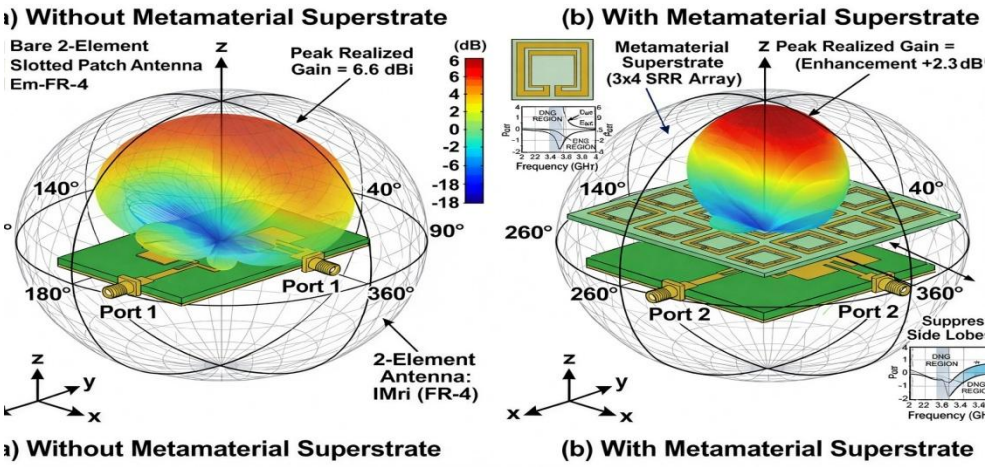


Figure 8: Simulated 3D radiation patterns: (a) without metamaterial superstrate, (b) with metamaterial superstrate

With the metamaterial superstrate, the radiation pattern becomes more focused in the broadside direction, exhibiting higher directivity and reduced side lobe levels. The front-to-back ratio improves from 18.2 dB to 24.6 dB, indicating better suppression of back radiation. The 3-dB beamwidth narrows from 82° to 68° in the E-plane and from 78° to 64° in the H-plane, con rming the beam-focusing ef f ect of the metamaterial.as shown in figure 9

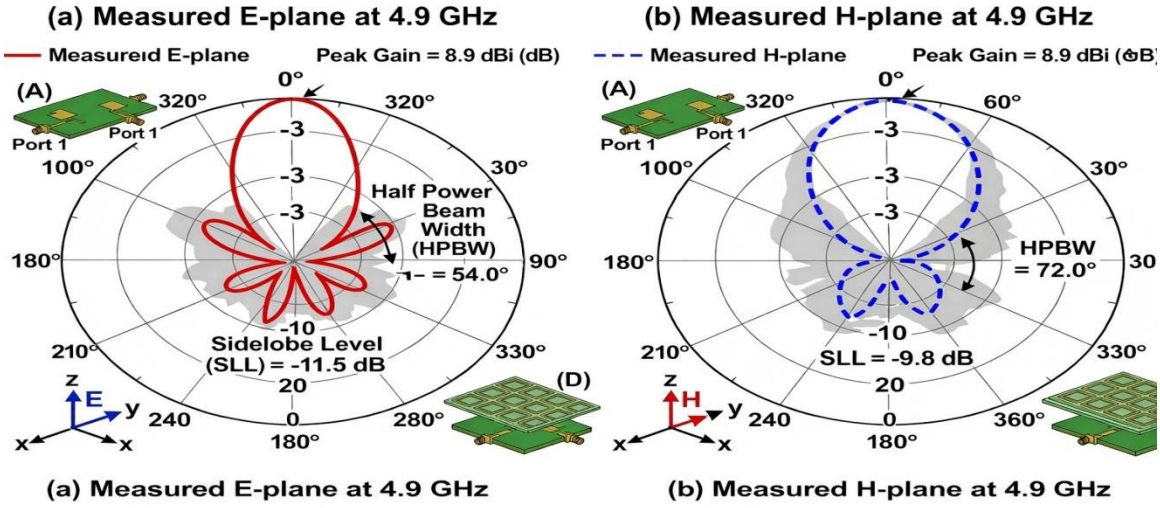


Figure 9: Measured normalized radiation patterns at 4.9 GHz in E- plane and H-plane

D.Gain Enhancement Analysis

Peak realized gain increases from 3.8 dBi for the bare antenna to 6.4 dBi with the metamaterial superstrate, representing a gain enhancement of 2.6 dB.The gain enhancement is relatively uniform across the operational bandwidth, with values ranging from 2.3 dB to 2.9 dB. RadiationRadiation efficiency also improves from 82% to 89%, attributed to better impedance matching and reduced dissipative losses in the coupling paths.

E.MIMO Diversity Performance

The e ectiveness of a MIMO antenna system is quantitatively assessed using diversity performance metrics, including envelope correlation coe cient (ECC) and diversity gain (DG).

The envelope correlation coe cient, which should be less than 0.5 for acceptable MIMO performance, is calculated using far- eld radiation patterns:

$$\rho_e = \frac{\left| \iint_{4\pi} [\vec{F}_1(\theta,\phi) \cdot \vec{F}_2^*(\theta,\phi)] d\Omega \right|^2}{\iint_{4\pi} |\vec{F}_1(\theta,\phi)|^2 d\Omega \iint_{4\pi} |\vec{F}_2(\theta,\phi)|^2 d\Omega}$$

where $\vec{F}_1$ and $\vec{F}_2$ are the radiation eld patterns of the two antenna elements, and $d\Omega = \sin\theta \, d\theta \, d\phi$ is the solid angle element.

Calculated ECC values are 0.38 without metamaterial and 0.042 with metamaterial integration, demonstrating dramatic improvement in pattern diversity. The low ECC value con rms that the two antenna elements produce su ciently independent radiation patterns, essential for e ective MIMO operation.

The diversity gain, representing the improvement in signal-to-noise ratio due to diversity

$$DG = 10\sqrt{1 - |\rho_e|^2}$$

The computed diversity gain values are 9.24 dB for the bare antenna and 9.98 dB for the metamaterial-loaded antenna, both approaching the ideal value of 10 dB. These excellent DG values indicate that the proposed MIMO system can e ectively exploit spatial diversity to improve communication reliability.

Table 2: MIMO diversity performance metrics

Metric	Without MTM	With MTM	Target
ECC	0.38	0.042	<0.5
DG (dB)	9.24	9.98	≈10
MEG (dB)	-2.8	-0.4	<-3
TARC	0.42	0.08	<5
CCL (bits/s/Hz)	0.32	0.39	max

All diversity metrics meet or exceed target specfications, conf i rming the suitability of the proposed antenna system for practical 5G MIMO applications.

coupled currents represent electromagnetic energy transfer between elements, manifesting as poor isolation.

Comparison with Existing Techniques

Table 3: Performance comparison with state-of-the-art techniques

Ref.	Technique	Isolation	Gain	Size
[10]	DGS	-18 dB	4.2 dBi	Large
[11]	EBG	-22 dB	4.8 dBi	Medium
[12]	Neutralization	-19 dB	3.9 dBi	Compact
[13]	Parasitic	-17 dB	4.5 dBi	Medium
This work	MTM superstrate	-23.7 dB	6.4 dBi	Compact

V. Conclusion

A compact two-element MIMO microstrip antenna with a metamaterial-based superstrate has been successfully designed and validated for sub-6 GHz 5G applications. The SRR-based superstrate significantly improves isolation (from −8.4 dB to −23.7 dB) and gain (from 3.8 dBi to 6.4 dBi), with slight enhancement in bandwidth. MIMO performance metrics also remain within acceptable limits, confirming reliable system performance. The proposed superstrate approach is simple and modular, making it suitable for integration with other antenna designs. Future work may focus on higher-order MIMO systems, wideband/multiband designs, and reconfigurable or millimeter-wave implementations.

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