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Enhancing terahertz patch antenna performance with metamaterials for biomedical applications

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ABSTRACT

This paper presents the performance enhancement of a terahertz (THz) patch antenna using the metamaterials (MTM). The antenna design features a rectangular patch with a modified ground structure, implemented on an FR4 substrate with dielectric properties of 4.4, a tan (δ) of 0.02, and a thickness of 1.6 µm. Operating at 4.92 THz, the antenna exhibits a -10 dB bandwidth of 0.25 THz (250 GHz), catering to diverse biomedical applications. To investigate the impact of incorporating MTM, the proposed MTM is positioned beneath the antenna at a separation of 12.8 µm. A comparative analysis of the antenna's performance with and without MTM reveals a significant influence of MTM insertion. However, the results confirm the big influence of the addition of the MTM. As results, the return loss was improved from -23.16 dB to -44.73 dB. The gain was additionally elevated from 1.46 dB to 5.06 dB. The design and simulation of the antenna were carried out through high frequency structure simulator (HFSS) software.

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1. INTRODUCTION

The world is witnessing continuous development in various fields, including the world of communications and antennas. Due to the significant increase in demand for small antennas with high specifications, which can be integrated into various applications, including 5G [1], wireless communication systems [2], and medical field [3], [4]. Patch antennas are characterized by their small size and ability to be used in applications that required small spaces like cell phones [5], Bluetooth applications [6], and biomedical capsule [7].

The need for advanced technologies in the field of biomedical has created significant interest in terahertz (THz) frequencies due to its special properties in probing biological tissues. As presented in Figure 1, THz waves occupy the spectrum between microwaves and infrared radiation, offering non-invasive and non-ionizing characteristics ideal for various biomedical imaging and sensing applications. Moreover, THz waves exhibit exceptional penetration capabilities, enabling them to traverse various materials without deterioration, such as clothing, and biological tissues (fat, skin, and muscle). This penetrating power facilitates the use of THz patch antenna in various biomedical application such as THz imaging techniques [8], which provide detailed insights into internal structures and abnormalities within tissues. Additionally, with its wide bandwidth, THz technology also presents a strong candidate for high-speed communication [9], [10] and data transfer applications [11] and other applications that require a wide bandwidth.

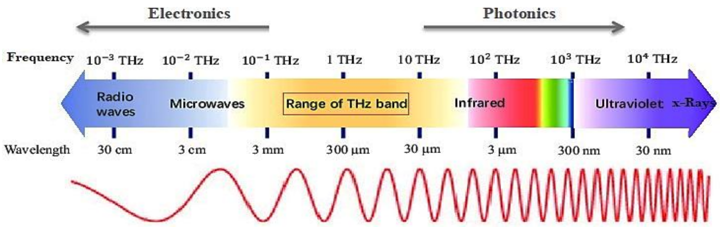


Figure 1. Electromagnetic spectrum

Patch antennas have used as effective candidates for THz applications due to their flexibility and their very small size [12], [13]. Nevertheless, conventional patch antennas encounter some limitations in performance, particularly in terms of bandwidth, gain, and directivity. To address these challenges, the integration of metamaterials (MTM) has proposed by the researchers as a recent solution to improve the characteristics of patch antennas [14], [15]. MTM, engineered structures with tailored electromagnetic characteristics that are absent in natural substances [16], offer special control over electromagnetic waves at various frequencies ranges including THz frequencies. As results, the incorporation of MTM unlocks novel functionalities and features in patch antennas world, paving the way for innovative solutions in biomedical applications, sensing [17], and imaging [18].

The gain improvement of THz patch antennas with MTM is proposed in [19], the antenna operates at 1.85 THz, and the gain was increased by 45% using an enz MTM superstrate composed of (InSb) an (SiO_2) multilayers. The authors [20]-[22] proposed the utilization of a reflective frequency structure simulators (FSSs) for the gain enhancement patch antennas. Resonates at 1.07 and 1.7 THz. The improvement in bandwidth of patch antenna utilizing metasurfaces is presented in [23], the suggested antenna reached a bandwidth of 45.4 % accompanied by a maximum gain of 3.8 dBi. The use of artificial magnetic conductor (AMC) is presented in [24], operating at 3.5 GHz, with gain improvements of about 3.3 dB (about 42%). The bandwidth enhancement of a planar antenna using MTM is presented, the MTM is directly integrated inside the feed line, the gain was improved by 2.7 dBi and the efficiency increased by 12% [25].

This work presents the integration of the MTM with patch antennas to propel the advancement of THz technology in biomedical applications. Specifically, we investigate the proposed design and the characterization of the MTM based antennas. Through comprehensive theoretical analysis, numerical simulations, this study provides a detailed insight into the performances improvement achieved through the inclusion of MTM into a THz antenna. Especially, the focus lies on assessing the enhancement impact on the return loss (S_{11}), voltage standing wave ratio (VSWR), and gain. The structure of our paper is as follows: the first part presents the patch and MTM designs. Following that, the part two delves into a parametric analysis, and the third section analyzes the results. Lastly, a concise conclusion and future work are presented in the final section.

2. THE PROPOSED METAMATERIAL BASED ANTENNA DESIGN

2.1. The configuration of the antenna

Our antenna features a patch design with a partial ground structure, implemented on an FR4 substrate, measuring $L\times W$ in total dimensions. The measurements of the patch antenna were established utilizing the subsequent (1) [26]:

$$W_p = \frac{c}{2f}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

where C is the the velocity of light, f the frequency and ε_r is the dielectric of the substrate,

$$\varepsilon_{reff}=\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left[1+\frac{12h}{w}\right]^{-\frac{1}{2}} \tag{2}$$

where ε_{reff} is the effective dielectric and h_s the substrate thickness:

$$\Delta L=0.412h_s\frac{(\varepsilon_{ref}+0.3)\left(\frac{w}{h_s}+0.264\right)}{(\varepsilon_{ref}-0.258)\left(\frac{w}{h_s}+0.8\right)} \tag{3}$$

where $\triangle L$ is the length extension,

$$Lp = L_{eff} - 2 \triangle L \quad (4)$$

where Lp is the patch length and L_{eff} is the effective length.

$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{reff}}} \quad (5)$$

Following the initial antenna design, certain adjustments were made to enhance the antenna characteristics. These modifications involved slotting the radiating element and reducing the size of the ground. The ultimate design is detailed in Figure 2. The utilization of a partial ground, as opposed to a full ground, plays a crucial role in achieving a good impedance matching. The antenna resonates at 4.92 THz, the resonance at this frequency signifies the antenna's capability to emit and receive THz waves, a capability poised to revolutionize biomedical applications. THz imaging and sensing, enabled by such antennas, offer unparalleled precision in visualizing biological structures, and probing molecular compositions. Table 1 presents the antenna dimensions values.

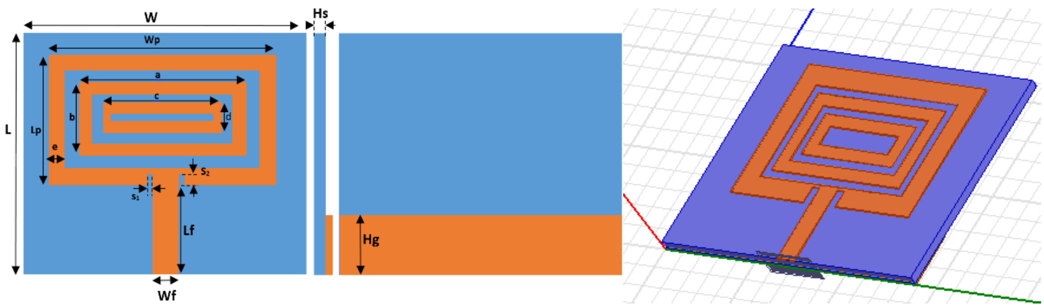


Figure 2. Antenna structure

Table 1. The antenna parameters

Variable	W	L	Wp	Lp	Wf	Lf	a	b	c	d	e	S_1	S_2	Hs	Hg
Value (µm)	49	35	39	25	4.8	15	35	21	25	11	5	2	4.2	2	12.9

2.2. The metamaterials design

The suggested MTM consists of a split-ring resonator integrated in a substrate of FR4. The resonators are strategically placed and separated by a distance W_3 to minimize the mutual coupling and interact with incident waves and control the propagation characteristics. Figure 3 illustrates the configuration of the MTM design. The overall dimensions of the design are specified as $L_m \times W_m$, and detailed design parameters can be found in Table 2.

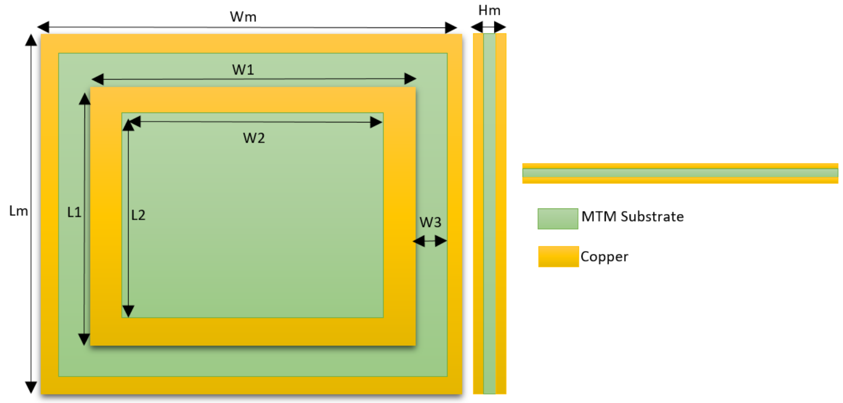


Figure 3. The MTM design

Table 2. The MTM parameters values

Variable	Wm	Lm	W1	W2	W3	L1	L2	Hm
Value (µm)	80	70	64	50	5	54	40	1.7

2.3. Metamaterials based antenna

As disputed in Figure 4, the MTM is located beneath the antenna, with a gap (G) of 12.8 µm. The MTM alters the local electromagnetic environment, leading to enhanced impedance matching, reduced backward radiation, and improved radiation pattern control. These effects contribute to increased antenna performance.

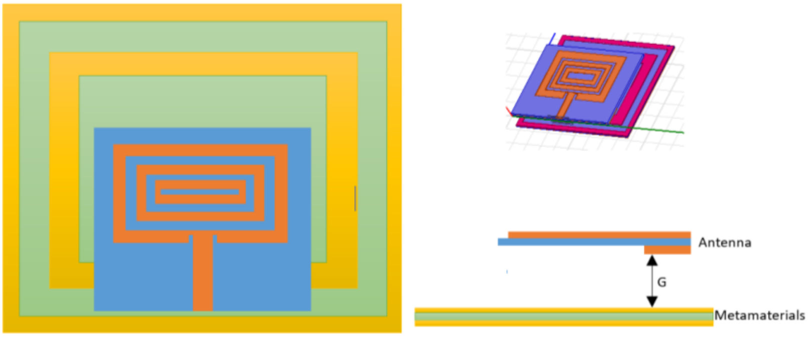


Figure 4. Configuration of the MTM based antenna

2.4. Parametric analysis

2.4.1. Effect of the ground length (Hg)

The ground plane's dimensions play a crucial role in establishing the suited frequency and attaining a good impedance matching, which is a critical factors for minimizing reflection and optimizing power transfer. Adjusting the ground plane length becomes a strategic approach to tune the antenna's resonant frequency and tailor its impedance characteristics. Figure 5 illustrates the reflections coefficients with various Hg values. The parameter underwent adjustments within the range of 10.9 to 13.9 µm, with increments of 1 µm. It's very clear that the parameter plays a big influence. The antenna reached a S_{11} of -44.73 dB with Hg=12.9 µm, marking it as the optimal outcome. Whereas it did not surpass the value of -17 dB for the other Hg values.

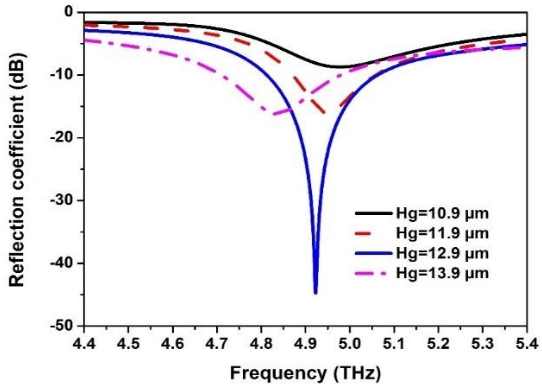


Figure 5. Reflection coefficient with differents Hg values

2.4.2. Effect of the air gap between the metamaterials and the antenna (G)

In order to more improve the MTM based antenna performance, a parametric study was conducted by varying the air gap value between the MTM and the antenna. The parameter was ranged from 10.8 to 13.8 µm. Figure 6 disputed the obtained results, the S_{11} was enhanced from -30 dB at G=10.8 µm to -44.73 dB at G=12.8 µm signify a substantial reduction in reflected power. Notably, the observed peak at an air gap of 12.8 µm highlights an optimal configuration within the studied range.

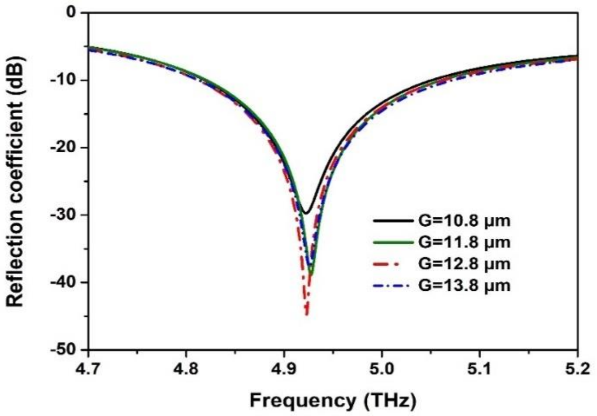


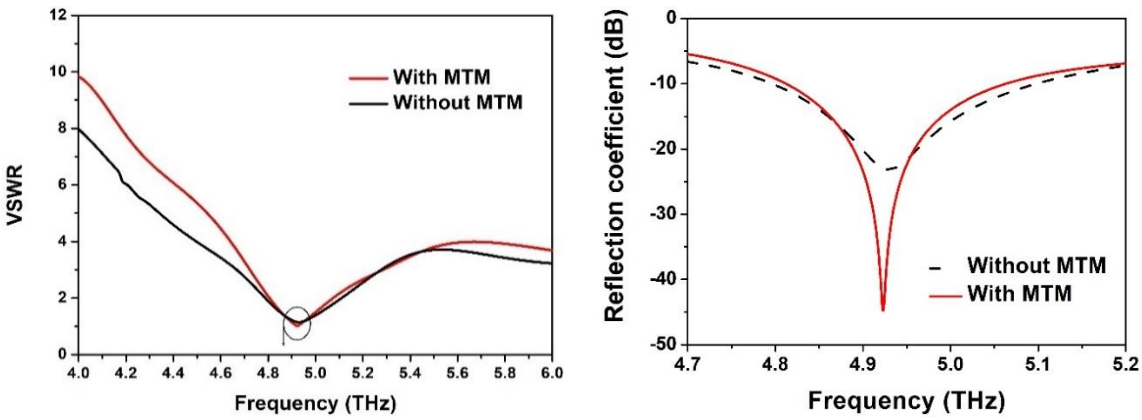
Figure 6. Reflection coefficient with differents G values

3. RESULTS AND DISCUSSION

In this part, we introduce and present the obtained results. Providing analysis and insights garnered from our research.

3.1. Reflection coefficient and the voltage standing wave ratio

The reflection coefficient and VSWR serve as pivotal indicators elucidating the patch antenna's behavior and offering a precise assessment of power transmission quality. Optimal performance is typically indicated by S_{11} values below -10 dB and VSWR values below 2 (S_{11}<-10 dB and VSWR<2). Figures 7(a) and (b), present our proposed antenna S_{11} and VSWR characteristics, respectively. Integration of MTM noticeably enhances antenna performance. The reflection coefficient experiences a significant improvement from -23.16 dB to -44.73 dB, accompanied by a bandwidth of 250 GHz (4.81-5.06 THz) with a resonance frequency of 4.92 THz, while the VSWR attains an impressive value of 1.02. This remarkable improvement indicates a substantial decrease in the amount of reflected power, signifying improved impedance matching and overall antenna efficiency.



(a) (b)

Figure 7. MTM based antenna; (a) reflection coefficient and (b) VSWR

3.2. Radiations patterns

The radiations patterns of an antenna are a crucial parameter that illustrates how effectively it emits electromagnetic waves into space. In Figures 8(a) and (b), the 2D radiations patterns, without and with MTM, are depicted. While the 3D radiations without and with MTM are presented in Figures 8(c) and (d), respectively. Notably, the integration of MTM has yielded a noticeable enhancement in antenna gain. The antenna experienced a gain enhancement from 1.42 dB to 5.06 dB at 4.9 THz (increased by approximately 256%). This enhancement in gain signifies an improvement in the antenna's capability to concentrate and steer the radiation in a specific direction, resulting in more efficient signal transmission and reception.

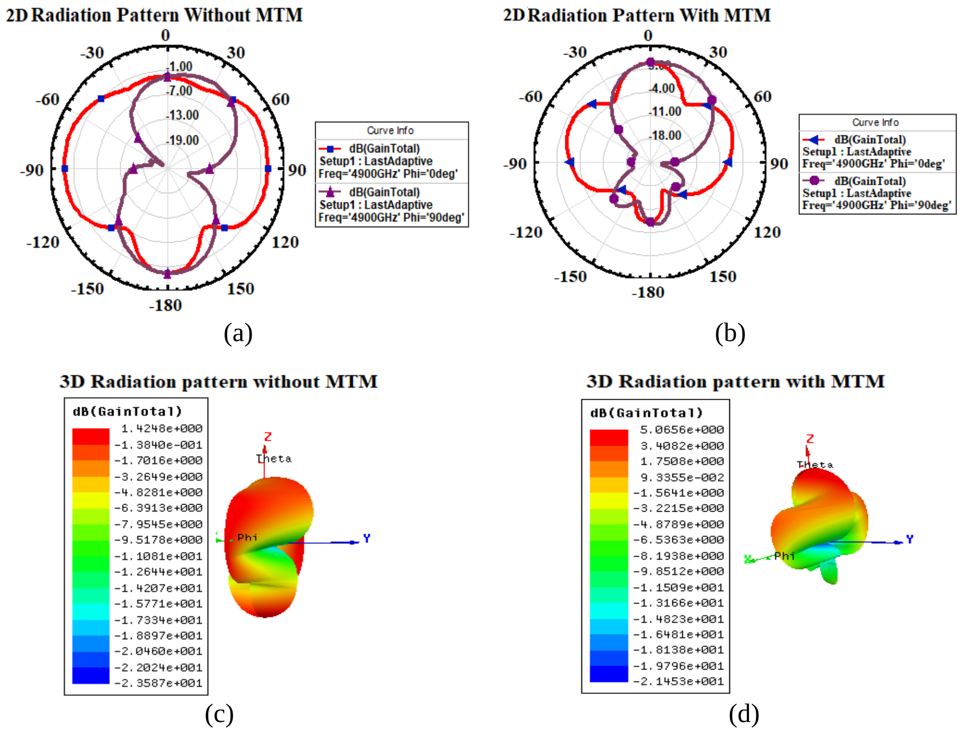


Figure 8. Radiations patterns; (a) 2D without MTM, (b) 2D with MTM, (c) 3D without MTM, and (d) 3D with MTM

3.3. Current distribution

The antenna current distribution without and with MTM are showed in Figures 9(a) and (b), respectively. This comparison reveals the significant enhancement that MTM brings to antenna performance. Without MTM, the current is more dispersed, especially towards the edges of the patch, with a maximum density of 7.75×10^4 A/m, leading to inefficient electromagnetic field confinement and increased surface wave losses. This results in lower gain and directivity. In contrast, with MTM, the current becomes more concentrated and uniform, particularly around the feed line and the inner edge of the patch, with the peak current density rising to 9.34×10^4 A/m. This focused distribution reduces energy losses, enhances field confinement, and improves the various antenna performance, including gain and directivity.

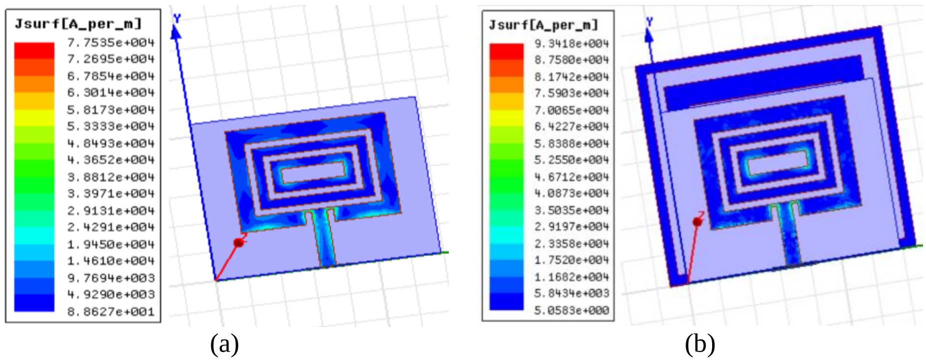


Figure 9. Current distribution of the suggested antenna; (a) without MTM and (b) with MTM

Table 3 presents a comprehensive comparison of the performance of the suggested antenna both with and without MTM, through this comparison, it becomes evident that the inclusion of MTM has exerted a significant influence on various key parameters, notably the reflection coefficient, VSWR, and gain. Table 4 presents a comparison of our antenna with previous antennas. By showcasing the best results, our proposed antenna establishes itself as a leading candidate in antenna design.

Table 3. Antenna performance comparison with and without MTM

Parameter	Frequency (THz)	S_{11} (dB)	VSWR	Gain (dB)
Antenna alone	4.92	-23.16	1.2	1.42
With MTM	4.92	-44.73	1.02	5.06

Table 4. Antenna performance comparison with other antenna designs

Ref.	Size (μm^2)	Frequency (THz)	S_{11} (dB)	Gain (dB)
Prince *et al.* [27]	23×19	4.95	−55.31	4.25
Christydass and Nurhayati [28]	32×36	4.60	−44.28	3.10
Shalini [29]	50×50	4.83	−38.00	4.30
This work	49×35	4.92	−44.73	5.06

4. CONCLUSION

This paper presented the use of MTM for the improvement of a patch antenna performance. The suggested design is a very small patch antenna with size of 49×35 μm^2 and an incomplete ground plane optimized for operation at 4.92 THz for biomedical applications. The radiating element is positioned over a substrate of FR4 and fed with a feed line of 50 Ω. The proposed MTM is a periodic SRR integrated into an FR4 substrate and positioned bellow the antenna at a gap of 12.8 μm. This integration enhances clearly the antenna characteristics in terms of return loss, VSWR, and the radiation pattern. The S_{11} underwent an improvement from -23.16 dB to -44.73 dB. Additionally, the VSWR saw an improvement, decreasing from 1.2 to 1.02, while the gain increased by 3.64 dB, rising from 1.42 dB to 5.06 dB. The integration MTM offer the capability to overcome inherent limitations of conventional antennas, enabling the realization of compact, high-performance antennas tailored for THz frequencies. As results, the utilization of MTM with THz patch antennas represents a promising path for advancing biomedical applications in the THz frequency range, including cancer detection, tissue characterization, and non-invasive imaging. For future work, we aim to simulate the suggested antenna alongside a human body model to examine its performance in proximity to a human body.

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