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Novel Antenna-Based Metamaterial Structure with Slotted and Parastic Patches For 5G- Sub 6 Ghz Applications

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ABSTRACT

Keywords:

MTM; reconfiguration; Beam splitting; the Hilbert; Taconic FR-30

This paper proposes multiband antenna-based Metamaterial for beam splitting and gains improvement. Here, the focus is on developing the smart antenna using a Metamaterial technique for modern wireless applications. The proposed antenna consists the patches, the first one has a square shape placed on a Taconic FR-30 substrate. At the end of the design process, the proposed patch seems U-shaped to ensure the antenna beam is splitting at the desired frequency bands. In addition, the capacitive coupling is used for exciting the second patch, whereas the first patch is excited by conduction with a 50 Ω discrete port. Furthermore, a metasurface layer is designed and mounted on the second patch as a superstrate to increase the antenna gain toward the bore-sight direction. The results show a maximum gain of 8 dBi at 4.2 GHz with maximum dimensions of 280x 280mm². Moreover, this antenna operates at additional frequency bands (1.9 GHz, 3.3 GHz, 3.8 GHz, 4.4 GHz, 4.5 GHz and 5.9 GHz), with a minimum reflection coefficient of -18.5db, -11.1db, -25.2db, -25.2db -17.4 dB and -11.5 dB, respectively. The proposed antenna is designed and analyzed using the CST MWS simulator.

1. Introduction

Wireless communications are rapidly facing the challenge of providing high-speed services with low noise, which constitutes a challenge and a motivation for the growth of communications to the next generation to keep up with the development and provide the necessary requirements [1,2]. 5G is introduced to deliver maximum throughput and high gain with the ability to beamform to reduce

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noise and adapt to the changing environment. As a result, the 5G system is incorporated with arrays of multiple antennae to satisfy the requirements of high capacity and efficiency as the antenna arrays, and multi-beam antennas can increase the system capacity and cover a wide range, in addition, to reducing the overall cost [3]. These system characteristics will be very advantageous for the lower band of the 5G system. However, the array structures at the lower frequency bands are characterized by their big size, which makes it inconvenient for the 5G environment. Therefore, many researchers have used metamaterials to provide low-profile [4], minimized antennas with high-gain and beam-steerable capabilities. As a result, antenna arrays have been used as a source for multi-beam antennas which has the disadvantage of large size, especially in the designs characterized by multilayer structures, where a Gap exists between the radiating patch and the metamaterial. Therefore, a single antenna capable of producing multiple beams with scanning ability is very needed in the 5G system [5]. Several techniques have been used to obtain a multi-beam antenna; for example, a digital coding metasurface is used to split the main beam into two lobes. However, splitting the main beam into more than two lobes requires complex digital coding [6].

This paper presents a reconfigurable antenna based on PIN diodes for beam-switching applications and dual-band operations with split beams depending on the PIN bias voltage. The results for the proposed design show good impedance matching and gain control over the operated bands [7]. The purpose of the proposed design is to create a compact antenna with a low-profile capable of splitting the beam into multiple beams to reduce the interference from the obstacle and surrounding buildings, in addition, to increasing the traffic capacity and reducing the number of antennas necessary to provide multiple beams thus increase the efficiency of 5G system in urban areas [8].

2. Methodology

2.1 Antenna Design

The following Eq. (1) can be used to determine the length L and width W of any rectangular patch antenna [9].

$$W = \frac{c}{2f_0 \sqrt{\frac{\epsilon_r + 1}{2}}} \quad (1)$$

where ϵ_r denotes the dielectric constant and f_0 is the resonance frequency. The radiation propagates through the atmosphere and partially penetrates the substrate to reach the ground. Because the dielectric constants of the air and the substrate are different from each other, it is necessary to consider an effective dielectric constant (ϵ_{eff}), which is determined using the provided in Eq. (2) [9].

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + \frac{12h}{W} \right]^{-1/2} \quad (2)$$

where h represents the substrate thickness. The patch length is determined by utilizing the following Eq. (3) [9].

$$L = \frac{c}{2f_0\sqrt{\epsilon_{eff}}} \quad (3)$$

Figure 1 shows the proposed structure; the design is constructed from a parasitic patch represented by a third order Hilbert curve structure separated by a Gap from the main radiator and inductively coupled to it, as shown in Figure 1. A metasurface of unique shape is designed and placed directly above the parasitic patch with a specific Gap selected for improving the overall performance [9, 10]. A transonic FR-30 substrate with $\epsilon_r = 3$, $\tan\delta = 1$ is selected for the design.

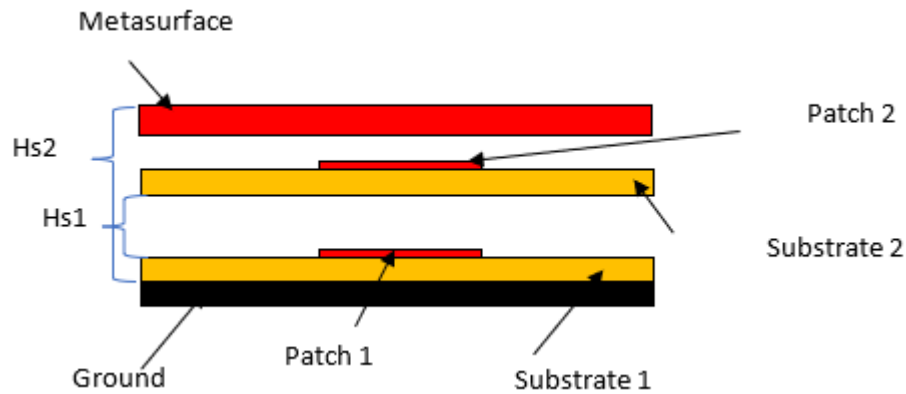


Fig. 1. Side view of design antenna

2.1.1 Design the patch antenna

First, a regular microstrip patch antenna with a rectangular shape is designed and simulated; next, slots are etched from the patch sides to create irregular MPA; these slots increase the frequency resonance due to path discontinuity[11]. The design dimensions are presented in Figure 2.

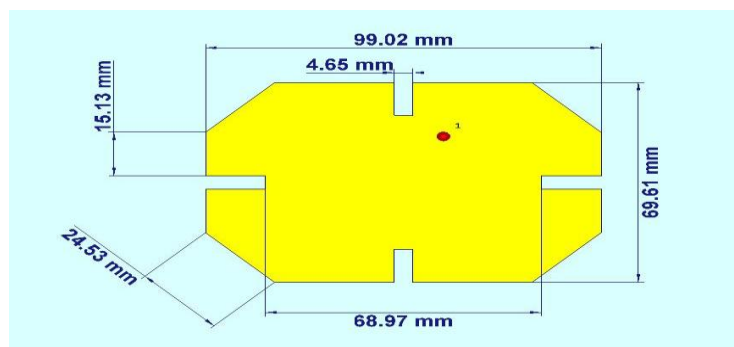


Fig. 2. The first patch design

2.1.2 The Hilbert shape design

A third order Hilbert curve structure is designed and occupies an area equal to $49.47 \times 74.79 \text{ mm}^2$, as shown in Figure 3. The fractal structures reduce the storing losses by equalizing the capacitive part to the inductive part through increases the electric length of the design structures, as well as its importance in providing multiple resonance[12]. in this design, The Hilbert curve act like a parasitic patch that inductively coupled to the main radiator and reradiate the EM waves with good energy

thus increase the operated frequency range. the proposed structure is printed on a Taconic RF-30 substrate with a thickness of 1.5 mm, as shown in Figure 3[13].

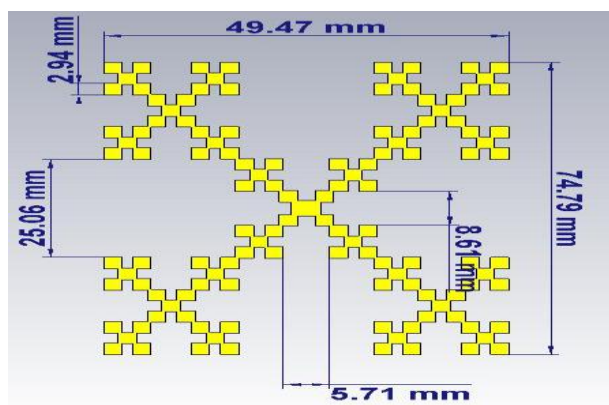


Fig. 3. The square shape design

2.1.3 The metamaterial unit cell design

Figure 4 shows the metamaterial structure. The MTM consists of two arrays with different unit cells; the first array comprises a 1D array of 5*5-unit cells, each occupying an area equal to 40mm². The next array is constructed to fill the spaces between the cells of the first array and comprises 5*4-unit cells. Each cell occupies an area of 20 mm², as shown in Figure 4. This combination provides high gain, as will be seen later [14].

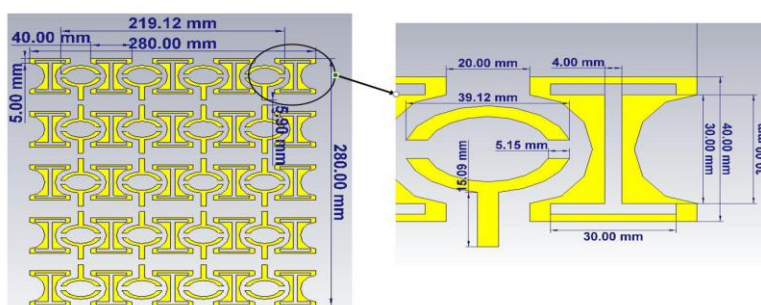


Fig. 4. The MTM structure design

To clarify the importance of the proposed patch design in getting the beam splitting property, a surface current density is calculated at 1.9 GHz for the proposed structure see the Figure 5 , it is clear from the current density that the slots play an important role in splitting the beam and create an extra resonance due to path discontinuity [13,15]. While the MTS directed the beam and reduce the sides lobes thus increase the current density and a high gain is achieved.

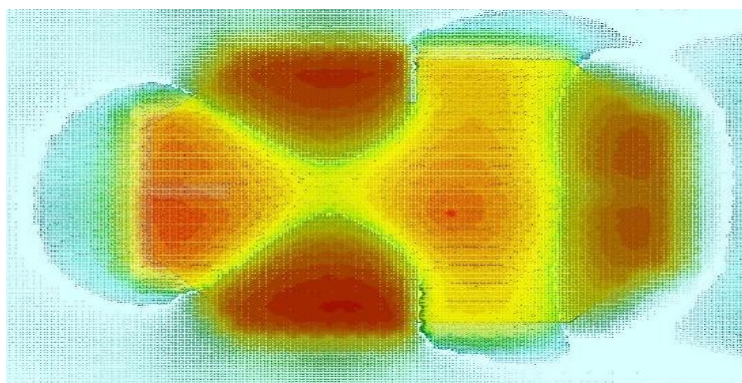


Fig. 5. The current surface for antenna at frequency 1.9 GHz

2.1.4 Metasurface with Microstrip Patch Antenna

The proposed design with MTM structure is shown in Figure 6 the impedance matching and gain are calculated for the MTM antenna design[7], and it is found that gain of 11.7 dBi and 11.1dBi at frequency 2.5 GHz and 2.6GHz is achieved.

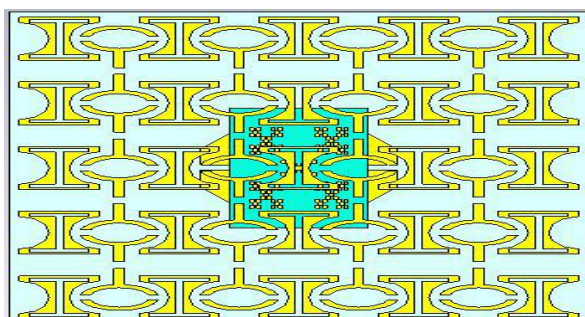


Fig. 6. The MTM with patch antenna structure

3. Results

3.1 Antenna Structure Design

To clarify the influence of the proposed antenna structure on the obtained results. The antenna is defragmented into three models; the first model represents the MPA structure only, the second model is the MPA plus the Hilbert structure, and the third model represents the proposed antenna with MTM. The models are compared in terms of s_{11} and gain spectra. Due to path discontinuity, the MPA produce a splitting in the main lobes as a result of the slots that split the radiation into two lobes. The Hilbert curve provides the extra resonance and reduces capacitive losses generated from the ground plane, thus enhancing the overall impedance, see the Table 1. In addition, it acts like a parasitic patch that reradiated the electromagnetic waves with high energy. Finally, the metamaterial directs the beam with higher energy. It reduces the back lobes, thus reducing the losses that increase the antenna directivity and, as a result, increase the overall gain, as shown in Figure 7.

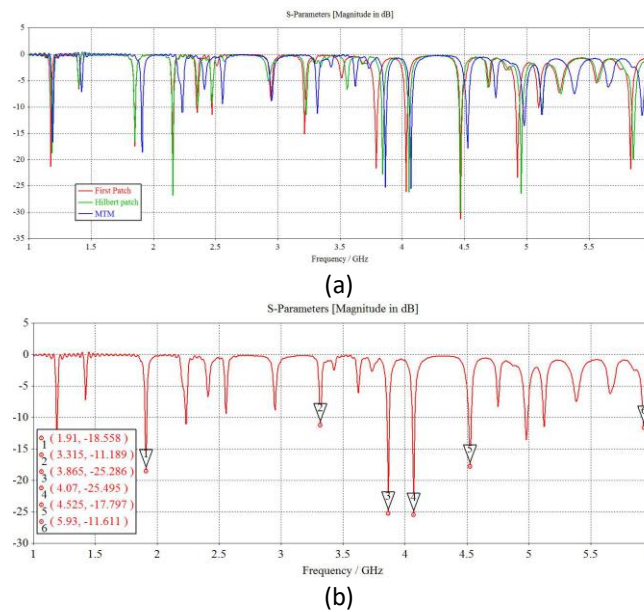


Fig. 7. The reflection coefficient (a) modeling of antenna (b) proposal antenna

Table 1

The modeling case of proposal of antenna

Parameter	Value	Parameter	Value
6.11	-0.27	1.9	First patch
6.0	-1.4	3.3	
8.6	-11.1	3.8	
6.2	-4.7	4	
7.7	-5.2	4.5	
8.9	-1.07	5.9	
1.9	-0.22	6.5	Hilbert curve
3.3	-1.1	6.12	
3.8	-22.7	6.5	Second Patch
4	-3.4	6.2	
4.5	-3.2	7.7	
10.2	-2.8	5.9	

3.2 Radiation Pattern

Figure 8 shows the radiation pattern at the resonance frequencies with the presence of the MTM structure. The antenna provides a beam split ranging from 2 lobes up to 12 lobes; this has the advantage of satisfying the 5G requirements by providing multi-beam radiation using a single antenna, resulting in low-cost infrastructure, in addition, to increase capacity, as well as using this beam to track users in the ODFM algorithms. Table I summarize the antenna resonance frequency, the gain and the impedance matching for the splitting cases.

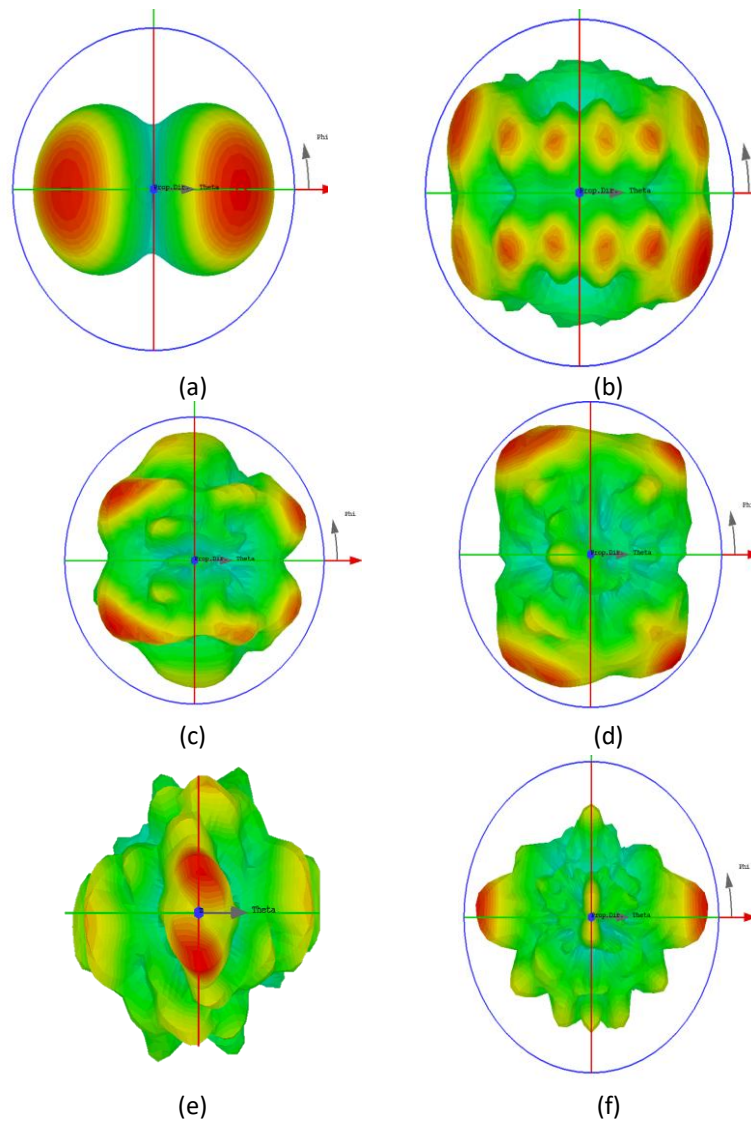


Fig. 8. the beam splitting at frequency (a)1.9 GHz, (b) 3.3GHz, (c) 3.8GHz, (d) 4GHz, (e) 4.5 GHz and (f) 5.9GHz

Table 2

The comparison of other work

Ref	Frequency GHz	Size	Max. Gain	Technique
[13]	4.95 to 5.42	65 * 65 * 4.862 mm ³	8.62	Metasurface
[16]	3.5	300*300 mm ²	2.3	super substrate
[9]	9.2	49*58 mm ²	8.8	16- Pin diodes
This work	4.5	280*280 mm ²	11.7	Patch antenna

Table 3

The result of antenna with MTM

Fr (GHz)	Reflection coefficient (dB)	Gain (dBi)
1.9	-18.5	6.84
3.3	-11.1	4.85
3.8	-25.2	6.55
4	-25.2	6.34
4.5	-17.4	11.7
5.9	-11.5	11.1

The proposed antenna is designed to achieve multiband operation, beam splitting, and gain enhancement. It features a U-shaped patch on a Taconic FR-30 substrate and incorporates a metasurface layer to improve gain. This antenna operates across multiple frequencies: 1.9 GHz, 3.3 GHz, 3.8 GHz, 4.2 GHz, 4.5 GHz, and 5.9 GHz, providing gains of up to 8 dBi and reflection coefficients ranging from -11.1 dB to -25.2 dB.

In comparison, authors in [17] explore a Mu-Near-Zero (MNZ) metamaterial antenna designed for wideband and high-gain MIMO applications targeted at 5G. Their design emphasizes high gain and wideband capabilities but does not incorporate beam-splitting or metasurface technology as seen in the proposed antenna.

The authors in [18] present a low-profile, slotted metamaterial antenna also aimed at 5G applications. Their design utilizes a bi-slot microstrip patch approach and focuses on high gain within the 5G band. However, it does not emphasize beam-splitting or support multiple frequency bands like the proposed antenna.

authors in [19] discuss a defected ground slotted patch antenna for Sub-6 GHz 5G applications. Their design uses a defected ground structure to enhance performance, focusing on slotting and ground defects for improved gain and bandwidth, but lacks the beam-splitting and multiband features of the proposed design.

Overall, the proposed antenna stands out due to its unique integration of metasurface layers for gain enhancement, its support for multiple frequency bands, and its specific beam-splitting capabilities. This makes it more complex and versatile compared to the simpler, single-band or dual-band designs found in the other studies [20-27].

4. Conclusions

This work represents a multi-beam antenna operating at various bands with good impedance matching and high gain. The proposed structure consists of three basic parts, a first patch MPA with second patch slots to create an antenna with multiple beams and a Hilbert structure inductively coupled to the main radiator to enable the antenna to work at various bands with different resonance frequencies.

Finally, a metamaterial is added on the top surface of the parasitic patch with a specified distance to increase antenna directivity and gain. The proposed structure operated at 1.9 GHz, 3.3 GHz, 3.8 GHz, 4 GHz, 4.5 GHz and 5.9 GHz with a minimum reflection coefficient of -18.5db, -11.1db, -25.2db, -25.2db, -17.4 dB and -11.5 dB respectively. Furthermore, After MTM introduction, the gain is enhanced to 6.84dBi, 4.85dBi, 6.55 dBi, 6.34 dBi, 11.7dBi, 11.1dBi, respectively.

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