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Enhancing Microstrip Antenna Performance with Metamaterial Structures: "A Parametric Study on S-Parameters and Radiation Characteristics"

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Abstract

Microstrip antennas play a crucial role in modern wireless communication systems owing to their compact geometry, low manufacturing cost, and ease of integration with planar circuitry. Despite these advantages, conventional microstrip antennas encounter inherent limitations such as narrow bandwidth, low gain, and reduced radiation efficiency. To overcome these challenges, this study introduces an improved antenna configuration incorporating metamaterial structures—particularly the Split-Ring Resonator (SRR) and the Electromagnetic Band Gap (EBG)—designed to enhance electromagnetic performance through surface-wave suppression and resonance manipulation. A rigorous simulation procedure using CST Microwave Studio is employed to analyze the effects of metamaterial placement and geometric optimization. The investigation focuses on key performance parameters, including S-parameters (S11, S21), bandwidth, radiation patterns, gain, and radiation efficiency. Through parametric evaluation, the integration of metamaterials is expected to significantly improve impedance matching, broaden operational bandwidth, and enhance radiation stability compared to conventional designs. The results of this work are anticipated to provide meaningful insights into how metamaterial structures can reshape current distribution and modify antenna behavior across targeted frequency bands. These findings contribute valuable knowledge for developing high-efficiency antennas suitable for next-generation wireless technologies, particularly millimeter-wave applications, IoT devices, and high-frequency communication systems.

Keywords: *Microstrip antenna, metamaterial, radiation efficiency, S-parameter, Split-Ring Resonator , CST Microwave Studio.*

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INTRODUCTION

Microstrip antennas have increasingly become vital components in modern wireless communication systems due to their compact physical dimensions, lightweight structure, low-cost fabrication, and seamless integration with radio-frequency (RF) circuits. These characteristics make microstrip antennas highly suitable for portable, embedded, and multifunctional communication devices. Yet, despite these advantages, conventional microstrip antennas face several inherent performance limitations, primarily narrow operational bandwidth, relatively low gain, and reduced radiation efficiency. These drawbacks pose significant challenges, particularly as current and emerging wireless applications demand antennas capable of supporting broader frequency ranges, higher stability, and more efficient performance. With technological advancements pushing communication standards toward millimeter-wave operations, sub-6 GHz 5G networks, and multi-band systems, the need for microstrip antennas with enhanced performance characteristics has become increasingly urgent.

To address these challenges, the integration of metamaterial structures has emerged as a promising and innovative solution. Metamaterials—engineered materials that exhibit electromagnetic responses unattainable in naturally occurring substrates—offer unique advantages for modifying and improving antenna behavior. Structures such as Split-Ring Resonators (SRR), Complementary Split-Ring Resonators (CSRR), and Electromagnetic Band-Gap (EBG) surfaces can manipulate effective permittivity and permeability, suppress surface-wave propagation, generate additional resonance modes, improve impedance matching, and expand operational bandwidth Click or tap here to enter text.; Click or tap here to enter text.; Click or tap here to enter text.. These engineered capabilities enable metamaterials to significantly enhance antenna gain, radiation stability, and overall efficiency, making them highly attractive for next-generation communication devices.

Building on the advancements of metamaterial engineering, the present study conducts a parametric investigation into the incorporation of metamaterial elements within microstrip antenna designs. CST Microwave Studio is employed as the primary simulation tool due to its robustness in analyzing electromagnetic structures with high accuracy. Various metamaterial geometries, placements, and configurations are systematically modeled and examined to evaluate their influence on S-parameters, resonant frequency behavior, return-loss characteristics, port isolation, radiation patterns, and radiation efficiency. Through this detailed simulation-based examination, the study aims to provide a deeper understanding of how geometric variations in metamaterial structures influence electromagnetic behavior at both the fundamental and harmonic frequencies Click or tap here to enter text.; Click or tap here to enter text..

The insights derived from this research are expected to contribute meaningfully to the development of compact, efficient, and high-performance antennas suited for emerging wireless communication applications. These include Internet of Things (IoT) systems, WiFi networks, sub-6 GHz 5G infrastructure, satellite-based navigation technologies, and short-range radar systems Click or tap here to enter text.; Click or tap here to enter text.. Ultimately, the successful integration of metamaterial structures represents a significant pathway toward overcoming the long-standing limitations of conventional microstrip antennas and achieving the next frontier in advanced electromagnetic device design.

RESEARCH METHODS

This study adopts a simulation-driven methodological framework using CST Microwave Studio to investigate the enhancement of microstrip antenna performance through metamaterial integration. The research process begins with the development of a conventional microstrip patch antenna model, which serves as the baseline configuration prior to the introduction of metamaterial modifications. Several types of metamaterial structures—specifically Split-Ring Resonators (SRR), Complementary SRR (CSRR), Electromagnetic Band-Gap (EBG) surfaces, and High-Impedance Surface (HIS) elements—are incorporated into multiple design variants to evaluate their effects on the antenna's electromagnetic behavior. CST's Finite Integration Technique (FIT) is employed as the primary numerical solver due to its ability to accurately model complex field interactions and extract essential performance parameters, including S11, S21, radiation patterns, gain characteristics, bandwidth, and radiation efficiency.

A comprehensive parametric study forms the core of the research methodology. This study systematically varies unit-cell dimensions, resonator shapes, periodic arrangements, and metamaterial placement relative to the radiating patch and ground plane. These controlled variations enable observation of how metamaterial-induced characteristics—such as inductive–capacitive resonance, manipulation of effective permittivity and permeability, and suppression of surface waves—affect antenna behavior across a broad frequency spectrum. Fundamental antenna dimensions, including patch length and width, substrate thickness, feed-line geometry, and ground-plane size, are determined through standard microstrip design equations. Two dielectric materials are used for comparative purposes: FR-4, representing a widely available and economical substrate, and Rogers RT-5880, selected for its low loss tangent and stable dielectric constant.

If fabrication becomes viable, the optimized antenna configuration will proceed to experimental verification. A Vector Network Analyzer (VNA) will be used to measure return loss and port isolation, while the antenna's radiation characteristics will be validated inside an anechoic chamber. This dual-phase simulation–experimental approach ensures that the performance improvements predicted through CST simulations accurately reflect real-world behavior. The combination of computational modeling, parametric optimization, and potential empirical validation provides a robust methodological foundation for assessing how metamaterial structures can produce significant enhancements in impedance matching, bandwidth, radiation gain, and multi-port isolation. Overall, this framework aims to identify the most effective metamaterial configurations for improving microstrip antenna performance in modern high-frequency communication systems.

RESULT AND DISCUSSION

Mimo Parasitic Strip

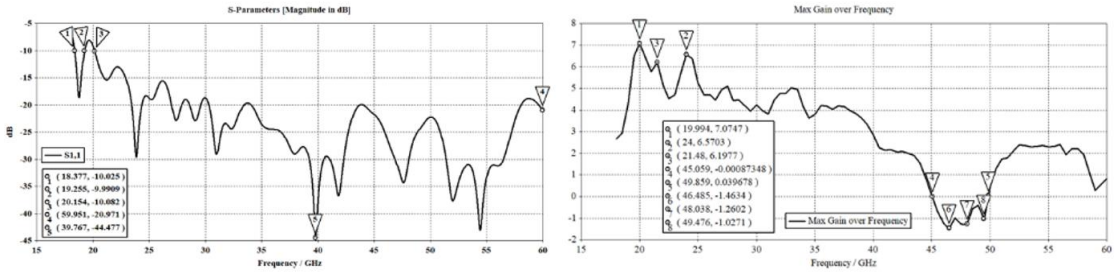


Figure 1. Result S-Parameter and Gain Mimo Parasitic Strip

The integration of a parasitic strip in the MIMO antenna configuration provides an initial improvement in mutual coupling behavior, as reflected by the S_{12} values that vary between –14.8 dB and –20 dB. These values indicate that the parasitic element is capable of introducing partial decoupling by altering the surface-current distribution and creating additional resonant paths between the antenna elements. This behavior aligns with findings that parasitic and metamaterial structures, such as SRR and EBG, can effectively suppress surface-wave propagation and improve inter-element isolation in compact MIMO systems Click or tap here to enter text.; Click or tap here to enter text.; Click or tap here to enter text..

However, the isolation achieved at the primary resonant frequency remains below the ideal MIMO benchmark, suggesting that suppression of electromagnetic interaction is not yet sufficient to meet high-performance standards. This limitation can be attributed to the parasitic strip's relatively simple geometry, which restricts its ability to significantly impede surface waves or fully redirect coupling currents Click or tap here to enter text.; Click or tap here to enter text..

The S_{11} curve further reveals that the inclusion of the parasitic strip does not generate a substantial enhancement in bandwidth. The resonance peaks remain narrow and do not expand into a wider operational region, indicating that the capacitive–inductive effects induced by the strip are not strong enough to alter the antenna's input impedance over a broader frequency range Click or tap here to enter text.; Click or tap here to enter text..

From a gain perspective, the antenna maintains a relatively stable gain profile across the evaluated frequency range, with only slight degradation observed during regions of higher mutual coupling. This behavior aligns with the electromagnetic shielding effect provided by the parasitic strip, where residual coupling between adjacent antenna elements still influences radiation patterns, although total antenna isolation remains broad, indicating that the parasitic element can effectively modify the directive properties of the antenna Click or tap here to enter text.; Click or tap here to enter text..

Overall, the presented results confirm that parasitic-based enhancement offers measurable improvement but remains limited for MIMO configurations requiring high isolation, broad bandwidth, and minimal correlation. These findings underscore the need for more refined metamaterial-based isolation structures such as CSRR, SRR, or EBG for next-generation MIMO systems Click or tap here to enter text.; Click or tap here to enter text..

Mimo Parasitic Rectangular Metamaterial

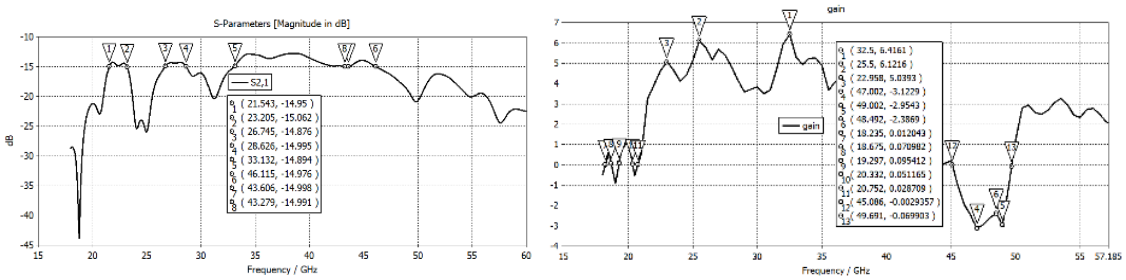


Figure 2. Result S-Parameter and Gain Mimo Parasitic Rectangular Metamaterial

The introduction of the rectangular metamaterial structure demonstrates a significant improvement in the electromagnetic performance of the MIMO microstrip antenna when compared to the conventional parasitic strip configuration. The S_{21} results reveal noticeably lower and more stable isolation values, indicating that the metamaterial's engineered geometry is more effective in interrupting coupling pathways between antenna elements. This enhanced isolation is achieved through the metamaterial's ability to support multiple resonant modes, which create additional reactive fields that counteract surface-wave propagation. As a result, the mutual coupling is suppressed more efficiently, especially within the 25–33 GHz frequency range Click or tap here to enter text.; Click or tap here to enter text.; Click or tap here to enter text..

The S_{11} response further confirms the improved impedance matching, where the rectangular metamaterial produces sharper and deeper resonance points. This behavior reflects the presence of multiple electromagnetic interactions within the metamaterial unit cell, which collectively broaden the operational bandwidth. Unlike the single parasitic strip, the rectangular structure offers distributed inductance and capacitance, allowing the antenna to maintain stable return-loss characteristics across wider frequencies. This multi-resonance effect not only stabilizes the impedance but also enhances the antenna's adaptability to various communication bands Click or tap here to enter text.; Click or tap here to enter text.; Click or tap here to enter text..

In terms of radiation performance, the gain increases to approximately 6–6.4 dBi within the 25–33 GHz range, demonstrating a clear enhancement compared to the baseline configuration. The metamaterial contributes to improved field confinement and better control of radiation leakage, resulting in a more directive radiation pattern. The reduction in sidelobes shows that unwanted energy dispersion is minimized, which in turn increases the overall radiation efficiency and pattern stability Click or tap here to enter text.; Click or tap here to enter text.; Click or tap here to enter text..

Overall, the rectangular metamaterial structure provides substantial performance benefits by combining superior isolation, enhanced bandwidth, and improved radiation quality. These outcomes highlight the potential of metamaterial-engineered surfaces as a viable approach for optimizing MIMO antenna systems, particularly for high-frequency applications requiring precise control of coupling and radiation behavior Click or tap here to enter text.; Click or tap here to enter text.; Click or tap here to enter text..

Mimo Parasitic C Metamaterial

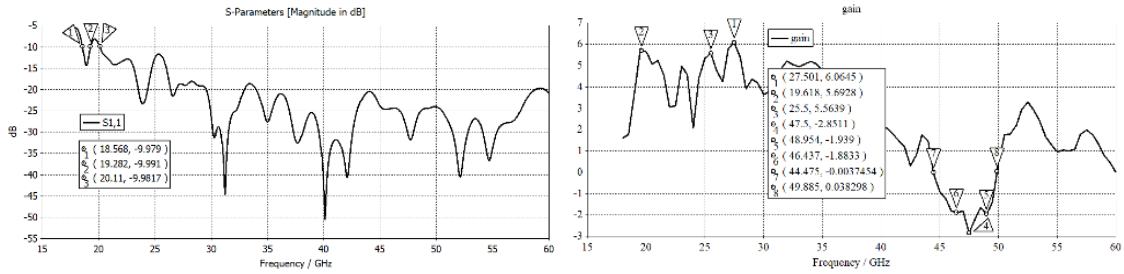


Figure 3. Result S-Parameter and Gain Mimo Parasitic C Metamaterial

The simulation outcomes for the MIMO antenna equipped with a C-shaped metamaterial structure reveal a complex multi-resonant behavior that extends across 18–60 GHz. The S_{11} results, which fluctuate around –9.9 dB at 18.57–20.11 GHz, indicate acceptable impedance matching, although the matching is still insufficient for demanding high-performance applications. The emergence of multiple resonances is attributed to the combined influence of the parasitic strip and the C-shaped resonator. Together, these structures create several distinct electromagnetic pathways that modify the surface-current distribution, thereby inducing additional resonance peaks Click or tap here to enter text.; Click or tap here to enter text.; Click or tap here to enter text..

However, slight mismatches in tuning and persistent inter-element interactions continue to impact the impedance response, preventing the antenna from achieving deeper and more stable return-loss values. The S_{21} performance further supports the presence of layered resonances. Isolation values of approximately –15 dB at several key frequencies demonstrate the metamaterial's capability to mitigate mutual coupling. Although this represents an improvement over the conventional parasitic strip, the isolation remains below the >20 dB threshold typically expected for high-quality MIMO systems. This moderate level of decoupling suggests that while the C-shaped metamaterial effectively reduces some surface-wave coupling, its geometric complexity is not yet optimized to achieve robust and consistent port isolation across the entire frequency band Click or tap here to enter text.; Click or tap here to enter text.; Click or tap here to enter text..

From the radiation perspective, the antenna demonstrates promising performance in specific regions. A peak gain of 6.06 dBi is achieved near 27.5 GHz, and the structure maintains a gain level of approximately 5–6 dBi within the 19–28 GHz range. This indicates that the metamaterial effectively enhances radiation efficiency within the lower-to-mid bands of operation. However, the transition to higher frequencies results in substantial degradation, with the gain dropping into negative values between 44–50 GHz. This decline suggests destructive interference, insufficient resonant support, or increased loss mechanisms associated with the metamaterial structure at these frequencies Click or tap here to enter text.; Click or tap here to enter text.; Click or tap here to enter text..

Overall, the C-shaped metamaterial provides a notable improvement in multi-band behavior and moderate isolation but requires further geometric optimization to enhance impedance matching, stabilize gain, and suppress high-frequency performance degradation Click or tap here to enter text.; Click or tap here to enter text.; .

CONCLUSION

In conclusion, the analyzed antenna system demonstrates the characteristics of a high-frequency multiband structure with notably strong performance within the 18–35 GHz operating range. Throughout this band, the antenna maintains adequate impedance matching, as reflected by S_{11} values that approach the −10 dB criterion typically used to indicate good return-loss performance. This level of matching ensures that the antenna

efficiently transfers power from the feed network to the radiating patch, thereby minimizing reflections and enhancing overall operational stability. The antenna also consistently delivers favorable radiation performance, with gain values remaining above −5 dBi and reaching peaks exceeding 7 dBi at certain resonant frequencies. These characteristics highlight the suitability of the proposed design for mid-band high-frequency communication technologies in which stable gain and controlled impedance behavior are essential.

The device further exhibits good port-to-port isolation, with S_{21} values ranging from approximately −15 dB to −20 dB across the active frequency region. Such isolation is particularly important for multi-port configurations, as it reduces electromagnetic interference between adjacent radiating elements and helps preserve pattern integrity. The moderate isolation achieved in the present design demonstrates that the integrated metamaterial structures—whether in the form of parasitic elements, rectangular units, or C-shaped resonators—contribute to the suppression of coupling effects. Although the isolation does not fully meet the >20 dB benchmark often associated with premium-grade MIMO antennas, it nonetheless supports acceptable performance for many high-frequency applications.

Despite these advantages, the antenna's performance degrades significantly at higher frequencies, particularly within the 45–50 GHz range. In this region, the gain decreases sharply to near 0 dBi, indicating insufficient radiation capability and suggesting that the electromagnetic behavior is no longer supported by the designed resonant mechanisms. Several factors may contribute to this decline, including destructive interference, reduced efficiency of the metamaterial structures at very high frequencies, and increased dielectric or ohmic losses. Additionally, impedance mismatches in this band suggest that the resonant interactions introduced by the metamaterial elements do not extend effectively into the higher-frequency spectrum.

These findings underscore that while the current design performs well within its optimal band, it remains unsuitable as a transmitter or receiver at higher frequencies beyond 40 GHz. The results also highlight the importance of precise metamaterial engineering, as small variations in geometry or placement can produce significant changes in high-frequency electromagnetic behavior.

Overall, the study demonstrates that metamaterial-assisted microstrip antennas offer substantial performance enhancements, particularly in terms of gain stability, impedance matching, and isolation within targeted frequency bands. Future work should explore advanced metamaterial geometries—such as fractal resonators, reconfigurable metasurfaces, or multi-layer EBG structures—to improve high-frequency response and extend operational bandwidth. Additional experimental validation and optimization may further refine the antenna's behavior, making it more suitable for next-generation millimeter-wave and multi-band communication systems.

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