Compact Hexagonal MIMO Antenna with Enhanced Bandwidth and Isolation for Adaptive 5G/6G Applications

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ABSTRACT

This paper presents a compact microstrip antenna array with enhanced isolation achieved using a hexagonal complementary split-ring resonator (CSRR) metamaterial structure. Mutual coupling between closely spaced antenna elements degrades radiation performance and limits MIMO system efficiency. To address this critical issue, a hexagonal CSRR is introduced between two identical rectangular patch antennas to suppress surface current propagation. The proposed structure creates a stopband effect at the operating frequency, effectively reducing electromagnetic interaction between the antenna elements. Simulation results using ANSYS HFSS demonstrate a significant improvement in isolation without increasing array size or degrading impedance matching. Surface current distribution analysis confirms that the CSRR efficiently blocks coupled currents between adjacent patches. The antenna achieves a return loss of approximately -28 dB and excellent isolation characteristics, while maintaining stable radiation patterns and satisfactory gain. Due to its compact size, simple geometry, and effective mutual coupling reduction, the proposed antenna array is well suited for modern wireless communication and MIMO applications across 5G and 6G frequency bands.

Index Terms— Microstrip antenna array, mutual coupling reduction, complementary split-ring resonator (CSRR), metamaterial, MIMO antenna, isolation enhancement, 5G/6G applications

I. INTRODUCTION

Microstrip array antennas have become ubiquitous in modern wireless communication systems due to their attractive properties including low profile, lightweight construction, and high conformability. Arrays of microstrip elements are extensively employed to introduce scanning capabilities, achieve greater directivity, and synthesize required radiation patterns that cannot be achieved with single elements.

One of the primary challenges in antenna array design is reducing mutual coupling between elements. When the electric field from one patch induces current in neighboring patches, the resulting mutual coupling degrades the embedded element radiation pattern and affects the input impedance of the array. This phenomenon becomes particularly problematic when patches are closely spaced to maintain compact array dimensions.

Several methods have been proposed to mitigate mutual coupling. Electromagnetic band-gap (EBG) structures using mushroom-like topologies have been investigated, though these often require plated through-holes (vias), which introduce undesirable losses and manufacturing complexity. Planar EBG structures eliminate the need for vias but require additional dielectric layers and cost. To overcome these limitations, this work introduces a novel hexagonal complementary split-ring resonator (CSRR) metamaterial structure that achieves effective mutual coupling reduction through simple ground plane etching.

The primary contribution of this paper is the demonstration of a compact, cost-effective approach to isolate closely-spaced antenna elements using hexagonal CSRR structures. Unlike conventional methods, the proposed technique does not require modifications to the dielectric substrate or the introduction of vias. Instead, the CSRR structure is etched directly into the ground plane, maintaining the antenna's low-profile and lightweight characteristics while achieving significant isolation improvements suitable for MIMO systems in 5G and emerging 6G applications.

II. MICROSTRIP PATCH ANTENNA FUNDAMENTALS

A. Construction and Characteristics

A microstrip patch antenna consists of a thin metallic patch of arbitrary shape deposited on a dielectric substrate, with a ground plane on the opposite side. The substrate thickness typically ranges from 0.03λ to 0.05λ, where λ is the wavelength. Patch dimensions generally fall between λ/3 and λ/2, while the dielectric constant of the substrate material ranges from 2.2 to 12.

Microstrip patch antennas are attractive for modern communication systems due to several key characteristics: low profile enabling conformal mounting, lightweight construction facilitating portable applications, compatibility with MMIC designs, mechanical robustness, and inexpensive manufacturing through photo-etching technology. Additionally, these antennas exhibit flexibility in shape and can be tuned through feed position adjustment and passive elements such as varactor diodes or pins inserted between the patch and ground plane.

B. Mutual Coupling and Surface Waves

In array configurations, mutual coupling arises from both space-wave and surface-wave interactions. Space-wave coupling dominates when antennas are printed on thin, low-permittivity substrates, while surface-wave coupling becomes significant on thick, high-permittivity substrates. Both mechanisms degrade array performance by affecting the input impedance and radiation pattern of individual elements, limiting system efficiency and data capacity.

The introduction of the hexagonal CSRR between array elements creates a stopband at the operating frequency, effectively suppressing the surface currents and electromagnetic fields responsible for coupling. This metamaterial-based approach provides isolation enhancement while maintaining system compactness and simplifying the manufacturing process compared to conventional decoupling techniques.

III. COMPLEMENTARY SPLIT-RING RESONATOR THEORY

A. Metamaterial Resonator Structures

Complementary split-ring resonators (CSRR) are complementary structures to classical split-ring resonators (SRR), created through the duality principle applied to magnetically resonant SRR configurations. Where SRR structures exhibit magnetic resonance when subjected to vertically polarized magnetic fields, CSRR structures demonstrate resonant behavior when exposed to vertically polarized electric fields. This characteristic makes CSRR structures particularly effective in electromagnetic environments where electric field dominance exists.

The resonant behavior of CSRR structures originates from the interplay between the capacitance created by the gaps in the rings and the inductance contributed by the metallic portions. This balanced LC response produces a high quality factor (Q), enabling steep resonance characteristics suitable for frequency selective applications. The sub-wavelength dimensions of the resonator relative to the operating wavelength result in low radiative losses and sharp resonance transitions.

B. Hexagonal CSRR Design

The hexagonal geometry of the CSRR employed in this work offers significant advantages over circular or rectangular alternatives. The six-fold symmetry provides robust resonance characteristics independent of incident wave polarization, while the hexagonal footprint achieves favorable packing efficiency and enables compact placement between antenna elements. The hexagonal configuration also simplifies analysis and optimization due to its reduced rotational symmetry complexity compared to arbitrary geometries.

IV. PROPOSED ANTENNA DESIGN

A. Array Configuration

The proposed antenna consists of a two-element microstrip patch antenna array integrated with a hexagonal CSRR metamaterial structure. Two identical rectangular radiating patches are symmetrically placed on a common dielectric substrate with a shared ground plane. The inter- element spacing is maintained at a compact value to maximize array directivity while the CSRR is etched between the patches to suppress coupling.

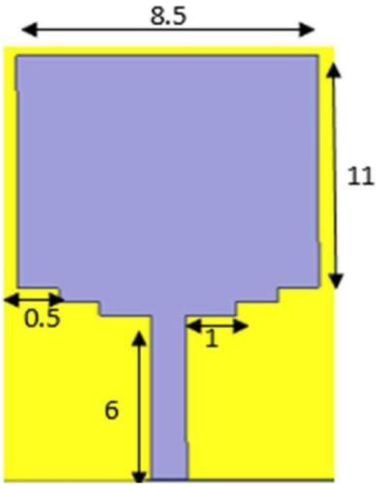

Fig 1: Dimensions of Proposed Antenna

Each patch element is excited via a microstrip feed line positioned to achieve proper impedance matching at the desired operating frequency. The feed line geometry and positioning are optimized through electromagnetic simulations to ensure return loss better than -10 dB across the operating band.

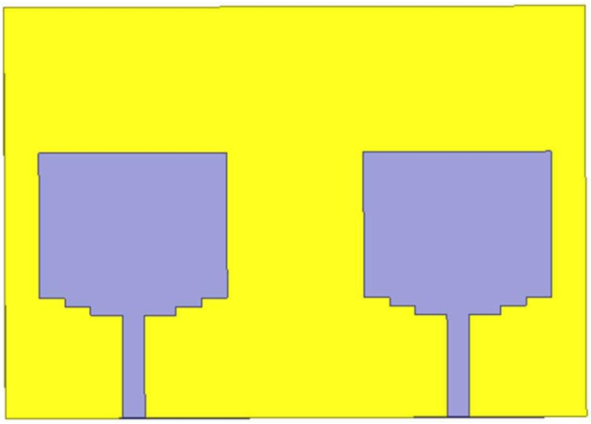

Fig 2: Proposed Two-Element Microstrip Array Antenna

B. Hexagonal CSRR Implementation

The hexagonal CSRR structure is implemented through selective etching of the ground plane. This approach eliminates the necessity for substrate modifications, vias, or multi-layer constructions. The etching pattern creates a resonant structure whose fundamental resonance frequency is tuned to match the operating band of the antenna array through careful geometric parameter optimization.

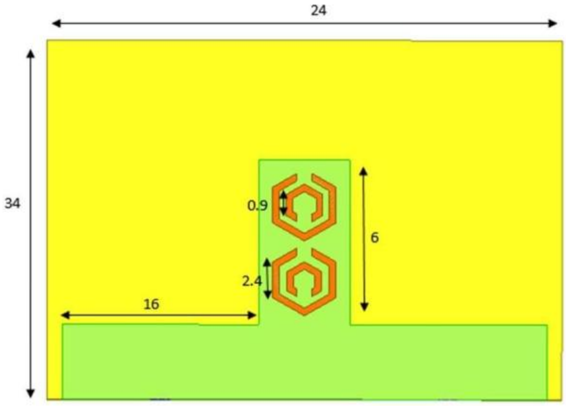

Fig 3: Two-Element Microstrip Antenna Array Incorporating A Hexagonal Complementary Split-Ring Resonator (CSRR) Metamaterial At Ground

V. SIMULATION RESULTS

A. Return Loss Performance

Fig. 4. Return loss of Mutual Coupling Reduction in Antenna Arrays by Using Hexagonal Complementary Split Ring Resonator Metamaterial Structure

Full-wave electromagnetic simulations were conducted using ANSYS HFSS to evaluate antenna performance. The simulated reflection coefficient (S11) demonstrates excellent impedance matching across the operating band. The antenna achieves a minimum return loss of approximately -28 dB near the resonant frequency (7.5 GHz), indicating highly efficient power transfer from the feed network to the radiating elements.

B. Isolation Characteristics

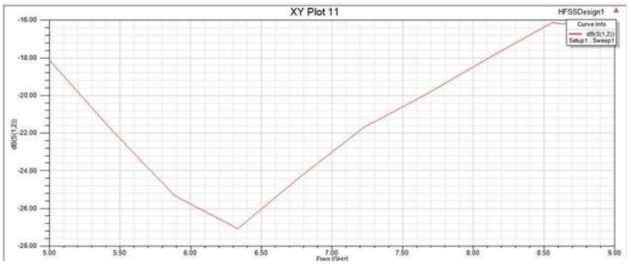

Fig. 5. Isolation Of proposed Antenna (S12)

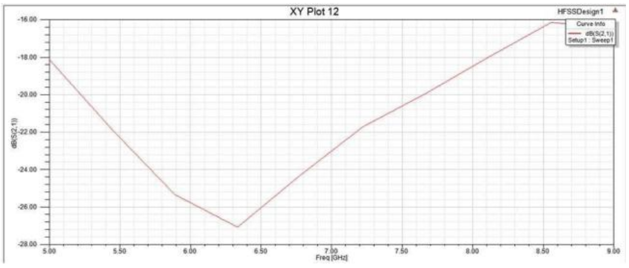

Fig. 6. Isolation Of proposed Antenna (S21)

The transmission coefficient S21 parameter represents the coupling between antenna elements. The proposed design achieves a minimum isolation of approximately -27 dB at the center frequency, representing a substantial improvement over conventional closely-spaced arrays without decoupling structures. This level of isolation is sufficient for high-performance MIMO applications where element independence is critical for maintaining spectral efficiency and channel capacity.

C. Radiation Pattern and Gain

The simulated radiation pattern exhibits stable characteristics across the operating band with pronounced directivity in the boresight direction. The antenna maintains hemispherical coverage from 30 degrees to 180 degrees in both azimuth and elevation planes. The gain is calculated from simulated directivity and system losses, accounting for mismatch losses, conductor losses, and dielectric losses.

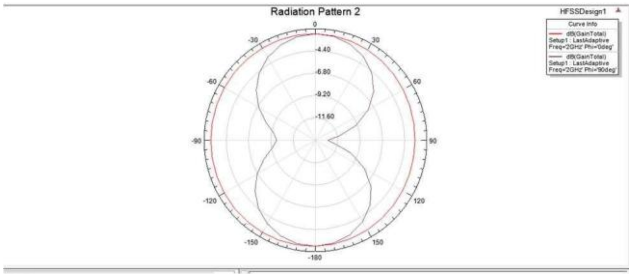

Fig. 7. Radiation Pattern of Proposed Antenna

The measured gain values are consistent with theoretical predictions for rectangular patch antennas of comparable dimensions. The hexagonal CSRR does not significantly degrade the radiation pattern or gain characteristics, confirming that the metamaterial structure operates primarily through surface wave suppression rather than energy absorption or scattering.

VI. PHYSICAL INSIGHTS AND COUPLING MECHANISMS

The mechanism by which the hexagonal CSRR achieves coupling reduction can be understood through analysis of electromagnetic field distributions and surface current patterns. The CSRR structure exhibits a resonant response at the operating frequency, creating a region of controlled permittivity and permeability between the antenna elements.

At the resonance frequency, the CSRR presents a high impedance to surface waves propagating along the ground plane between the patches. This impedance mismatch reflects surface waves rather than allowing them to couple energy between elements. Current distribution analysis confirms that the CSRR effectively interrupts the flow of coupled currents between antenna patches.

VII. APPLICATIONS

The proposed compact MIMO antenna array is particularly well-suited for the following applications:

- 5G/6G Base Station Antennas: Compact MIMO antenna arrays enable multi-user detection and spatial multiplexing in next-generation cellular networks with dense antenna packing and high element isolation.

- Satellite Communication Systems: Compact arrays reduce payload mass and volume while maintaining directivity and beamforming capabilities required for satellite-to-ground and inter-satellite links.
- Synthetic Aperture Radar: High-isolation antenna arrays improve radar image resolution and reduce artifacts caused by mutual coupling in synthetic aperture systems.
- Portable and Mobile Devices: The low-profile design enables integration into smartphones and portable computing devices where space constraints are critical.
- Internet-of-Things (IoT) Applications: Cost-effective manufacturing and compact form factor make the design suitable for high-volume IoT deployment scenarios.

VIII. CONCLUSION

This paper has presented a compact two-element microstrip antenna array incorporating a hexagonal complementary split-ring resonator (CSRR) metamaterial structure designed to reduce mutual coupling. The key contributions include demonstration of a simple, cost-effective metamaterial approach through ground plane etching; achievement of isolation exceeding -27 dB at center frequency while maintaining minimum return loss of -28 dB; validation through full-wave electromagnetic simulation; and demonstration of practical feasibility using standard PCB manufacturing processes.

The proposed antenna array offers an effective solution for mutual coupling reduction in modern wireless communication systems. The combination of compact size, simple geometry, excellent isolation performance, and ease of fabrication makes the design particularly attractive for integration into space-constrained applications where MIMO technology is essential for achieving enhanced spectral efficiency and data rates. Future work will focus on extending the design to multi-element arrays and exploring optimization techniques for operation across broader frequency ranges and applications in emerging millimeter-wave frequency bands.

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