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"Mutual Coupling Reduction in 2.4 GHz Microstrip Patch Antenna Array Using Metamaterial Structures"

Abstract: - This paper presents a microstrip patch antenna array integrated with metamaterial (MTM) to improve performance at the 2.4 GHz frequency band. The antenna array consists of two patch elements placed side by side on an FR4 epoxy substrate with coaxial feeding. To address mutual coupling, a metamaterial structure based on concentric split rings is introduced between the antenna elements. The results demonstrate that the inclusion of metamaterial significantly reduces mutual coupling from -28 dB to -54 dB, enhances the antenna gain from 2.77 dB to 3.61 dB, and maintains stable resonant frequency and return loss. The proposed design not only improves isolation between closely spaced antennas but also enhances radiation performance, making it suitable for Wi-Fi and other wireless communication applications.

Keywords: Microstrip Patch Antenna, Metamaterial (MTM), Mutual Coupling Reduction, 2.4GHz wireless communication.

I. INTRODUCTION

MIMO (Multiple-Input Multiple-Output) antennas are crucial for Wi-Fi frequency bands as they significantly enhance wireless communication performance by leveraging spatial multiplexing and diversity techniques. Operating within Wi-Fi frequency bands such as 2.4 GHz, 5 GHz, and increasingly 6 GHz, MIMO systems utilize multiple antennas at both the transmitter and receiver to transmit parallel data streams, effectively increasing data rates without requiring additional bandwidth or power [1]. However, the performance of MIMO antennas can be affected by mutual coupling, which occurs when the electromagnetic fields of closely spaced antennas interfere with each other. Mutual coupling can lead to degradation in antenna efficiency, reduced isolation, and correlation between MIMO channels, thereby limiting the potential performance gains. In Wi-Fi frequency bands, where compact device designs often necessitate closely spaced antennas, minimizing mutual coupling is critical. Techniques such as optimizing antenna placement [2-4], incorporating decoupling structures [5-7], and using advanced materials [7-10] can help mitigate these effects. Addressing mutual coupling is essential to maintain the high data rates, reliability, and spatial diversity benefits that MIMO technology brings to Wi-Fi systems.

In this paper, we propose a microstrip patch antenna array integrated with metamaterial structures to effectively reduce mutual coupling at the 2.4 GHz frequency band. The design leverages the unique properties of metamaterials to suppress electromagnetic interference between closely spaced antenna elements, enhancing performance and maintaining the compactness required for modern wireless systems.

II. METHODOLOGY

This section demonstrates the design of microstrip patch antenna array to reduce mutual coupling

A. *Design of 1 x 2 Microstrip Patch Antenna array with Metamaterial*

The design of the proposed antenna system involves a microstrip patch antenna array consisting of two identical patch elements placed side by side. Each patch is rectangular, designed to operate efficiently at the 2.4 GHz frequency band. The antennas are mounted on an FR4 epoxy substrate, which has a dielectric constant (εr) of 4.4 and a thickness (1.57mm) suitable for maintaining compactness while providing sufficient mechanical support. The distance between the two antennas is denoted as 'd,' and this parameter is carefully optimized to balance mutual coupling reduction and overall size constraints.

The feeding mechanism for the antenna array is coaxial feeding, chosen for its simplicity, low loss, and ease of integration. Each antenna element is fed at the optimal location to achieve impedance matching, ensuring maximum power transfer and minimal reflection at the operating frequency. The coaxial feed consists of an inner conductor

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connected to the patch and an outer conductor grounded to the substrate's bottom layer. This configuration supports a stable and efficient excitation of the antennas while maintaining the array's compact design. The detailed specifications of the structure are listed in Table. 1

Table. 1: Antenna Array Specifications

Parameters.	Dimension in mm
Lsub	120
Wsub	67
Lp	28
Wp	38
d	32

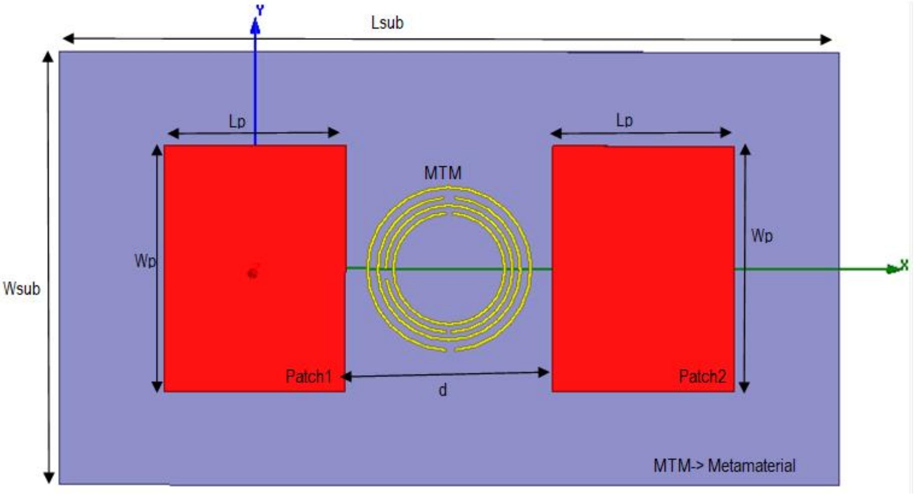

Figure. 1 Proposed Array Antenna with Metamaterial

B. *Design of a Metamaterial*

The metamaterial unit cells, illustrated in Fig 2 from a top-down view, form the foundation of the proposed design. These unit cells are constructed on a 28 mm x 26 mm FR4 epoxy substrate with a thickness of 1.57 mm. The substrate material has a dielectric constant of 4.4 and a dielectric loss tangent of 0.02. The design features concentric split rings as its core structure, with the resonators made of copper that is 0.1 mm thick. Outer circular ring has a diameter of 12 mm, and the rings are separated by a gap of 1.5 mm. Additionally, the splits in the rings are uniformly spaced at 0.4 mm. Table 2 provides a detailed summary of the dimensional specifications for the metamaterial unit cell.

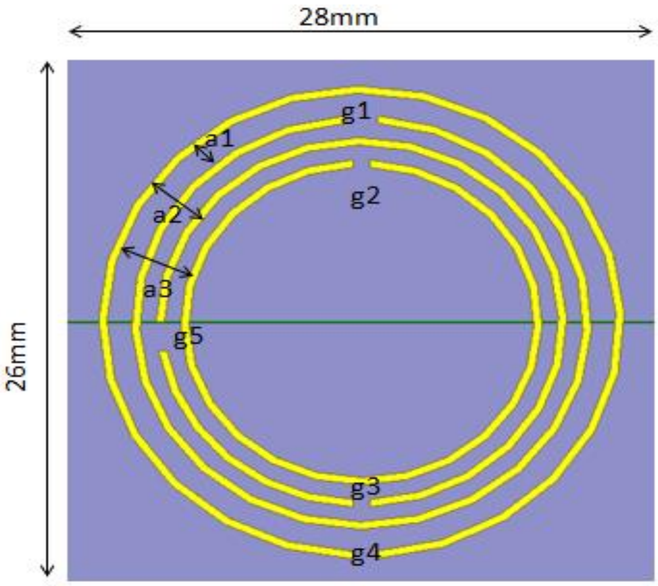

Figure. 2 Metamaterial structure

Table. 2 Metamaterial Specifications.

Parameters	Dimension in mm
a1	2
a2	1
a3	1
g1	1.5
g2	1
g3	1
g4	1.5
g5	1.5

III. RESULTS & DISCUSSIONS

The performance of the proposed antenna array with and without the inclusion of metamaterial (MTM) is analyzed and presented through separate graphs (Fig. 3-Fig. 11), focusing on critical parameters such as resonant frequency, return loss, VSWR, mutual coupling, and gain. For **Port 1**, the resonant frequency remains stable at 2.44 GHz in both cases, while the return loss shows a minor change, improving from -24 dB without MTM to -23.9 dB with MTM, indicating excellent impedance matching. On **Port 2**, the resonant frequency slightly shifts from 2.44 GHz to 2.446 GHz without MTM and improves to 2.44 GHz with MTM, alongside a significant improvement in return loss from -23.81 dB to -23.86 dB. The Voltage Standing Wave Ratio (VSWR), a measure of impedance matching, slightly increases from 1.27 without MTM to 1.8 with MTM, but remains within acceptable limits for practical applications. These results indicate that the metamaterial has minimal impact on frequency stability while maintaining sufficient return loss and impedance matching for the antenna array.

A significant improvement is observed in mutual coupling and gain when metamaterial is introduced into the design. Without MTM, the mutual coupling between the two antennas is -28 dB, whereas with the MTM structure, it is substantially reduced to -54 dB, showcasing the effectiveness of the metamaterial in suppressing electromagnetic interference between the closely spaced antennas. This reduction in mutual coupling directly contributes to improving the antenna's isolation and overall performance. Furthermore, the antenna gain increases from 2.77 dB without MTM to 3.61 dB with MTM, demonstrating the metamaterial's ability to enhance radiation efficiency and directivity. The graphical results clearly highlight the superior performance of the antenna array with the inclusion of metamaterial, making it a promising solution for applications requiring improved isolation and gain in the 2.4 GHz frequency band. The summary is shown in Table. 3.

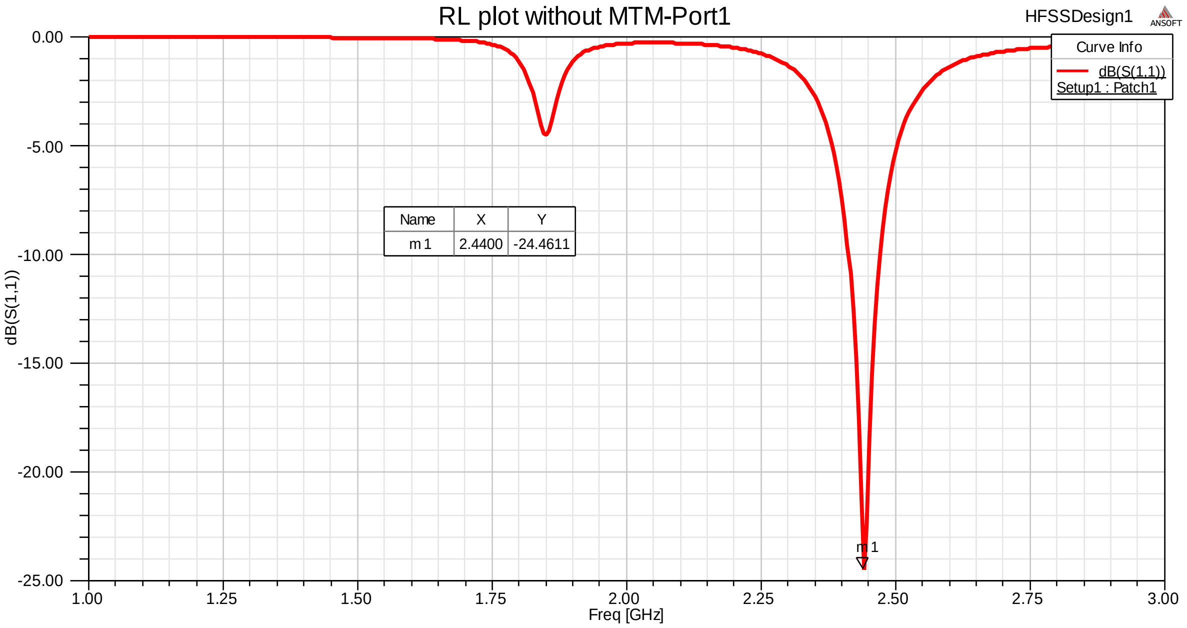

Figure. 3 Return Loss plot –Port 1 without MTM

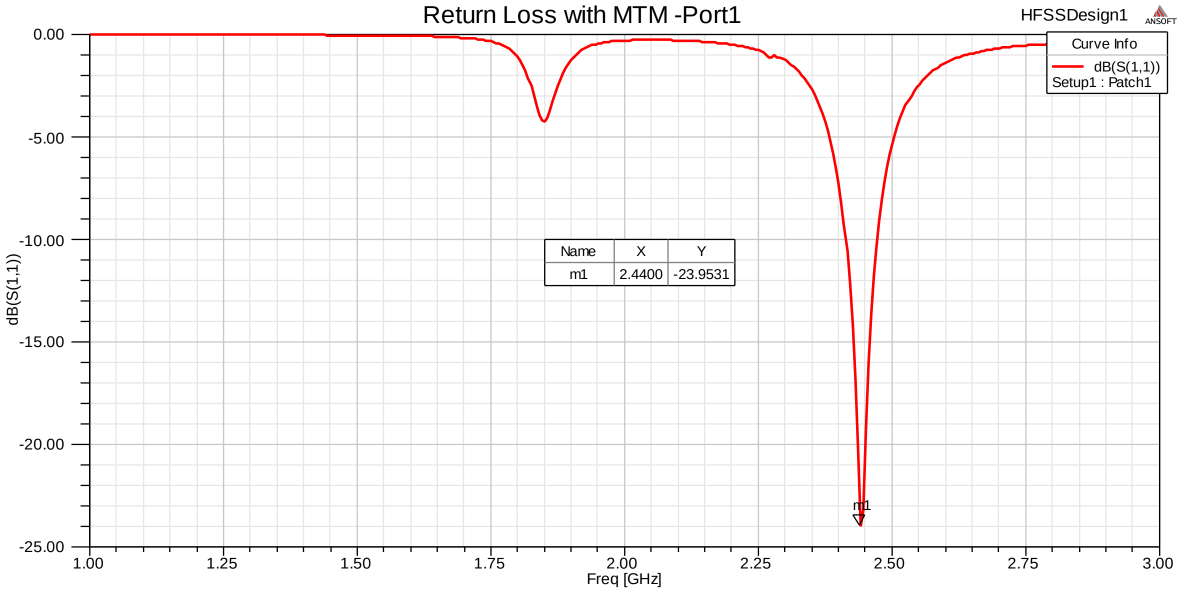

Figure. 4 Return Loss plot –Port 1 with MTM

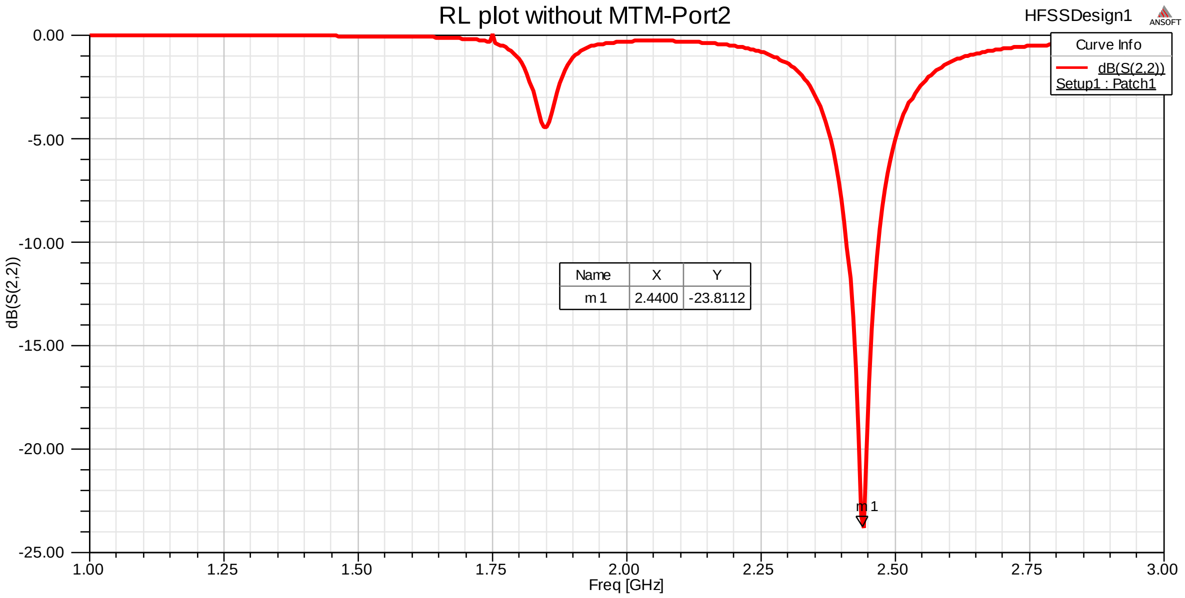

Figure. 5 Return Loss plot –Port 2 without MTM

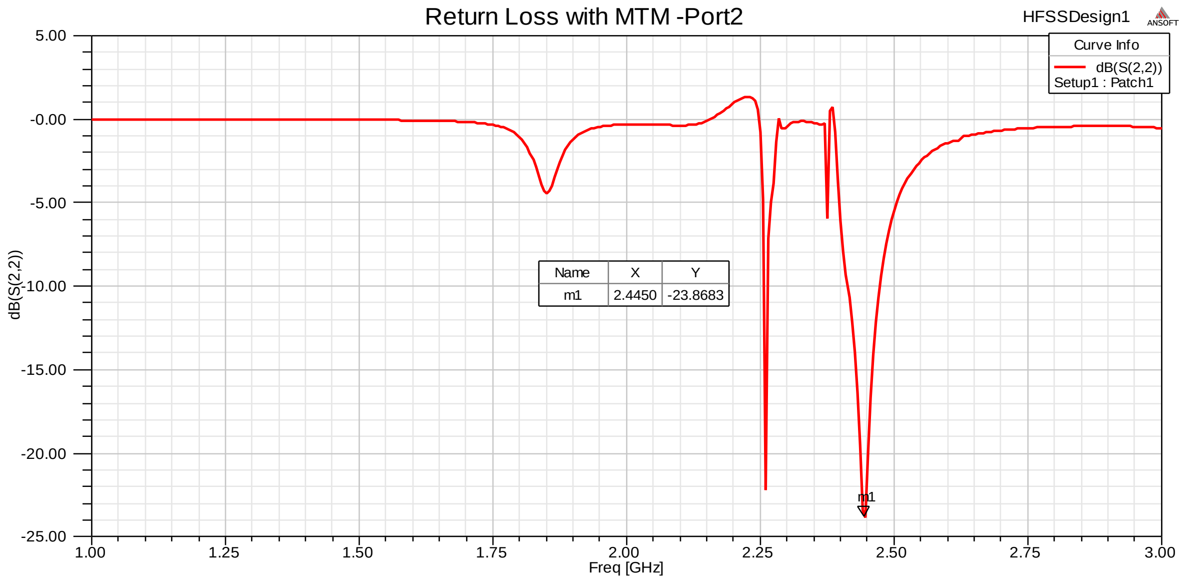

Figure. 6 Return Loss plot –Port 2 with MTM

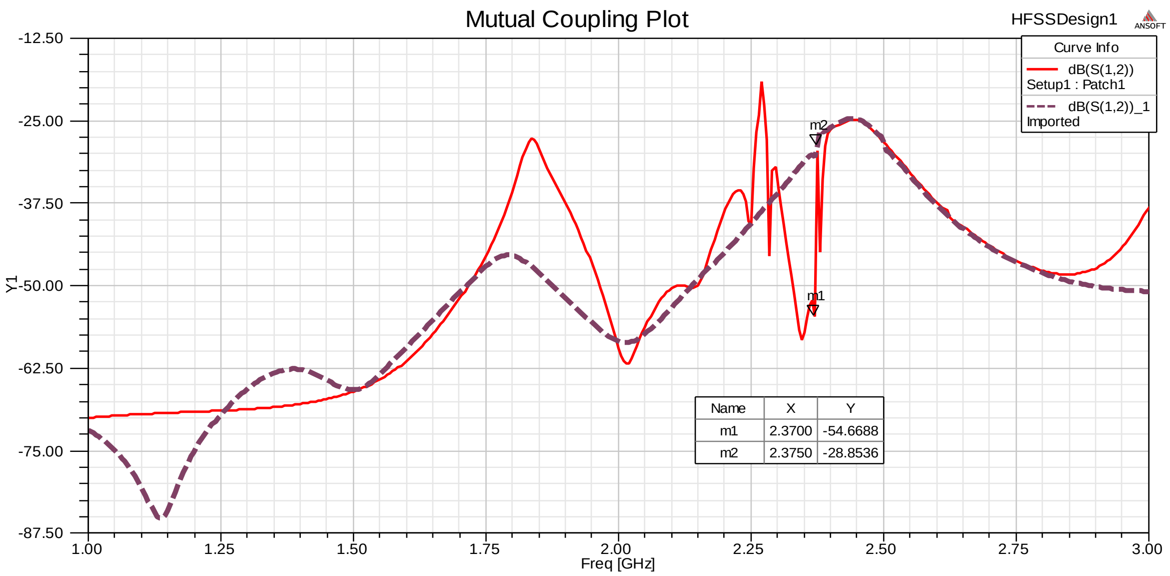

Figure. 7 Mutual Coupling Plot with MTM

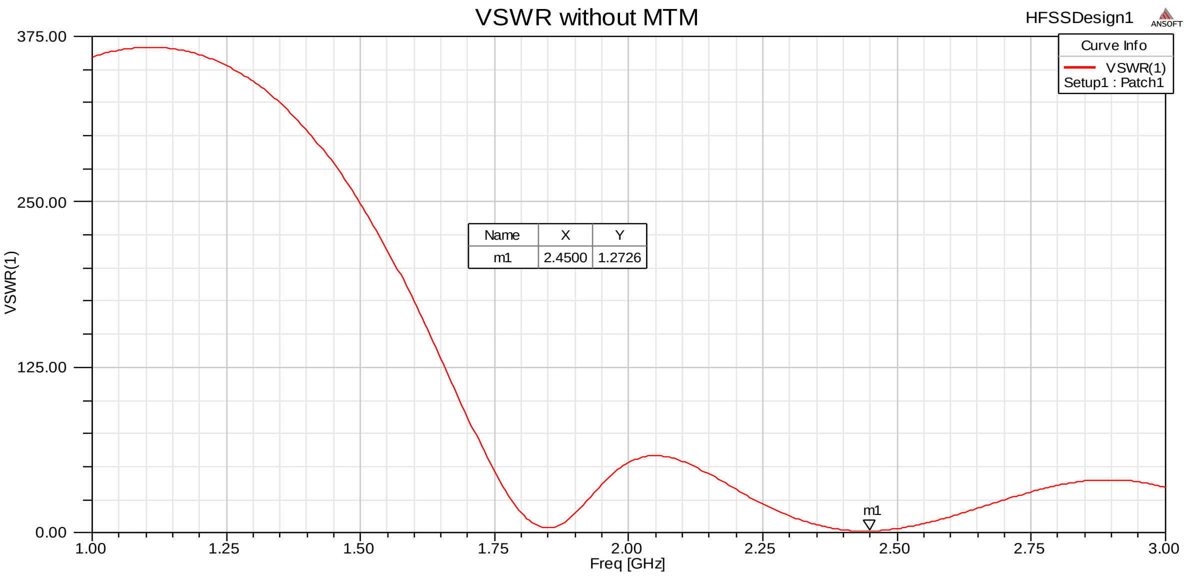

Figure. 8 VSWR Plot without MTM

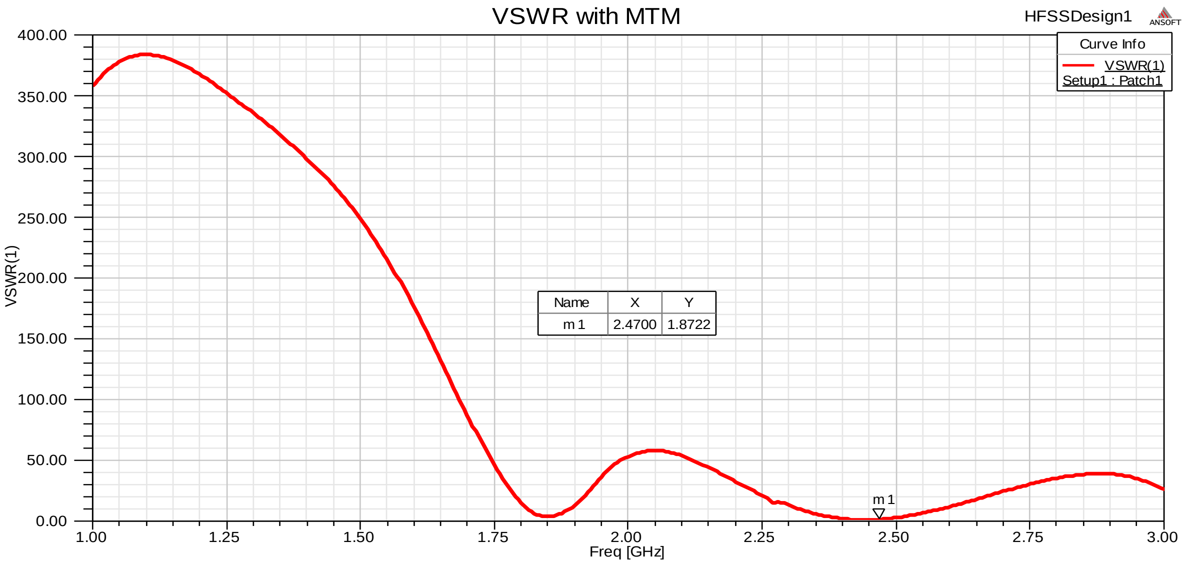

Figure. 9 VSWR Plot with MTM

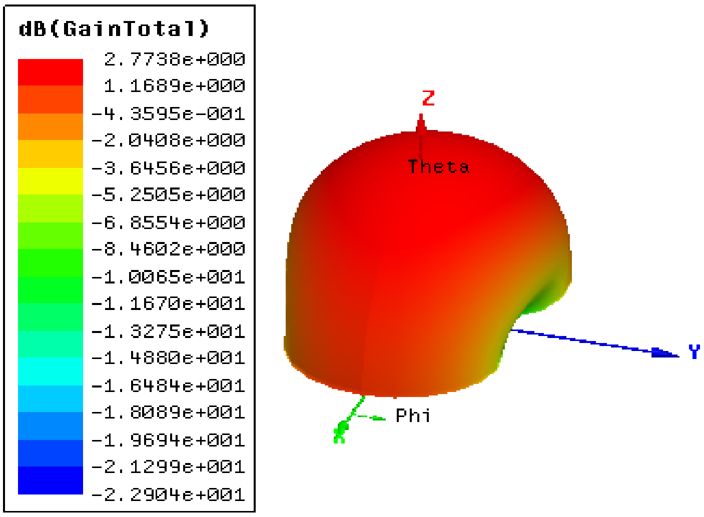

Figure. 10 Gain Plot without MTM

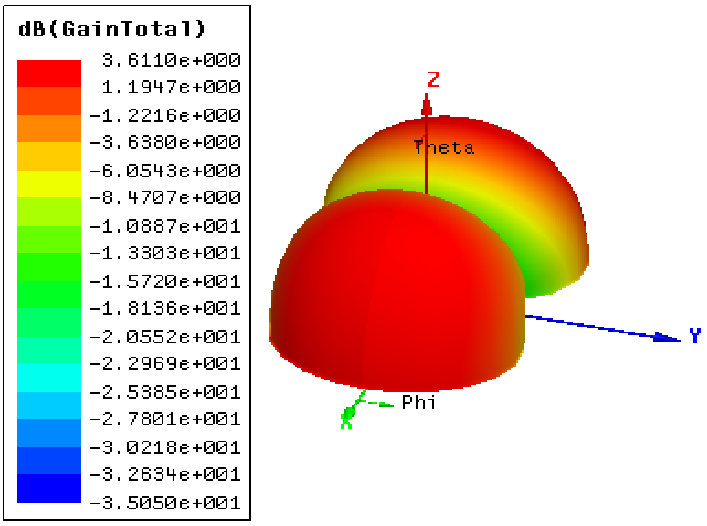

Fig. 10 Gain Plot with MTM

Table 3: Summary of Results

Parameters	Without MTM	With MTM
Port 1 resonant frequency in GHz	2.44	2.44
Port 1 return loss in dB	-24	-23.9
Port 2 resonant frequency in GHz	2.44	-23.81
Port 2 return loss in dB	2.446	-23.86
VSWR	1.27	1.8
Mutual Coupling in dB	-28	-54
Gain in dB	2.77	3.61

IV. CONCLUSION

The proposed microstrip patch antenna array integrated with metamaterial demonstrates significant improvements in performance at the 2.4 GHz frequency band. The inclusion of metamaterial effectively reduces mutual coupling from -28 dB to -54 dB, enhances the antenna gain from 2.77 dB to 3.61 dB, and maintains stable return loss and resonant frequencies. These results confirm the ability of metamaterials to suppress electromagnetic interference and improve the efficiency of compact antenna systems. For future work, the design can be further optimized by exploring advanced metamaterial structures and configurations to achieve even lower mutual coupling and higher gain. Additionally, the antenna array can be extended to operate across multiple frequency bands to support modern wireless communication systems, including 5G and IoT applications.

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