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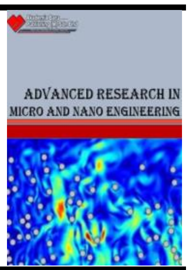

A Split Square-shaped Metamaterial Loaded Microstrip Patch Antenna for 5G Communication

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ABSTRACT

This paper describes a split square-shaped metamaterial (MTM) design which was applied for the performance enhancement of a rectangular-shaped microstrip patch antenna (MPA). A proposed split square-shaped MTM-based microstrip patch antenna resonates at two frequencies, 18.57 GHz and 25.24 GHz. In both cases, the bandwidths were obtained at 2 GHz and 6.72 GHz respectively. The proposed antenna was designed on FR-4 substrate material, with the dimensions of 20×20 mm^2. For the performance investigation, the MTM was placed first at the front side of the antenna and subsequently placed at the back side of the antenna. It was found that the antenna showed better performance when the MTM was placed at the back side of the antenna instead of the front side. The wide bandwidth, high directivity and enhanced gain have made the antenna a potential one for the 5G communication.

1. Introduction

A receiving antenna serves as a device in communication systems, allowing the reception of electromagnetic waves for transmission. This device was used to convert electrical signals into electromagnetic waves during transmission. Design, size, materials, and impedance matching were among the factors affecting the antenna's performance. The antenna's primary function was to collect and analyze broadcast data as well as transform incoming electromagnetic waves back into electrical signals. Microstrip Patch Antennas (MPAs), which received Federal Communication Commission (FCC) accreditation for use in 2002 [1], are widely used in a variety of wireless and mobile communication systems.

MPAs have generated a lot of interest in the field because of qualities like their lightweight design, low-profile construction, cost, and simplicity in production. But the Microstrip Patch Antenna (MPA)

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demonstrated several drawbacks, including constricted bandwidth, poor gain, reduced directivity, and limited power handling capacity [2]. The MPA has been a challenge that has been overcome by the use of metamaterial structures, which have improved properties including bandwidth, gain, directivity, and efficiency. High-performance ultra-wideband antennas with compact dimensions had to be developed to meet these challenges while maintaining up with technological developments. The ultra-wideband antenna, which exceeds conventional antennas in many ways, has become a popular substitute because of its broad bandwidth, high efficiency, small size, low spectral density, affordability, and flexibility. At the top of these efforts have been metamaterials (MTMs), which offer distinctive properties including negative permeability and specific-frequency range permittivity [3,4].

MTM surfaces have been successfully incorporated into MPA systems was conducted by Wajid *et al*., [5] to significantly improve MPA performance, particularly in terms of gain, directivity, efficiency, and bandwidth. Boutayeb *et al*., [6] investigated that MTM surfaces efficiently reduce surface wave propagation and enhance in-phase reflections. For instance, using a cylindrical Electromagnetic Band Gap (EBG) structure resulted in significant improvements, including a 2.9 dBi gain improvement at 2.6 GHz. Pattnaik *et al.*, [7] serve as an example of how improvements resulting from MTM technology led to unique multiband MPA designs where MTM impact led to the lowering of resonance frequency from 14.08 GHz to 6.15 GHz. According to Singh *et al*., [8], intriguing results were also found in examinations investigating the impact of structural factors on MTM-embedded structures. Notably, the patch size was decreased while the resonant frequency and bandwidth were improved, making the design suitable for X-band applications. Islam and Misran [9] designed meander-shaped microstrip patch antennas with a bandwidth of 146 MHz and a gain of 1.347 dBi to support IoT applications. Arora *et al*., [10] conducted the implementation of slotted double-layer microstrip patch designs led to the fabrication of ultra-wideband antennas with gains of 4.685 dBi and bandwidths of 22 MHz. To strategically reduce noise from WLANs and WiMAX, Tang *et al*., [11] designed an MPA including triband slots and SRR structures. To improve performance, Patel *et al*., [12] presented a novel MPA design that included MTM superstrates and SRRs to boost bandwidth. Similar to this, Rajkumar *et al*., [13] showed a portable open SRR MPA for multiband applications, and Alam *et al*., [14] offered a triangular-shaped MTM-inspired triband MPA. Saravanan *et al*., [15] demonstrate that the gain of planar resonant MPAs was significantly enhanced by integration of MTM and photonic crystal. According to Khatun and Islam [16], the small lightweight rectangular microstrip patch antenna for the 2.45 GHz ISM band was created using the slotted patch approach. Saghati *et al*., [18] employed a novel switchable single and multi-frequency triple-slot antenna for 2.4-GHz Bluetooth, 3.5-GHz WiMax, and 5.8-GHz WLAN. In the aim of achieving an exceptionally ultra-wide operating band, various techniques and methods have been explored.

Several authors introduce a proposal for a compact monopole antenna designed to exhibit wideband capabilities, specifically modified for SWB applications. The study encompasses a comprehensive presentation of the antenna's design evolution and a parametric analysis conducted using HFSS to offer valuable insights into the antenna's design, optimization, and fundamental radiation mechanism. Additionally, the research also introduces a compact planar antenna with a multi-slotted ground plane, where the incorporation of rectangular slots on the top side of the partial ground plane has proven effective in enhancing the impedance bandwidth of the printed planar antenna [30,31]. Tiang *et al.,* [32] employed a new dual-frequency antenna has been developed with a single-layer patch containing two parallel slots and meandered slots near the non-radiating edges. These design features enhance the antenna's performance, resulting in a low-profile design, high gain, wide bandwidth, and favorable radiation characteristics for dual-frequency operation. Jamlos *et al.,* [33] proposed an antenna has been designed with a resonance frequency at 5.8GHz. The patch and the ground plane of the antenna, made up of a radiating element such as copper, are characterized by a thickness of 0.053mm and dimensions of 70 X 70 mm. According to Othman and Nur Amirah [34], an antenna with a 2.70 GHz Split Ring Resonator MTM unit cell was built, and research was done to find the optimal design that achieves zero indexes, permittivity, and permeability at this frequency.

These numerous initiatives using different antenna structures desire to increase gain, bandwidth, and effectiveness. In addition, a revolutionary rectangular MPA design with split square-shaped MTM reflectors and superstructures was introduced for 5G applications, leading significant change in gain, bandwidth, and directivity. The following sections of this study elaborate on the design principles, geometry, findings from the research, and closing thoughts associated with this new strategy.

2. Methodology

In the initial phases of the research, the focus was on understanding the core principles behind antenna and metamaterial design. The aim was also to determine the specific frequency range suitable for the antenna's operation. The essential equation for antenna design calculated the antenna's length, width, and thickness, enabling the definition of precise physical dimensions. With the acquired design parameters, the antenna was constructed. A simulation was conducted to investigate if the proposed microstrip patch antenna effectively covered the required frequency range. When the frequency range was not sufficient, adjustments were made. A slot was introduced to the antenna's ground plane to attain the necessary frequency range. Furthermore, a unit-cell-based metamaterial (MTM) was innovated to enhance performance. Enhancing the metamaterial's characteristics through permittivity and permeability characterization resulted in improved behavior and application. Adjustments were made in the metamaterial's placement on the antenna's surface to optimize performance. The design's simulated outcomes represented directivity, gain, and frequency range, with an emphasis on optimizing directivity and gain. The result was verified at the proposed frequency range. The result confirms the specifications for 5G radar and satellite communication network requirements, that ended the design process.

2.1 Mathematical Equation

The proposed antenna dimensions are calculated using the following equations

- Patch width (W) [25]

$$W = \frac{c}{f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

Where, c = light speed in vacuum, f_r = resonant frequency

- Substrate height (h) [16]

$$\frac{W}{h} > 1 \tag{2}$$

- Effective dielectric constant (ε_{reff}) [16]

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{w}\right]^{1/2} \tag{3}$$

- Patch length (L) [25]

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

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

$$\Delta L = 0.412h \frac{(\varepsilon_{reff}+0.3)(\frac{w}{h}+0.264)}{(\varepsilon_{reff}-0.248)(\frac{w}{h}+0.8)} \quad (6)$$

- Ground plane measurement [16]

$$L_g = L + 6h \quad (7)$$

$$W_g = W + 6h \quad (8)$$

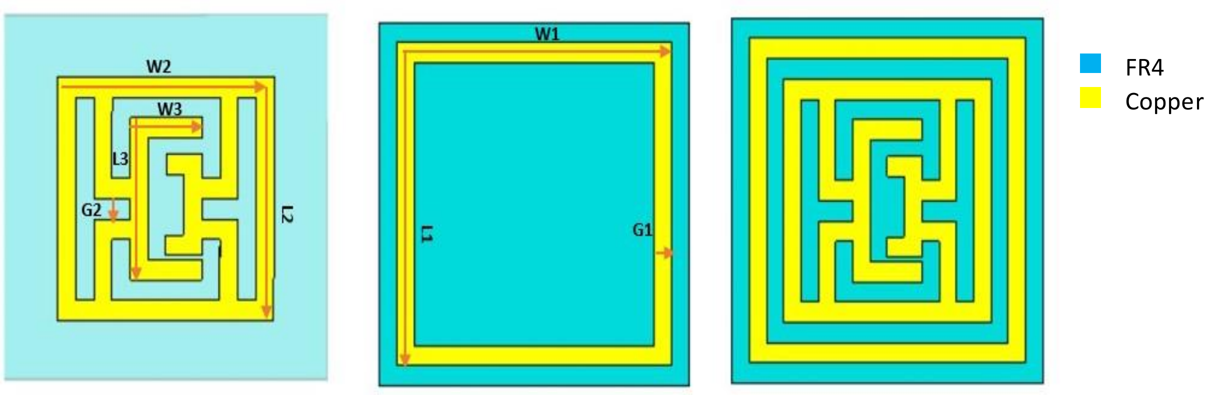
2.2 Design of the Split Square-Shaped MTM Structure

The split square shape MTM unit cell was designed for 5G communication antenna. The structure was used with FR-4 substrate with a dielectric constant of 4.3. By making the unit cell size significantly smaller than the metamaterial's guided wavelength, homogeneity is ensured. The metamaterials unit cell for the 5G network system operates between 16 and 28 GHz. The substrate is 1.9mm thick and 18×18 mm^2 in size. Table 1 represents the dimension values of unit cell metamaterial.

Table 1
Dimension value of the unit cell MTM

Parameter	Value (mm)
L1	16
W1	16
L2	12
W2	12
L3	8
W3	4
G1	2
G2	1

Figure 1 illustrated the proposed unit cell metamaterial design, consists of two square slots. In the first stage, two C shape designs were incorporated in this 12×12 mm^2 square slot which exhibits an S_{21} parameter higher than -10 dB. Then, in the next step, a final rectangular slot 16×16 mm^2 had been designed. This proposed metamaterial demonstrated an intriguing quality through its S_{11} and S_{21} parameter. The copper material is used as a conductor with thickness of 0.035 mm. At a resonating frequency of 24.79 GHz, the return loss is -21.31 dB, and it achieves a level below -10 dB, which was showed in Figure 2. The split-shaped unit cell exhibits multiband properties. The study presented a designed unit cell metamaterial that demonstrates outstanding near-zero negative permittivity features at specific frequency ranges 16.58-19.2 GHz and 23.82-25.43 GHz, and the metamaterial maintains desirable permeability between 16-18 GHz and 20.21-25.19 GHz which is depicted in Figure 3. Metamaterials with near-zero negative permeability and permittivity are typically more desirable for certain applications, especially when aiming to attain advantageous electromagnetic properties. The unit cell can potentially indicate negative permeability and or permittivity within the effective medium when the EMR is >4 which is considered an ideal value. The negative index properties, compactness, and bandwidth of the proposed unit cell and array structure was performed by analyzing how electromagnetic waves propagate through them [26]. This design aims to simultaneously enhance both the isolation and the overall performance of the patch antenna system.



(a) (b) (c)

Fig. 1. (a) First phase of unit cell metamaterial (b) second phase of unit cell metamaterial (c) structure of the proposed unit cell metamaterial

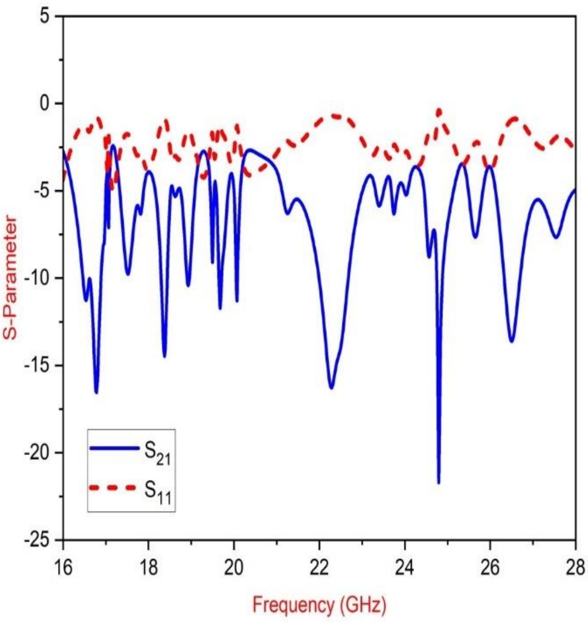


Fig. 2. S-parameter of proposed MTM structure

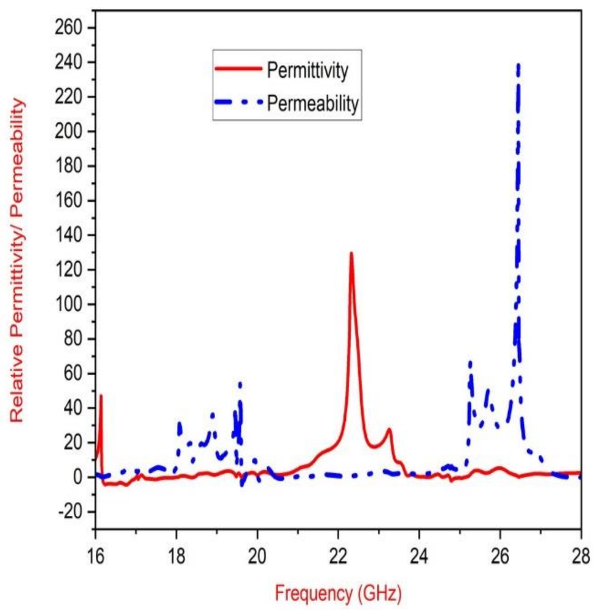


Fig. 3. Relative permeability and permittivity of proposed MTM structure

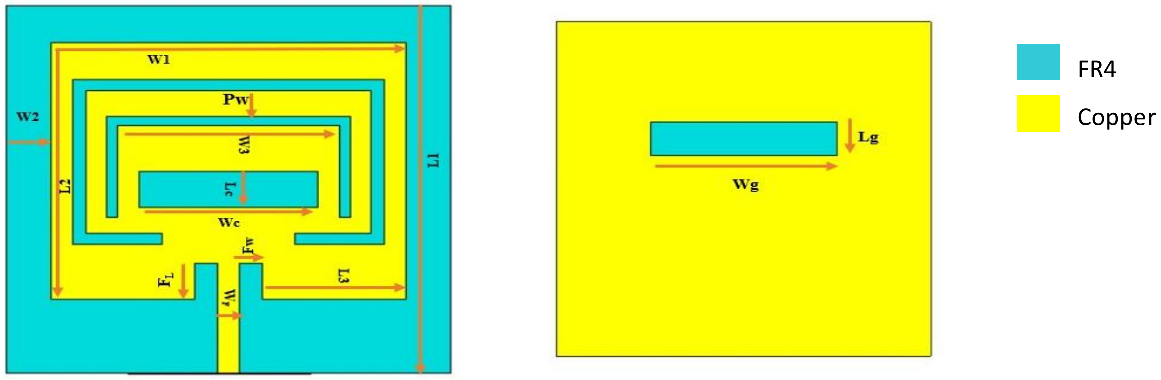
2.3 Design Structure of Antenna

With the frequency range of 16 to 28 GHz and FR4 as the substrate, a research investigation into the characteristics of a square-shaped microstrip patch antenna was started. Simulation utilizing CST microwave software was used to achieve this. An FR4 substrate was used as the surface for a copper patch, an update from traditional antenna designs, in the recommended antenna's construction. At the feed line's end, a coaxial probe was connected using a 50 Ohm connector for excitation. It was common for the patch antenna's impedance bandwidth to decrease when a high permittivity dielectric substrate material was used. However, by adding three rectangular slots: two small ones, one large one, and one in the middle, in the copper patch this drawback had been solved. This slot creates additional resonance frequencies that align with the desired operating frequencies. This resonance can enhance the antenna's gain at those specific frequencies. The slots contribute to the radiation pattern and potentially steers the main beam in a satisfactory direction. This can result in higher gain in the desired direction. Also included in the ground plane was a sizable rectangular slot. A new compact microstrip patch antenna with a double L-shaped configuration was designed. The slotted patch shape and the antenna dimensions enhanced the reflection coefficient and properties of the radiation pattern at the expected frequency band [27]. The main radiating element is established by the modified patch and ground structure, accompanied by a curved slot line, radiating fins, and the feeding line. These parameters are adjusted carefully to achieve the desired antenna specifications through the process of slot etching [28]. This paper introduced a S-band patch antenna for small satellite applications, with characteristics like CP, high-gain, a single-feed system, and a single-layer design. The experimental results closely match with the numerical simulations, providing confirmation that these antennas can be feasibly constructed and integrated into HORYU-IV's small satellite communication systems [29]. The mathematical equation was used to determine the suggested antenna's size. The patch size was 14×16 mm^2 for both 18.57 GHz and 25.24 GHz calculated from Eq. (1), (4), while the substrate was 20×20 mm^2 in size. The size of the ground plane was deduced from Eq. (7), (8). The thickness of FR4 substrate was 1.6 mm. The substrate, patch, and ground are three fundamental layers that constitute the antenna structure. The dimension value of the antenna is presented in Table 2.

Table 2
Dimension value of the rectangular MPA

Parameter	Value (mm)	Parameter	Value (mm)
L1	20	Wc	8
W1	16	Lc	2
L2	14	Fw	1
W2	6	F_L	2
L3	7	W_F	1
W3	10	Lg	2
Pw	2	Wg	10

The proposed antenna structure is illustrated in Figure 4. The designed antenna exhibits an outstanding characteristic in the absence of the metamaterial. The simulated reflection coefficient S_{11} parameter is depicted in Figure 5. At resonating frequencies, 18.57 GHz and 25.24 GHz it displays the return loss of -23.62 dB and -25.05 dB respectively along with an impressive bandwidth of 1.62 GHz and 6.64 GHz**.** The antenna's results 18.57 GHz and 25.24 frequency which implies within the K-band (18-27 GHz), mm-wave band (24-100 GHz) respectively. The K-band and mm-wave band are used for satellite communications and other specialized applications like radar systems in United States, Canada, and various European countries.



(a) (b)

Fig. 4. Proposed MPA a) front view b) back view

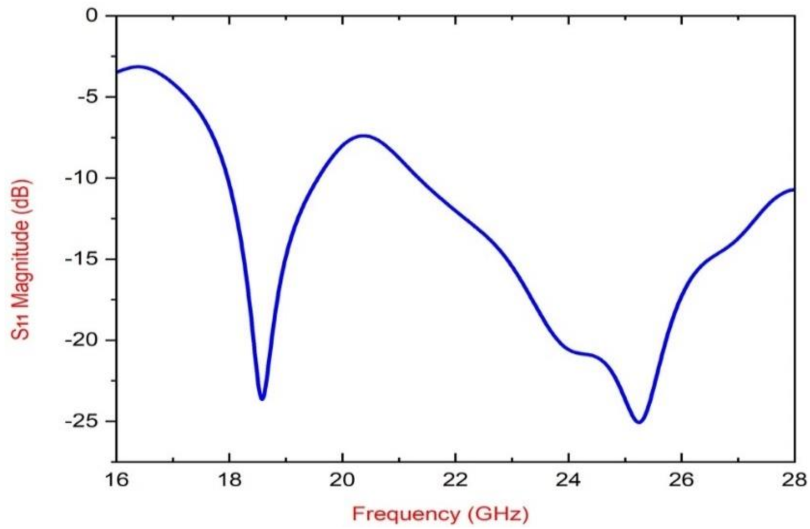


Fig. 5. S_{11} parameter of antenna without metamaterial

2.4 MTM Loaded Microstrip Patch Antenna

A Unit Cell Metamaterial (MTM) is positioned in front of the 5G antenna surface in Figure 6. As a result, it is capable of reflecting an antenna's backside emission. The gain of an antenna is boosted if the waves that are reflected by a metamaterial surface at the antenna plane are in phase with the waves that are directly radiated by the antenna.

A new configuration was obtained by placing the metamaterial in front of the proposed antenna. The return loss was decreased to -21 dB and -18 dB at the resonant frequencies of 18.57 GHz and 25.24 GHz, respectively shown in Figure 8. The reduction was complemented by 2.23 GHz and 2.11 GHz bandwidths. On the other hand, positioning the metamaterial in front of the proposed antenna resulted in a different configuration in Figure 7. At the resonant frequencies of 18.57 GHz and 25.24 GHz, respectively, return loss values of -25.52 dB and -21.21 dB were obtained in this scenario demonstrated in Figure 9. This improvement was accompanied by bandwidths of 2 GHz and 6.72 GHz.

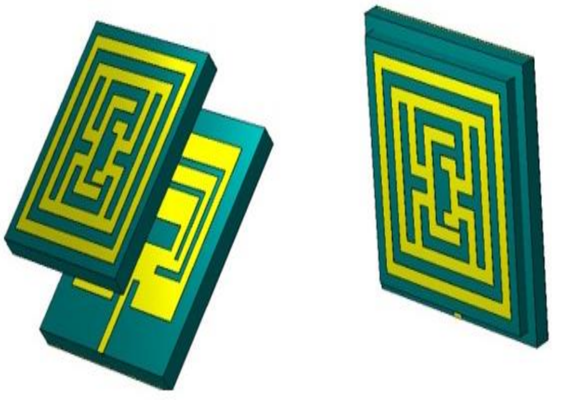


Fig. 6. MTM placed in front of the antenna

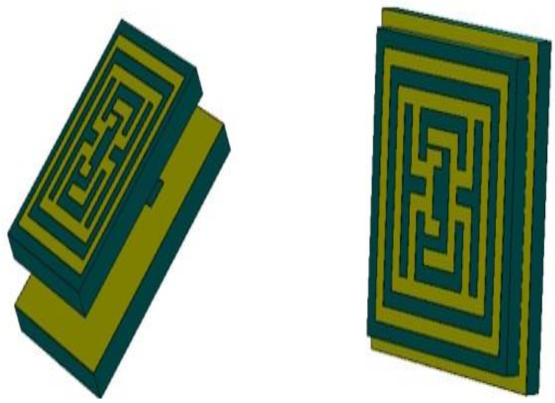


Fig. 7. MTM placed backside of the antenna

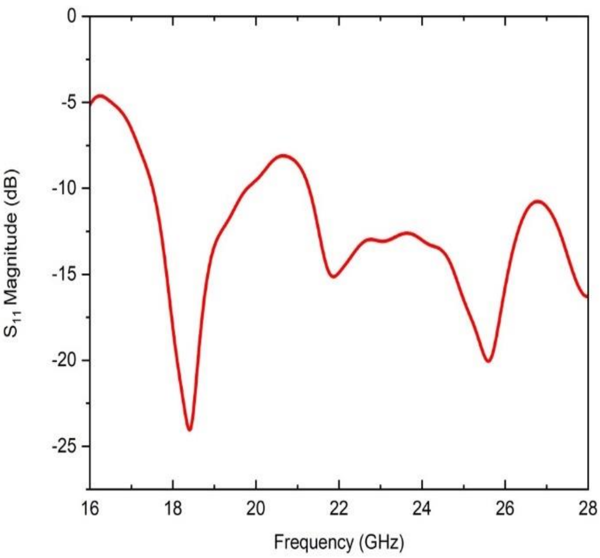


Fig. 8. S11 parameter of antenna with metamaterial loaded (front) antenna

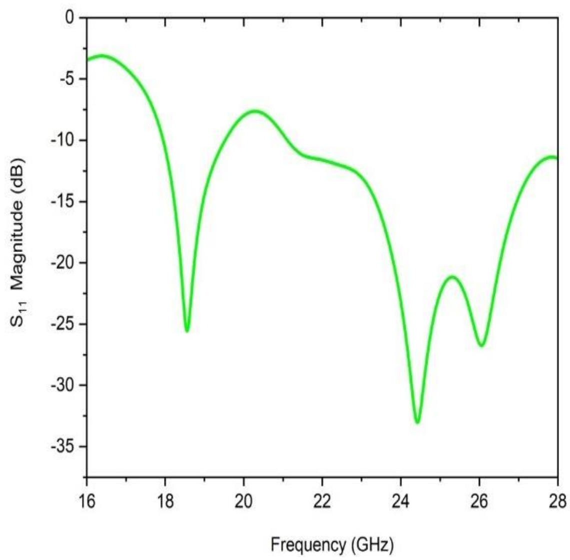


Fig. 9. S_{11} parameter of antenna with metamaterial loaded (back) antenna

3. Result Analysis

The representation in Figure 10 shows the simulated reflection coefficient S_{11} (dB) for the rectangular MPA and when the split square-shaped MTM loaded with MPA both at the front side and the backside. It is observed that the rectangular MPA displays resonance at frequencies of 18.57 GHz and 25.24 GHz.

The gain was found for the unloaded antenna 4.52 dBi and 2.82 dBi respectively at the resonant frequency of 18.57 GHz and 25.24 GHz. It is significant to note that when the split square-shaped MTM is positioned on the front side, the gain for both resonant frequencies decrease to 0.408 dBi and 0.403 dBi respectively. Conversely, when the MTM is positioned on the backside of the MPA, a considerable increase in bandwidth occurs, with gains of 4.58 dBi and 3.02 dBi, respectively. A representation of the antenna gains for both the unloaded and loaded antenna is shown in Figure 11.

The improved gain of the metamaterial-loaded antenna when placed on the backside is due to factors such as enhanced constructive interference, beam steering, improved impedance matching, and reduced interference when compared to placing the metamaterial on the front side. This placement may introduce a phase delay or reflection that concentrates radiation in the desired direction, leading to higher gain.

The directivity, gain, realized gain, and bandwidth of the unloaded and loaded configurations of the proposed antenna at resonant frequencies of 18.57 GHz and 25.24 GHz are compared in Tables 3 and 4. Integrating the unit cell metamaterial leads to a significant improvement in the antenna's gain. By integrating the unit cell metamaterial behind the antenna surface, notable enhancements are observed in the directivity, gain, bandwidth and realized gain of the proposed antenna.

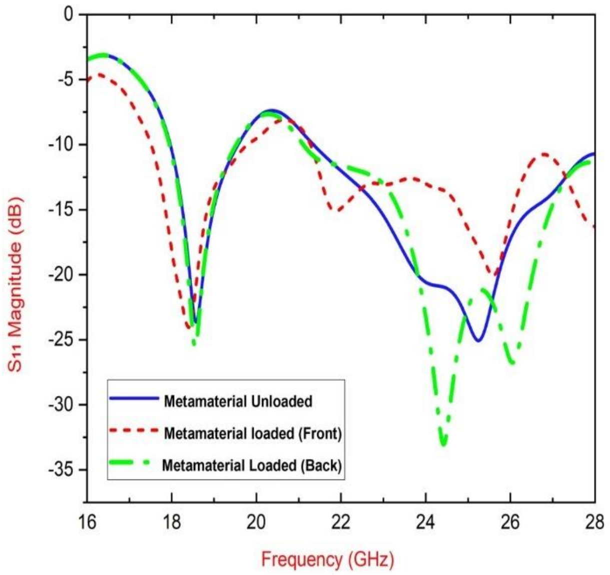


Fig. 10. Comparison of simulated reflection coefficient (S_{11}) of the rectangular MPA and split square-shaped MTM loaded rectangular MPA

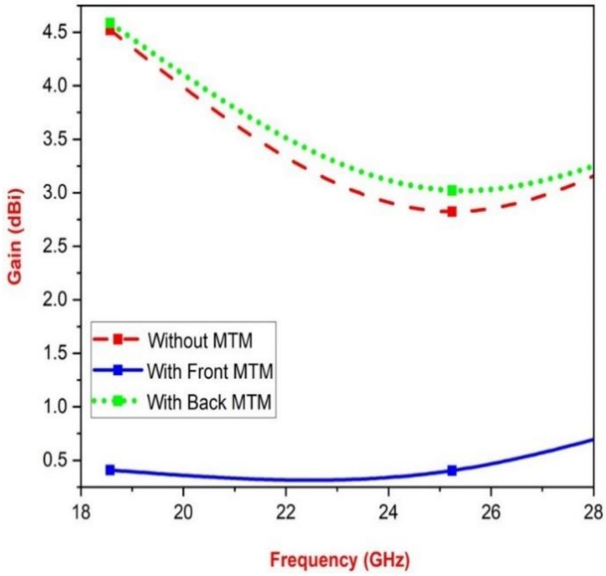


Fig. 11. Comparison of simulated MPA gain and MTM-loaded MPA

Table 3
Comparison between metamaterial loaded antenna and unloaded antenna for 18.57 GHz

Parameter	Unloaded antenna	Loaded (front) antenna	Loaded (back) antenna
Frequency (GHz)	18.57	18.57	18.57
Directivity (dBi)	9.56	7.35	9.71
Gain (IEEE) (dBi)	4.52	0.408	4.58
Realized gain(dBi)	4.50	0.37	4.57
Bandwidth (GHz)	1.62	2.23	2

Table 4
Comparison between metamaterial loaded antenna and unloaded antenna for 25.24GHz

Parameter	Unloaded antenna	Loaded (front) antenna	Loaded (back) antenna
Frequency (GHz)	25.24	25.24	25.24
Directivity (dBi)	7.28	6.97	7.46
Gain IEEE (dBi)	2.82	0.403	3.02
Realized gain (dBi)	2.81	0.332	3.00
Bandwidth (GHz)	6.64	2.11	6.72

The simulated radiation pattern corresponding to the proposed resonant frequencies has been depicted in Figure 12 and 13 in 2D representation. These illustrations include detailed representations of the radiation pattern from various angles. The unloaded antenna design showed directivity values of 9.56 dBi at 18.57 GHz and 7.28 dBi at 25.24 GHz. When a unit cell metamaterial was placed in front of the antenna the directivity values were found 7.35 dBi and 6.97 dBi at 18.57

GHz and 25.24 GHz, respectively. The MTM was placed back of the antenna to simulate the radiation pattern at the proposed resonant frequencies. This representation is shown in a two-dimensional style. Directivity values of 9.71 dBi and 7.46 dBi at frequencies of 18.57 GHz and 25.24 GHz, respectively. Figure 12 depicts the 2D radiation pattern for unloaded MPA, and when the MTM was placed both at the front and the backside of MPA at 18.57GHz. Whereas Figure 13 represents the 2D radiation pattern of 25.24GHz frequency for unloaded MPA, and when the MTM was placed both at the front and the back side of MPA.

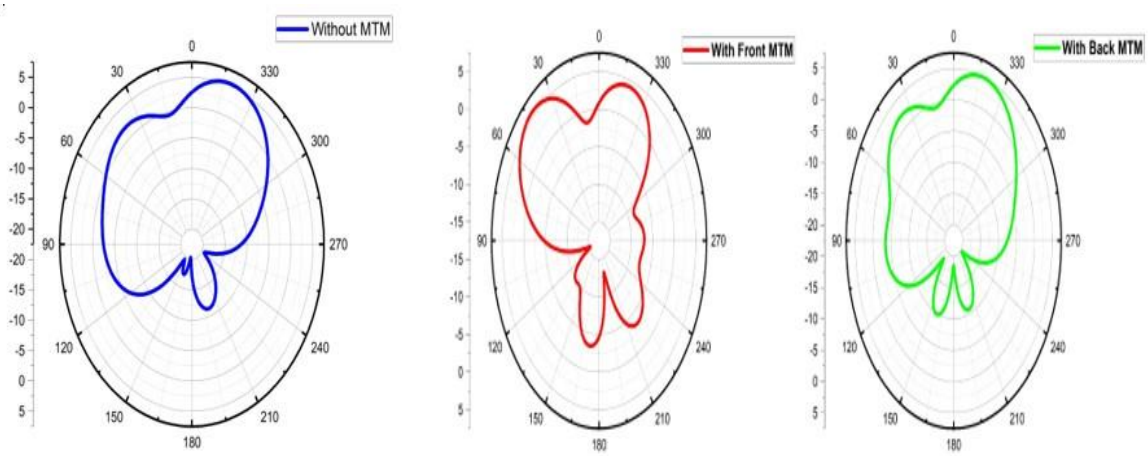


Fig. 12. Comparison of 2D radiation pattern of unloaded antenna and MTM loaded antenna for 18.57GHz

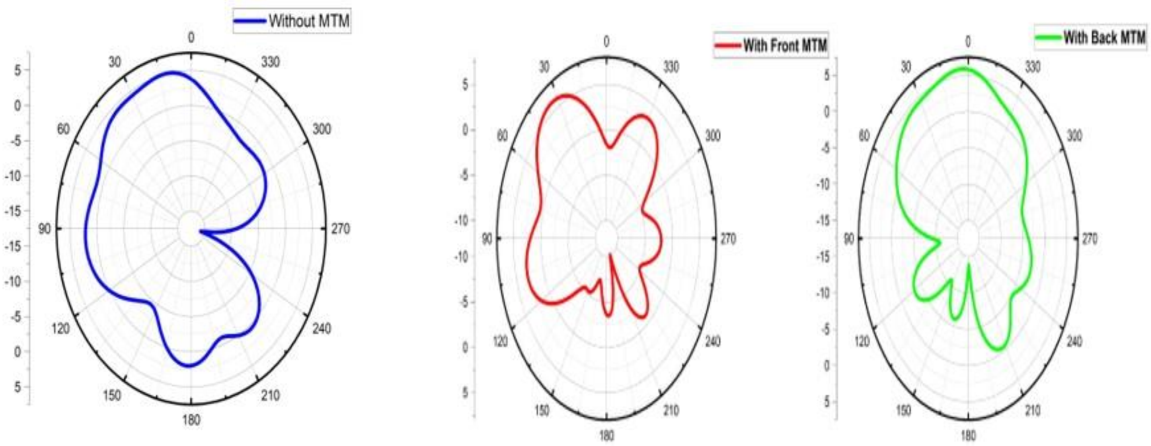


Fig. 13. Comparison of 2D radiation pattern of unloaded antenna and MTM loaded antenna for 25.24GHz

By incorporating the metamaterial with zero-index properties into the antenna design, the directivity of the antenna is enhanced. Directivity refers to the measure of how focused the antenna's radiation pattern is in a particular direction. With the metamaterial's zero-index properties, the antenna can better concentrate and direct the radiated energy, leading to an increase in directivity. Additionally, the gain of the loaded antenna is also increased with the integration of the metamaterial. The gain represents the measure of the antenna's ability to radiate or receive electromagnetic energy in a particular direction. The zero-index metamaterial can modify the radiation characteristics of the antenna, resulting in an improved gain. This means that the antenna becomes more efficient at transmitting or receiving signals, achieving a higher gain value. Overall, by exploiting the zero-index properties of the metamaterial at resonant frequencies, the loaded antenna can experience increased directivity and gain, enhancing its performance and capabilities. A comparison of several metamaterials used in 5G applications is shown in Table 5.

Table 5
Compare between proposed antenna with other 5G antenna

[ref]	Year	Material	Size(mm^2)	Resonant frequency (GHz)	Gain (dBi)	Bandwidth (MHz)	Application
[17]	2008	FR-4	60×100	1.03,2.13	0.66, 1.74	980,2010	5G communication
[18]	2010	FR-4	80×80	2.4,3.5, 5.8,	2.33,3.14,2.89	---------------	5G communication
[19]	2023	FR-4	15×16	5.5, 5.8	1.34	2493,2935	5G communication
[20]	2021	FR-4	46×61.2	10.9	3.5	304	5G communication
[21]	2020	Rogers RT 5880	20.24×22.61	28.46	8.71	4470	5G mm wave communication
[22]	2022	Kapton polymide (lossy)	5.12×5.12	28	6.46	1680	5G communication
[23]	2019	Rogers RT/duroid 5880	35×40	3.5	7.43	100	5G communication
[24]	2022	------------	60×60	4.74	9.45	120	5G application
Proposed Antenna	2023	FR-4	20×20	18.57,25.24	4.58,3.00	2000,6720	5G communication

4. Conclusion

A rectangular MPA integrated with a split square shape MTM has been presented. The proposed antenna utilizes a split square shape MTM to improve antenna parameters through the use of metamaterials in antenna design. The focus of the study is an antenna with a metamaterial-integrated surface that operates between 16 and 28 GHz for 5G communication. The antenna shows the formation of dual resonant frequencies at 18.57 GHz and 25.24 GHz with the addition of metamaterials. The proposed design presented an advanced unit cell metamaterial that demonstrates exceptional characteristics of near-zero permittivity at frequencies of 18.57 GHz and 25.24 GHz, as well as permeability at frequencies of 17.98 GHz and 25.21 GHz. Metamaterial integration can take place within the antenna construction, placed strategically in front of and behind the antenna to meet specific performance criteria. The antenna's gain and directivity significantly increase with the use of metamaterials with zero index property, and its bandwidth and radiation efficiency also improved. The proposed antenna is compact in size compared to other antennas which also use for 5G communication. Furthermore, this designed antenna demonstrates wider range of frequency in comparison with other 5G applications. These outstanding characteristics place the proposed antenna as a competitive option for numerous applications, such as 5G communication systems, radar systems, and satellite communications.

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