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Improving the performance of a U-shaped patch antenna using metamaterials for biomedical applications

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ABSTRACT

This paper discusses the performance improvement of a patch antenna using metamaterials (MTM). The suggested antenna is a U-shaped patch antenna with a modified ground plane dedicated to biomedical applications. The size of the antenna is 40×20 mm^2 with a FR4 substrate (εr=4.3, tanδ=0.02, H=1.6 mm) designed for operation at 2.4 GHz (ISM Band) and 6.23 GHz frequencies. The proposed MTM is 2×2 array positioned under the antenna at a distance of 2 mm. The integration of the MTM enhances clearly the antenna performance especially the return loss, voltage standing wave ratio (VSWR) and the gain. However, the reflection coefficient was enhanced from -10.71 dB to -36.63 dB at 2.45 GHz and from -13.88 dB to -36.54 dB at 6.23 GHz, the VSWR improved from 1.66 to 1.03 at 2.45 GHz and from 1.75 to 1.04 at 6.23 GHz. Additionally, the peak gain also was increased from 1.77 dB to 3.48 dB. The obtained results confirm the suitability of the suggested antenna for biomedical applications.

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1. INTRODUCTION

The world of patch antennas has witnessed remarkable development in recent years, due to the increasing demand for high-performance antennas to meet the requirements of actual technologies. Patch antennas, with their compact size, simplicity, and flexibility, have become an innovative solution for various applications, including biomedical [1], WLAN [2], 5G [3] and 6G [4]. However, as the need for efficiency, wide bandwidth, and high gain, researchers have shifted their focus towards inventive solutions, such as slotting [5], [6], defected ground structure [7], [8], using superstrate [9], and also the use of various substrates types [10]. Among all these techniques, metamaterials (MTM) stand out as a promising avenue for enhancing the performance of patch antennas.

A MTM, are materials with unique electromagnetic properties that have garnered significant attention recently to the world of antennas. The integration of MTM into patch antennas offers a remarkable enhancement of the antenna performance and holds particular promise for various biomedical applications such as implantable devices [11]-[13], imaging [14], sensing [15], and diagnostic tools [16]. As the intricacies of the human body demand antennas with enhanced performance characteristics, the composition of MTM with patch antennas emerge as a compelling solution to address these challenges. Figure 1 illustrates the classification of MTM according to their permittivity and permeability. When both permittivity and permeability exhibit negative values, the material is termed as a double negative (DNG), which not naturally occurring. Materials with positive values for both epsilon and mu are labeled as double positive (DPS). Epsilon-negative (ENG) materials are characterized by a positive μ and negative ε. In other hands, the magnetically negative (MNG) materials are defined with a negative μ and positive ε. Each of these categories offers distinct advantages and can be tailored for specific applications in antenna design, making MTM a versatile and powerful tool in advancing antenna technology.

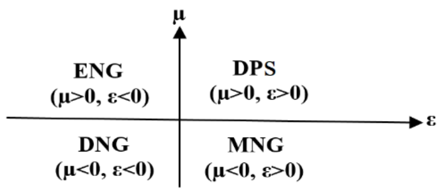


Figure 1. Categorization of MTM based on μ and ε

The enhancement of the antenna gain using MTM was presented in [17], [18]. Gozhenko *et al.* [19] discussed the effect of the integration of MTM on various antenna characteristic. The study of the coupling in antenna array using MTM is showed in [20].The bandwidth enhancement by the integration of MTM is presented in [21], the use of a left-handed metamaterials (LHM) structure has expanded the bandwidth to 175.7 MHz, achieving a bandwidth improvement of 213.75% larger than without LHM. The characterization of MTM based patch antenna is presented in [22], the results obtained demonstrate a significant increase in bandwidth, reduced reflection coefficient, improved gain, and lower voltage standing wave ratio (VSWR). The gain enhancement in a patch antenna using high negative refractive is presented in [23], using a 4×4 array of the suggested MTM unit cell, the gain is enhanced by about 5 dBi.

Conventional patch antennas, especially those employing a partial ground plane, frequently encounter problems such as limited bandwidth, low gain, and significant back radiation. These challenges are particularly problematic in biomedical applications, where they can interfere with sensitive equipment, disrupting the accuracy and reliability of wireless communication and imaging systems. The interference caused by back radiation can lead to cross-talk and signal degradation, affecting the performance of nearby medical devices. Additionally, the limited bandwidth and low gain restrict the antenna performance in sending and receiving signals, thereby reducing the overall efficiency and reliability of biomedical systems.

To address these problems, our study explores the effects of integrating MTM into a patch antenna structure, demonstrating significant improvements in antenna performance metrics such as reflection coefficient, gain, and VSWR. These enhancements make the antenna particularly suitable for biomedical applications, as the optimized reflection coefficient indicates better impedance matching, the increased gain leads to stronger signal transmission and reception, and the improved VSWR ensures efficient operation within the designated frequency range. By highlighting advancements in this field, the paper aims to contribute to the development of next-generation biomedical devices, fostering a new era of personalized, efficient, and patient-friendly healthcare technologies. Our paper is structured as follows: the first section introduces the designs of the antenna and metamaterial, providing detailed insights into their development. The second section focuses on a comprehensive parametric study, examining various parameters and their effects. The third section presents an in-depth analysis of the results obtained from the study. The paper concludes with a recap of the main findings and recommendations for future research.

2. DESIGN OF THE METAMATERIALS AND THE ANTENNA

2.1. Geometry of the metamaterials

The geometric structure of the 2×2 array MTM is depicted in Figure 2(a). The MTM is designed on an FR4 substrate with a dielectric of 4.3 and a loss tangent (tanδ) of 0.02, and a thickness (H2). The MTM structure has overall dimensions of L_x×W_x. As disputed in Figure 2(b), each unit cell of the MTM comprises two square resonant elements, with side lengths represented by 'X' and 'Y'. The two elements are separated by a distance 'Z' to minimize the interference. The simulation setup is presented in Figure 2(c) while the Table 1 detailed the specific dimensions and parameters of the MTM structure.

The analysis of the MTM unit cell reveals significant enhancements in antenna performance at the targeted frequencies of 2.45 GHz and 6.23 GHz as illustrated in Figure 3. At 2.45 GHz, as presented in Figure 3(a), the real part of permeability (μ_{real}) is significantly negative from 2.4 GHz to 3 GHz, with a sharp peak transitioning to positive values, indicating a strong magnetic resonance. Similarly, the real part of permittivity (ε_{real}) is positive, with a sharp dip into negative values around 2.43 GHz to 2.6 GHz as illustrated in Figure 3(b), suggesting a strong electric resonance. At 6.23 GHz, as presented in Figure 3(c),the real part of permeability is negative between 5.7 GHz and 7 GHz, with a peak at 6.4 GHz. Additionally, the real part of permittivity is negative, turning positive around 6.6 GHz with a peak around 6.8 GHz as figured in Figure 3(d). The presence of negative permeability and permittivity values around these frequencies suggests the unit cell possesses left-handed metamaterial properties, contributing to reduced back radiation and improved dual-band functionality. These detailed values underscore the efficacy of the metamaterial in enhancing antenna performance for biomedical applications.

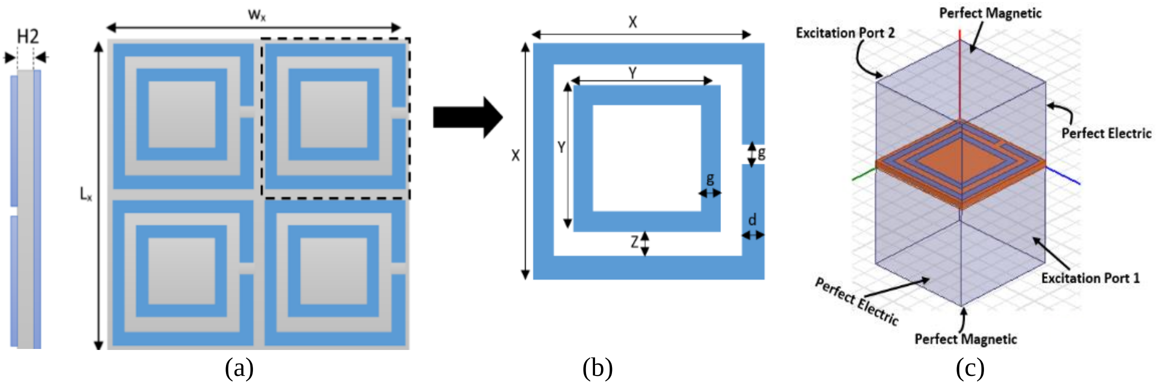


Figure 2. MTM architecture; (a) 2×2 MTM geometries, (b) unit cell architecture, and (c) simulation setup

Table 1. The MTM dimensions

Parameter	L_x	W_x	H2	X	Y	Z	d	g
Dimension (mm)	62	62	1.6	28	14	2.3	2.7	2

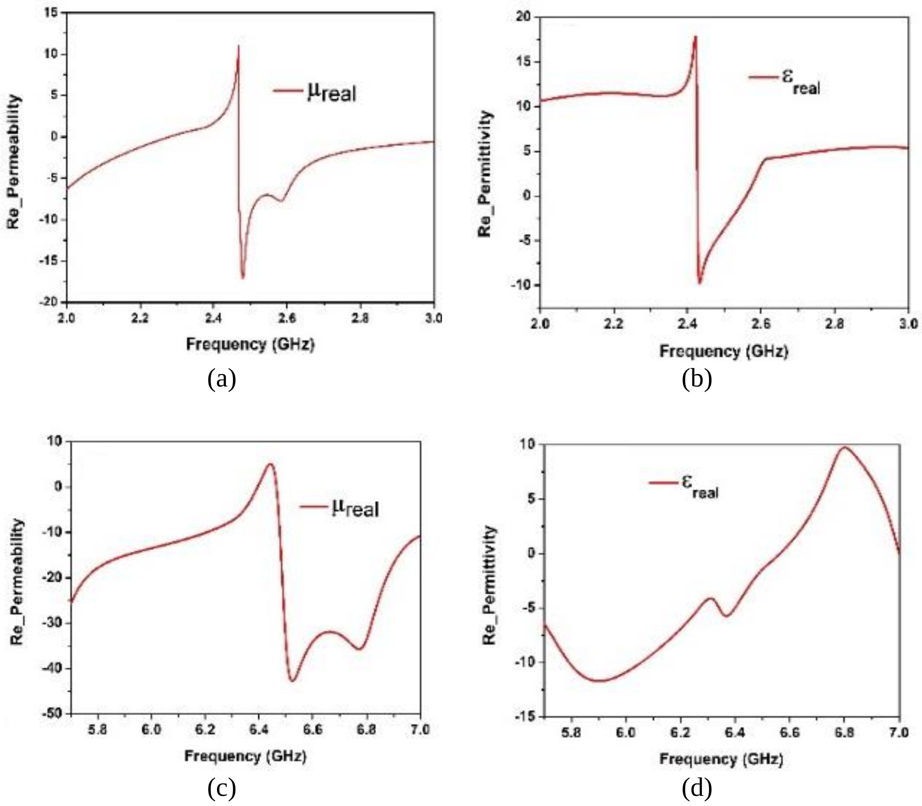


Figure 3. Unit cell characteristic; (a) permeability at 2.45 GHz, (b) permittivity at 2.45 GHz, (c) permeability at 6.23 GHz, and (d) permittivity at 6.23 GHz

2.2. Geometry of the antenna

The proposed antenna is a U-shaped patch with a modified ground plane, designed to work at 2.4 GHz (ISM Band) and 6.23 GHz (microwave range) frequencies which are two special frequencies used in biomedical for various applications. The 2.45 GHz situated in the ISM band used for biotelemetry systems, helps for transmitting data wirelessly from implanted or attached sensors to external monitoring equipment, and also can be used for wireless capsule endoscopy. In the other hands, the 6.23 GHz frequency is situated at the microwave range and serves different applications such as microwave medical imaging, wireless communication for medical devices, and biological molecular research. The resonant element is implemented on the FR4 substrate with a thickness H of 1.6 mm. The detailed antenna structure is presented in Figure 4 and the process of design development is illustrated in Figure 5. The total size of the antenna is denoted by Ls×Ws. Reducing the length of the ground was employed as a strategy to achieve effective impedance matching. As result, the antenna was implemented with slotted patch and a partial ground. The Table 2 provides a comprehensive summary of the antenna dimensions.

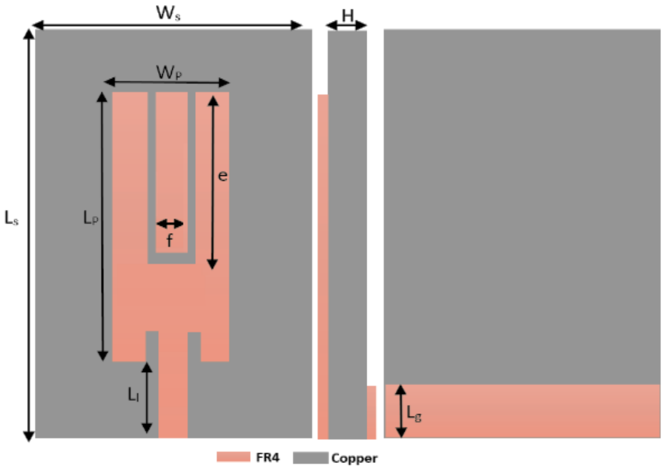


Figure 4. The structure of the suggested antenna

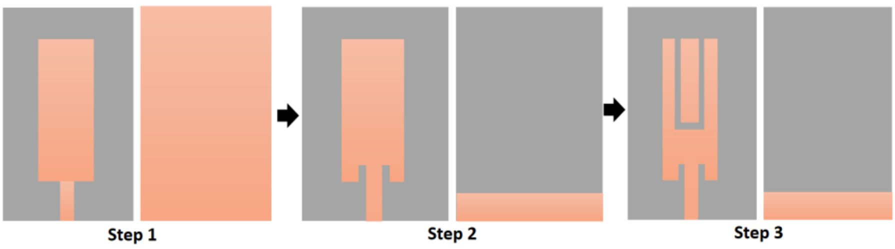


Figure 5. The design process of the antenna

Table 2. The antenna dimensions

Parameter	L_S	W_S	L_p	W_p	L_l	e	f	H	Lg
Dimension (mm)	40	20	30	9	5	16	2	1.6	6

2.3. Geometry of the patch with metamaterials and the mechanism enhancement

The architecture of the antenna along with the accompanying MTM is depicted in Figure 6. The antenna is strategically positioned at a distance G from the MTM to optimize its performance. The inclusion of MTM beneath the antenna enhances its performance through several key mechanisms. MTMs with negative permeability generate a reflection phase that causes destructive interference with backward-directed waves, reducing back radiation. They also suppress surface waves that typically travel along the substrate and contribute to inefficiencies. Additionally, these MTM act as artificial magnetic conductors (AMC), as shown in Figure 6, reflecting waves in phase with the incident waves to boost forward radiation and further reduce back radiation. This combination of effects results in improved antenna efficiency.

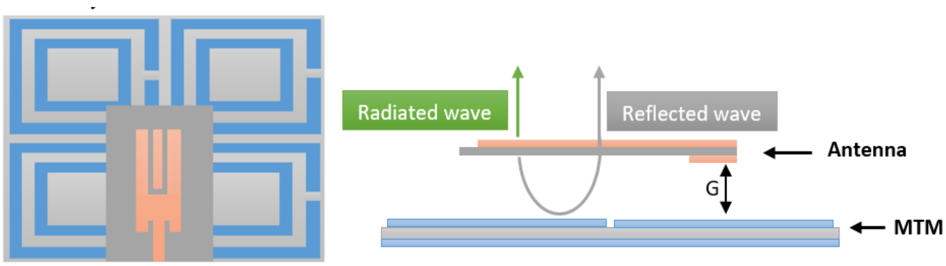


Figure 6. Design of the proposed MTM based antenna

2.4. Parametric study

A comprehensive parametric study was undertaken to analyze the influence of several design parameters on the antenna's performance characteristics. This study includes examining the gap between the antenna and the MTM as well as the height of the MTM substrate. By systematically varying these parameters, the study aims to identify optimal configurations that maximize the antenna's efficiency.

2.4.1. Effect of the gap G between the antenna and metamaterials

The impact of varying the distance between the antenna and the MTM was investigated by adjusting the gap parameter from 1 to 3 mm with a step of 1 mm. Figure 7 displays the return loss for different gap values. The study reveals how the reflection coefficient is influenced by the spacing between the antenna and the MTM. With a gap (G) of 1 mm, the obtained S_{11} values were -15.01 dB at 2.45 GHz and -25 dB at 4.5 GHz. For G=3 mm, the results showed -27.5 dB and -32.4 dB at 2.45 GHz and 6.5 GHz, respectively. The most favorable outcome was observed with G=2 mm, where the reflection coefficient reached -36.63 dB at 2.45 GHz and -36.54 dB at 6.23 GHz, indicating optimal performance with minimal reflection and improved overall antenna efficiency.

2.4.2. Effect of the metamaterials substrate height

To evaluate the impact of the MTM substrate height (H2) on the antenna performance, a parametric study was conducted, varying H2 from 1.4 mm to 1.6 mm in 0.1 mm increments. As displayed in Figure 8, the variation in H2 notably impacts the antenna characteristics, with a particular emphasis on the S_{11} parameter. The analysis revealed that the optimal performance, characterized by minimal reflection and the best impedance matching, was attained with a substrate height of 1.6 mm with S_{11} values of -36.63 dB at 2.45 GHz and -36.54 dB at 6.23 GHz.

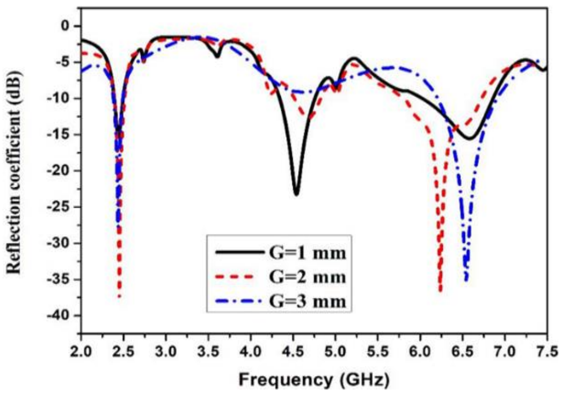


Figure 7. S_{11} with different G values

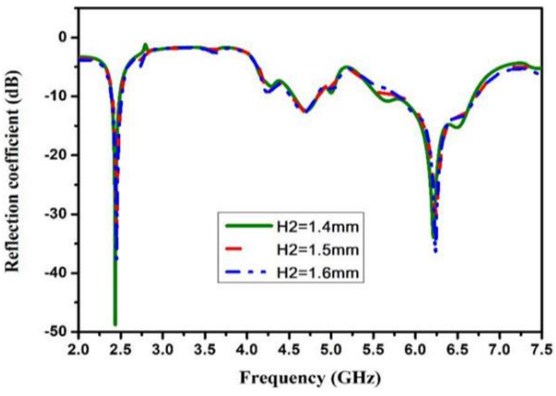


Figure 8. S_{11} with different substrate heights

3. RESULTS AND DISCUSSION

This section summarizes the findings and provides a comparative analysis of the antenna's performance in two scenarios: operating alone and when accompanied with the metamaterial. It highlights the differences in performance metrics, such as gain, impedance matching, and radiation pattern, to assess the impact of integrating the MTM on the overall antenna performance.

3.1. Reflection coefficient and voltage standing wave ratio of the metamaterials based antenna

The reflections coefficients of antenna with and without MTM are presented in Figure 9. The results highlight the substantial impact of MTM on the antenna performance. Without MTM, the reflection coefficient was -10.71 dB at 2.45 GHz and -13.88 dB at 6.23 GHz, indicating less efficient impedance matching and higher power reflection. With MTM integration, the return loss improved dramatically to -36.63 dB at 2.45 GHz and -36.54 dB at 6.23 GHz. This significant enhancement demonstrates that MTM integration effectively improves impedance matching, reduces reflected power, and maximizes power transfer, leading to better overall antenna performance.

The VSWR of the antenna with and without MTM are displayed in Figure 10, the VSWR value was improved from 1.66 to 1.03 at 2.45 GHz and from 1.75 to 1.04 at 6.23 GHz. The acceptable VSWR values are less than two (VSWR<2), in our case the antenna reached a VSWR values near to 1, indicating the very good impedance matching. This substantial reduction in VSWR indicates that the MTM significantly enhance the antenna performance by minimizing reflection and ensuring that most of the power is efficiently radiated.

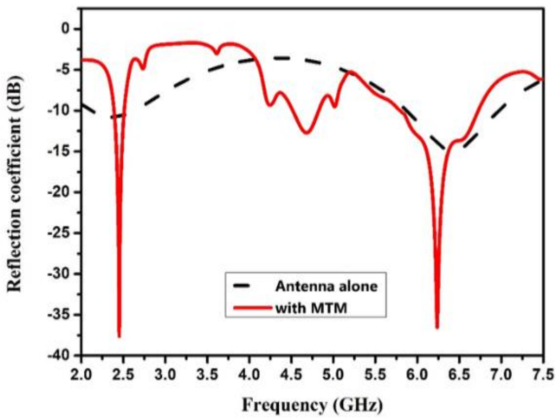


Figure 9. Return loss of the antenna

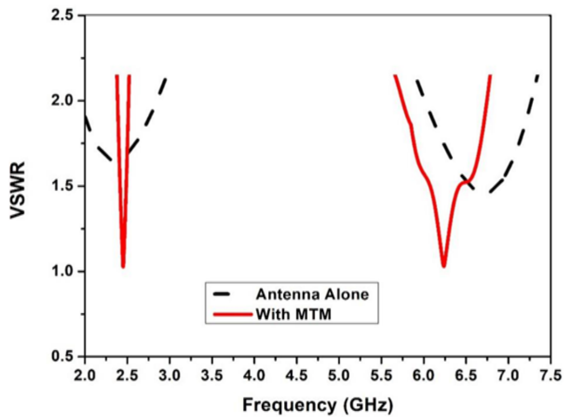
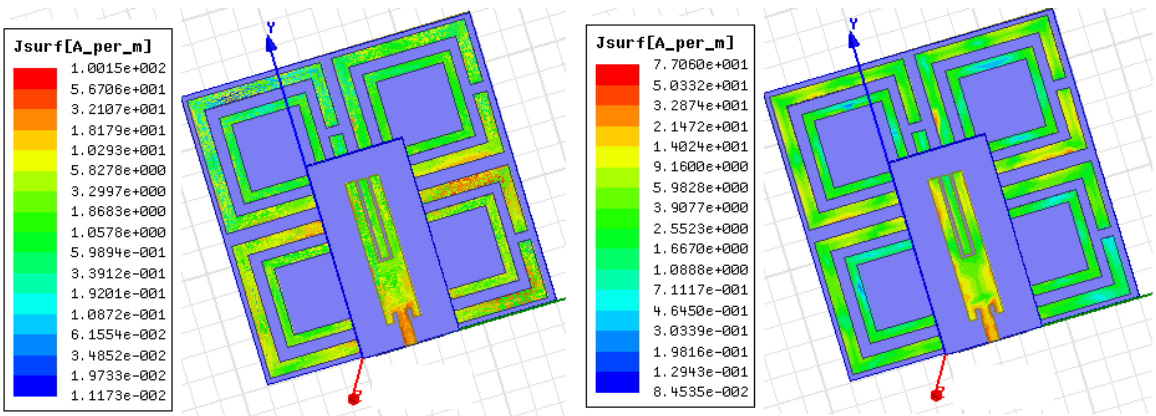


Figure 10. VSWR of proposed antenna

3.2. Current distribution of the proposed architechture

Figure 11 shows the current distribution at 2.45 GHz and 6.23 GHz with the integration of MTM. At 2.45 GHz, the highest current density is concentrated on the outer edges of the patch, while a more uniform current is distributed across the entire surface of the patch, as illustrated in Figure 11(a). At 6.23 GHz, the current distribution is more uniform across the entire patch and MTM structures, as shown in Figure 11(b). The MTM significantly influence these current distributions by modifying the antenna's electromagnetic properties. They optimize impedance matching and enhance radiation efficiency, leading to more focused and efficient current distribution.



(a) (b)

Figure 11. Surface current distribution; (a) at 2.45 GHz and (b) at 6.23 GHz

3.3. Rations patterns of the metamaterials based antenna

The 2D and 3D radiations patterns are disputed in Figure 12 and Figure 13 respectively. The integration of metamaterial results in a significant gain enhancement as demonstrated by the data. Initially, the antenna exhibited a bidirectional radiation pattern without MTM. However, with MTM, the antenna becomes more directional, indicating a more focused emission. The gain increased from 0.5 dB to 1.26 dB at 2.45 GHz and from 1.77 dB to 3.48 dB at 6.23 GHz. This improvement is due to the MTM ability to alter the antenna effective electromagnetic properties. The MTM optimizes the antenna impedance matching and enhances its radiation efficiency by reducing the back radiation and concentrating the radiation in the desired directions. The MTM also helps in reducing energy losses, contributing to the observed gain increase, making the antenna more effective for practical biomedical applications that required higher gain.

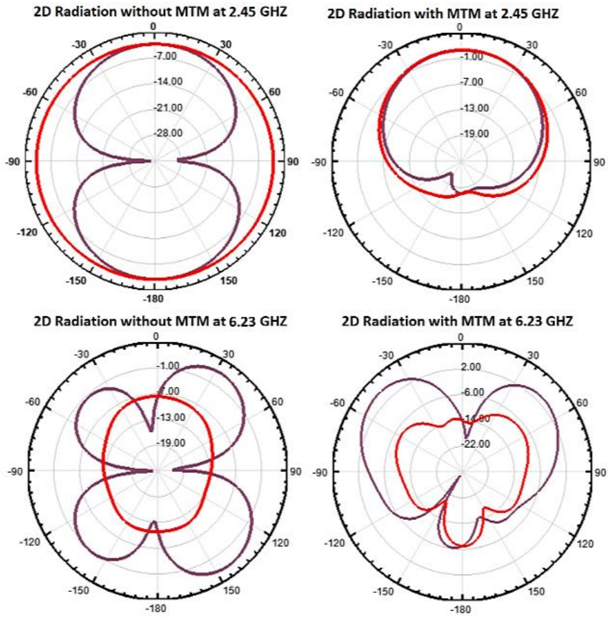


Figure 12. 2D radiation pattern of proposed design with and without MTM at 2.45 GHz and 6.23 GHz

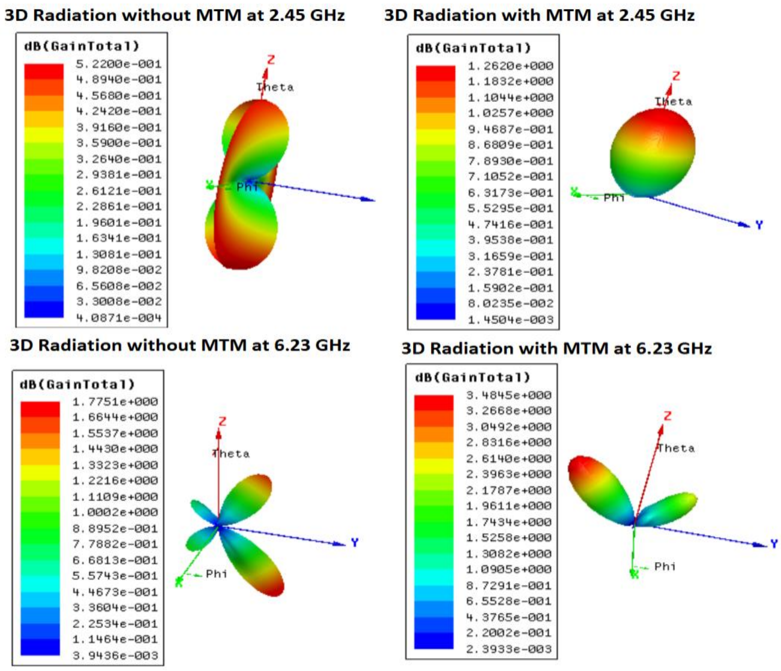


Figure 13. 3D radiation pattern of proposed design with and without MTM at 2.45 GHz and 6.23 GHz

The Table 3 provides a comprehensive summary of the results for the antenna, comparing performance metrics with and without the integration of MTM. It includes three key parameters: gain, return loss, and VSWR, highlighting the differences in performance between the two configurations. This comparison illustrates the impact of MTM on various aspects of the antenna's functionality, including improvements in impedance matching, gain enhancement, and radiation pattern.

Table 3. Parameters comparison of the antenna with and without MTM

Frequency (GHz)	2.45		6.23	
	Antenna alone	With MTM	Antenna alone	With MTM
S_{11} (dB)	-10.71	-36.63	-13.88	-36.54
VSWR	1.66	1.03	1.75	1.04
Gain (dB)	0.5	1.26	1.77	3.48

In evaluating our work, we conducted a thorough comparison with previously reported research. Notable points of comparison include the size, frequency,reflection coefficient, and gain. Compared to reference [24], which has a size of 30×30 mm^2, the antenna showed a S_{11} of -21.55 dB and -14.73 dB with an acceptable peak gain of 1.35 dB, our antenna is more compact (40×20 mm^2) and achieves better impedance matching. Uqaili *et al.* [25] proposed a patch antenna with a small size of 24×21 mm^2, the achieved peak gain is 3.9 dB. Research by Choudhary *et al.* [26] a dual band antenna was proposed, the reached peak gain and reflection coefficient are 2.55 dB and -42.29 dB respectively. Table 4 summarizes the comparison results.

Table 4. Comparison of our antenna with previous antennas

Ref.	Size (mm^2)	Freq. (GHz)	S11 (dB)	Gain (dB)
Roy *et al.* [24]	30×30	3.9/5.7	-21.55/-14.73	1.27/1.35
Uqaili *et al.* [25]	24×21	2.5/5.8	-29.9/-15.16	1.37/3.9
Choudhary *et al.* [26]	70×35	2.4/5.8	−42.29/−35.86	2.44/2.55
[Proposed]	40×20	2.45/6.23	-36.63/-36.54	1.26/3.48

4. CONCLUSION

This paper presented the performances of a MTM based antenna. The antenna is a U-shaped patch antenna with a modified ground plane and FR4 substrate resonates at 2.4 GHz and 6.23 GHz with a total size 40×20 mm^2. The dual-frequency capability of the antenna makes it versatile for specific biomedical needs, spanning from communication and imaging to molecular research. The MTM is a 2×2 array implemented on the FR4 substrate, situated at a distance of 2 mm under the antenna. The results affirm the significant impact of the MTM integration.Notably, the return loss was enhanced from -10.71 dB to -36.63 dB at 2.45 GHz and from -13.88 dB to -36.54 dB at 6.23 GHz. Additionally, the VSWR improved from 1.66 to 1.03 at 2.45 GHz and from 1.75 to 1.04 at 6.23 GHz. The peak gain also was increased from 1.77 dB to 3.48 dB. The integration of MTM into the U-shaped patch antenna significantly enhances its performance for biomedical applications, particularly at the frequencies of 2.45 GHz and 6.23 GHz. The 2.45 GHz frequency is commonly used in biomedical imaging techniques such as magnetic resonance imaging (MRI) and in wireless body area networks for patient monitoring, where its lower frequency allows for effective penetration and communication through biological tissues. Meanwhile, the 6.23 GHz frequency is beneficial for high-resolution imaging and advanced diagnostic applications, providing better spatial resolution and data throughput. The improved impedance matching and reduced back radiation from the MTM enhance signal quality and reliability at these frequencies, making the antenna more effective in delivering accurate and efficient medical diagnostics and monitoring. For more experience with the suggested antenna, the simulation near to human body can be done in the future.

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