

Original Article

Design and Analysis of a Hexagonal Patch Antenna with Integrated Metasurface for Satellite Applications

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Abstract - In this paper, the design, simulation, and analysis of a novel hexagonal patch antenna operating at a frequency of 10.5 GHz are proposed. The hexagonal shape of the patch is chosen for its unique geometric properties, providing improved radiation characteristics and enhanced bandwidth. The proposed antenna leverages slot characteristics to improve performance and is implemented on a cost-effective FR4 substrate. Integrating slots in the hexagonal patch structure is explored to achieve enhanced impedance matching, gain, and radiation efficiency. A unit cell metasurface is introduced on the substrate, enhancing the antenna's capabilities. The proposed antenna is analyzed using HFSS 2020 R2 software. The antenna is operational with a return loss of -31dB at 10.5 GHz, and it offers a gain of 5.3 dB with an ECC of 0.03 and a diversity gain of 9.99. The size of the proposed antenna is 26 x 19 mm, which was fabricated and tested successfully. The distinctive combination of hexagonal geometry, slot characteristics, and the FR4 substrate presents a versatile and adaptable solution, making it suitable for satellite applications.

Keywords - FR4 Substrate, Hexagonal Slot Antenna, Metasurface, Satellite Communication Systems.

1. Introduction

The need for high data rates, large channel capacities, and dependability is growing rapidly in satellite technology, earth observation, mobile communication, and radar due to the quick growth of current wireless communication systems. One of the most promising technologies for increasing the reach of terrestrial wireless communication systems is satellite communications [1, 2]. Multiple Input Multiple Output (MIMO) system implementation is a very feasible and promising technology to maximize data integrity and optimize channel efficiency. MIMO systems are best suited for achieving greater throughput, higher data rates, and enhanced dependability. MIMO technology allows for simultaneous data transmission, thus enhancing spectral efficiency by utilizing multiple antennas for both transmission and reception. Because of its adaptability and efficiency, MIMO systems are a good fit for a variety of applications, including current broadband systems and wireless communication networks where resilience, throughput, and dependability are critical [3]. Enhanced data speeds, stronger connection stability, more spectrum efficiency, and resistance against interference and fading are just a few of the main advantages that MIMO technology provides. Because of these benefits, MIMO is especially appealing for satellite communication applications, where delivering high-speed data, phone, and video services to remote and mobile customers requires optimum throughput and stability. Satellite communication

systems can address the increasing need for high-capacity, high-performance satellite communication services while also optimizing spectrum efficiency and performance by utilizing MIMO technology [4].

2. Literature Review

Several researchers have investigated different types of MIMO antennas for enhanced performance. Hexagonal patch antennas have been widely chosen because of their compact geometry and improved radiation characteristics. The hexagonal shape of the patch is chosen for its unique geometric properties, providing improved radiation characteristics and enhanced bandwidth. These features contribute to improved antenna performance, making hexagonal shapes suitable for various applications, especially where space constraints, frequency bandwidth, and regularity in array configurations are important considerations. Furthermore, the hexagonal patch's geometric characteristics enable resonance at several frequencies, allowing multi-band or broadband antennas to be designed to meet a variety of communication requirements. Moreover, the lack of sharp edges reduces edge effects, which leads to better antenna performance and cleaner radiation characteristics [5, 6]. The hexagonal patch presents inherent rotational symmetry, which ensures more uniform radiation patterns, making it suitable for applications requiring omnidirectional coverage [7]. Materials that are purposefully engineered to display synthetic



characteristics that are not commonly observed in nature are known as metamaterials. To obtain effective negative permittivity and negative permeability within particular frequency ranges of interest, these materials are developed with an appropriate periodic structure, frequently incorporating resonance structures [8]. At 27-32 GHz, metasurfaces have been utilized to improve isolation by up to 15 dB. With the use of metasurfaces, it may precisely regulate electromagnetic waves, changing characteristics of the antenna, including impedance matching, polarization, and radiation pattern. This facilitates the creation of compact and efficient antennas for diverse applications. Incorporating metasurfaces in antenna design enables the development of high-performance antennas with compact form factors, improved functionality, and versatility for various applications [9]. The chosen lowest distance in the study ($d = 0.2$ mm) still demonstrates very good isolation, less than 20 dB throughout the working bandwidth, fulfilling the MIMO isolation criterion. As the two antennas get farther apart, the isolation increases. The antenna exhibits high gain, efficiency, low correlation coefficient, and good radiation properties throughout the working bandwidth [10].

Incorporating a partial ground plane in antenna design offers a versatile solution with benefits including size reduction, improved performance, bandwidth enhancement, reduced back radiation, mechanical stability, and simplified installation [11, 12]. The antenna's resonance frequency decreases to 2.72GHz from 3.5GHz upon the introduction of slots on the radiating surface. Additionally, three consecutive slots are utilized to achieve antenna miniaturization. Using slots in antenna design offers several advantages; they enable size reduction without compromising performance, making antennas more compact and suitable for space-constrained applications. The introduction of slots will improve radiation characteristics, leading to directional radiation patterns with high gain and low side lobe levels [13]. An eight-open-slot MIMO antenna array with more than 17.5 dB isolation was proposed by Li et al. [14] for cell phones operating at 3.4-3.6 GHz. Additionally, it was stated that a MIMO patch antenna for smartphones with mutual coupling less than 17 dB over 3.4-3.6 GHz [15]. The Slot Antenna Array (SAA) is a single-layer antenna that operates in the X-band at 9.65 GHz and the C-band at 5.35 GHz, which is designed for efficient signal transmission in mobile communication systems. It has specific characteristics for each band. The corporate feeding technique ensures uniform excitation, enhancing performance and versatility [16].

Although previous studies have successfully employed hexagonal patches, slot loading, partial ground planes, metamaterials, and MIMO configurations, most of them focus on improving only one or two antenna parameters. Limited work has focused on the combined effect of a slotted hexagonal radiating patch integrated with a partial ground

plane on an FR4 substrate. Furthermore, achieving high isolation, wide bandwidth, high gain, low mutual coupling, and compact size simultaneously remains a significant challenge.

To address these limitations, this paper proposes a slotted hexagonal MIMO antenna with a partial ground plane and microstrip feed. In the proposed method, a hexagonal patch antenna is realized by constructing a hexagonal patch with partial ground and slot characteristics. To energize the antenna, the microstrip feeding technique is used. To achieve resonance at the desired frequency, a partial ground plane is introduced at the backside of the radiating element. The proposed antenna is made up of FR4 Substrate. The integration of slot characteristics on an FR4 substrate enhances the antenna's efficiency and widens its scope for use in modern wireless communication systems. The remaining part of this paper is organized as follows. Sections 3 and 4 cover the design technique of the proposed antenna, while Sections 5 and 6 focus on the Slotted Hexagonal MIMO antenna results and discussion. Finally, the conclusion is discussed under section 7.

3. Antenna Structure and Development

The proposed antenna's configuration is shown in Figure 1. The metallic radiating patch in the shape of a hexagon makes up the antenna structure that is explained. In Figure 1, the antenna is made up of 1 mm thick copper patches mounted on FR4 substrate with a dielectric constant between 3.8 and 4.8, a loss tangent between 0.02 and 0.04 mm in height, and a total dimension of 26 x 19 mm. This arrangement offers a useful compromise between simplicity of manufacture, affordability, and performance and is frequently utilized in antenna design. There are 50 Ω microstrip lines feeding into the patches. The suggested structure is then realized by engraving five circular slots, an H slot, and two U slots on the antenna. The thickness of the rectangular slots is 0.5 mm, while the diameter of the circular holes is $d = 0.55$ mm. The antenna's capabilities are further enhanced by the hexagonal patch's incorporation of slotted features, which provide precise control over electromagnetic waves. The antenna's response to various slot shapes contributes to increased isolation and bandwidth. It is important to remember that the U, H, and circular slots were chosen after careful examination of the patch's surface currents and the impact of various slot kinds on the antenna coupling. Because of this additional surface current reduction, the investigated slot shapes show superior coupling reduction than the others. The integration of slot characteristics on an FR4 substrate enhances the antenna's efficiency and widens its scope for use in modern wireless communication systems. Figure 2 shows the proposed Hexagonal MIMO antenna patch dimension and its corresponding 3D view. Table 1 shows the dimensions of the proposed Hexagonal MIMO antenna

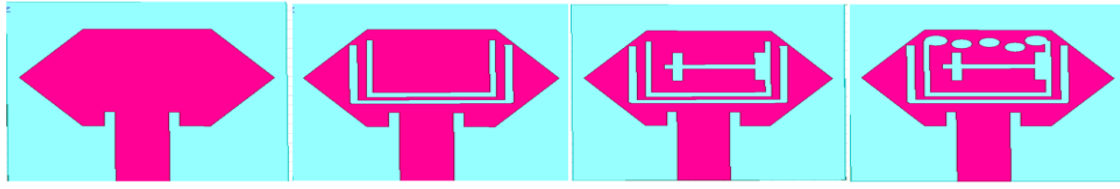


Fig. 1(a) Step 1 - Hexagonal patch antenna, (b) Step 2 - Hexagonal patch with U- slot, (c) Step 3 - Hexagonal patch with H-slot, and (d) Step 4 - Proposed antenna.

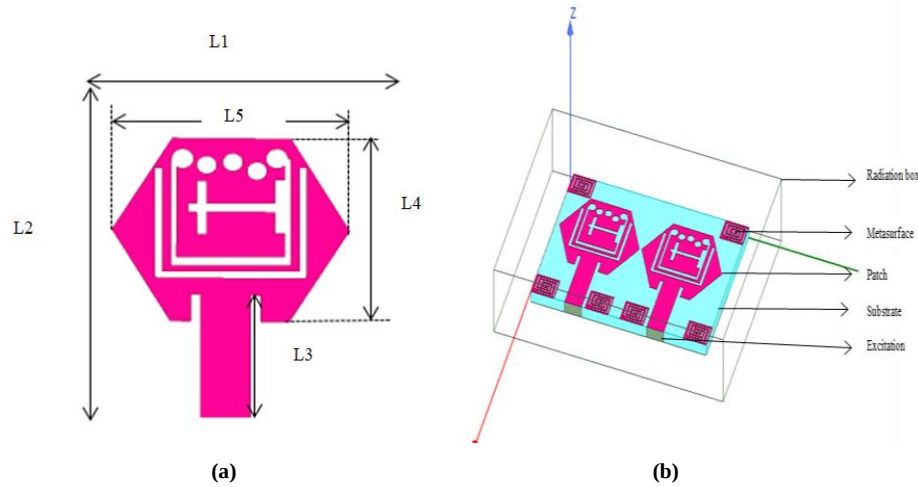


Fig. 2 Proposed Hexagonal MIMO antenna (a) Patch dimension, and (b) 3D view.

Table 1. Dimensions of the proposed Hexagonal MIMO antenna

Parameters	Value	Parameters	Value
L1	13mm	L5	11.8mm
L2	19mm	U Slot	6mm x 6mm x 6mm
L3	7.3mm	H Slot	3mmx4.5mmx3mm
L4	10.2mm	Circular Slot	D = 0.55mm

4. Antenna Design and Evolution

To showcase the design approach, two reference Antennas, Single port hexagonal antenna and Dual port hexagonal MIMO antenna, serve as a starting point. Single port hexagonal antenna (as depicted in Figure 4(a)) is initially a slotted hexagonal antenna. The antenna construction is made up of a metallic radiating patch with a hexagonal form on one side, called the dielectric substrate, and a metallic ground plane on the other.

The selected substrate material is FR4. Because of its extensive industry use, excellent electrical insulation, predictable dielectric characteristics, ease of production, and low cost, FR4 substrate is a desirable choice for antenna design. The relative permittivity, thickness and loss tangent of FR4 substrate are 4.4, 1 mm and 0.02, respectively.

The integration of slots in the hexagonal patch structure is to achieve enhanced impedance matching, gain, and radiation efficiency. The microstrip line model is used to feed the antenna. The proposed structure is then realized by

engraving five circular slots, an H slot, and two U slots on the antenna. The antenna has been designed with a partial ground structure (as depicted in Figure 3(b)) to improve the performance of the antenna. To enhance the gain and return loss, dual port hexagonal MIMO antenna (as depicted in Figure 4(b)) is engineered by replicating Single port hexagonal antenna with a separation distance of 0.3mm. This results in a slotted hexagonal MIMO antenna configuration, enhancing both gain and return loss properties.

These benefits of dual-port hexagonal MIMO antenna make it particularly well-suited for satellite applications. Essentially, dual port hexagonal MIMO antenna represents an upgraded iteration of Single port hexagonal antenna. In order to maximize the antenna's overall performance, a metasurface is added to the patch of the simulated antenna (as depicted in Figure 4(c))-this addition of a metasurface results in a significant enhancement of performance characteristics by manipulating electromagnetic waves. The metasurface contributes to improved antenna tunability, radiation efficiency, and impedance matching, thereby maximizing

overall performance. This integration of a metasurface represents a strategic enhancement to the antenna design, ensuring its adaptability and effectiveness across various

communication scenarios. The design of the metasurface and partial ground are illustrated in Figure 3(a) and Figure 3(b), respectively.

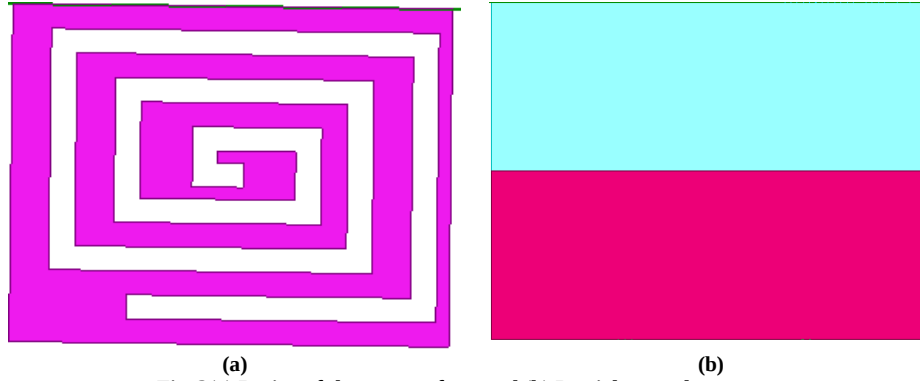


Fig. 3(a) Design of the metasurface, and (b) Partial ground structure.

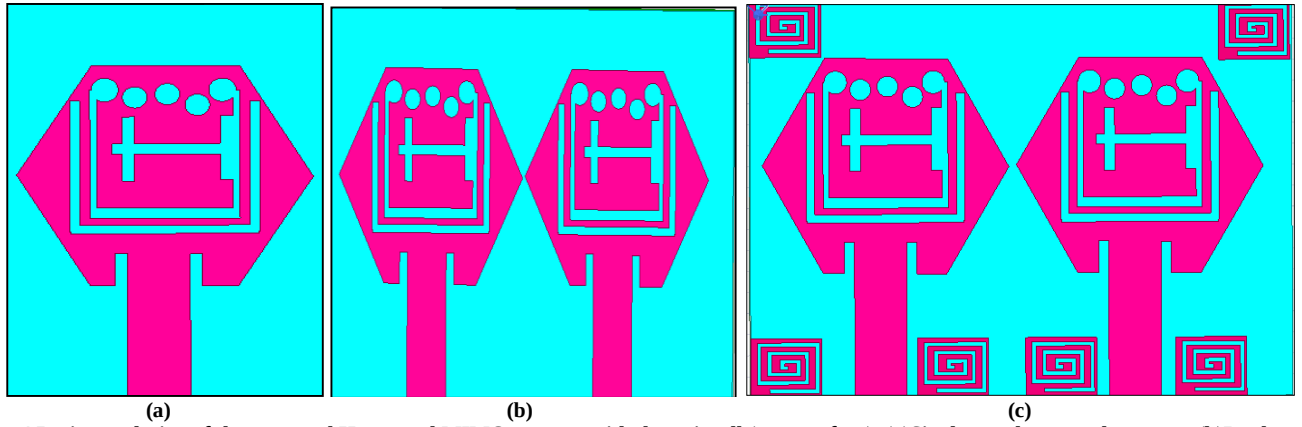


Fig. 4 Design evolution of the proposed Hexagonal MIMO antenna with the unit cell (metasurface), (a)Single port hexagonal antenna, (b)Dual port hexagonal MIMO antenna, and (c) Proposed Antenna.

5. Design Equation of Hexagonal MIMO Antenna

The radius of the hexagonal patch is as follows,

$$a_h = \frac{A}{\sqrt{\left\{ \frac{1+2h}{\pi \epsilon_r F} \left[\ln \left(\frac{\pi A}{2h} \right) + 1.7726 \right] \right\}}} \quad (1)$$

Where,

$$A = \frac{8.791 \times 10^9}{f_0 \sqrt{\epsilon_r}} \quad (2)$$

The length of the hexagonal patch is as follows,

$$l = \sqrt{\left\{ \frac{2\pi a_h^2}{3\sqrt{3}} \right\}} \quad (3)$$

The height of the hexagonal patch is as follows,

$$L = \sqrt{3}a_h \quad (4)$$

6. Results and Discussion

The simulation and measurement results of the S parameters for Single port hexagonal antenna, dual-port hexagonal MIMO antenna, and the proposed antenna are presented in the Figure. 5. These results offer valuable insights into the performance characteristics of each antenna configuration. An extensive understanding of the effects of design alterations and additions on antenna performance is made possible by the comparison of S-parameter data between the single-port hexagonal antenna, dual-port hexagonal MIMO antenna, and the proposed antenna.

Figure 6 illustrates the simulated gain of the proposed antenna, achieving a gain value of 6.3 dB. As compared to the single-port hexagonal antenna, the dual-port hexagonal MIMO antenna has an improvement in gain. The VSWR of the proposed antenna is shown in Figure 7. The proposed method achieves a VSWR value of 1.05, which signifies an exceptional match between the antenna and its connected transmission line or system.

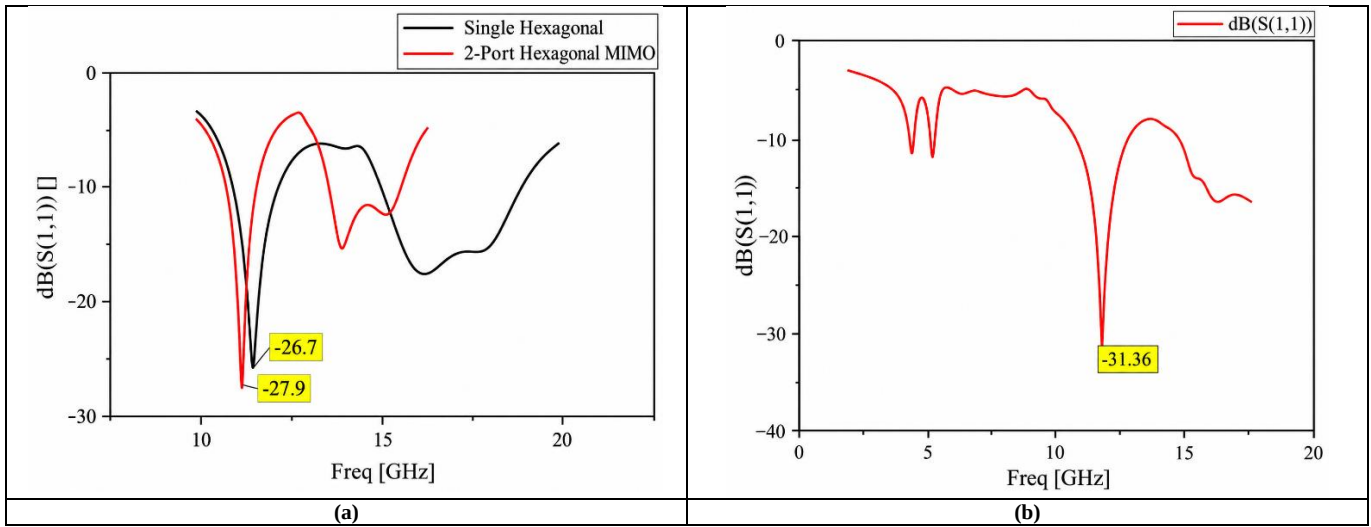


Fig. 5 S-plot (a) Comparison of Single port hexagonal antenna, and Dual port hexagonal MIMO antenna, and (b) Proposed Antenna.

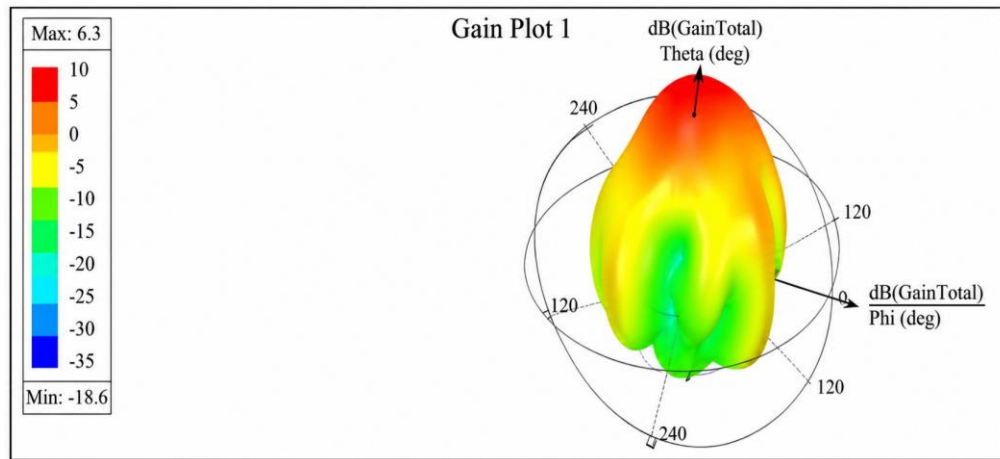


Fig. 6 Gain of Proposed antenna

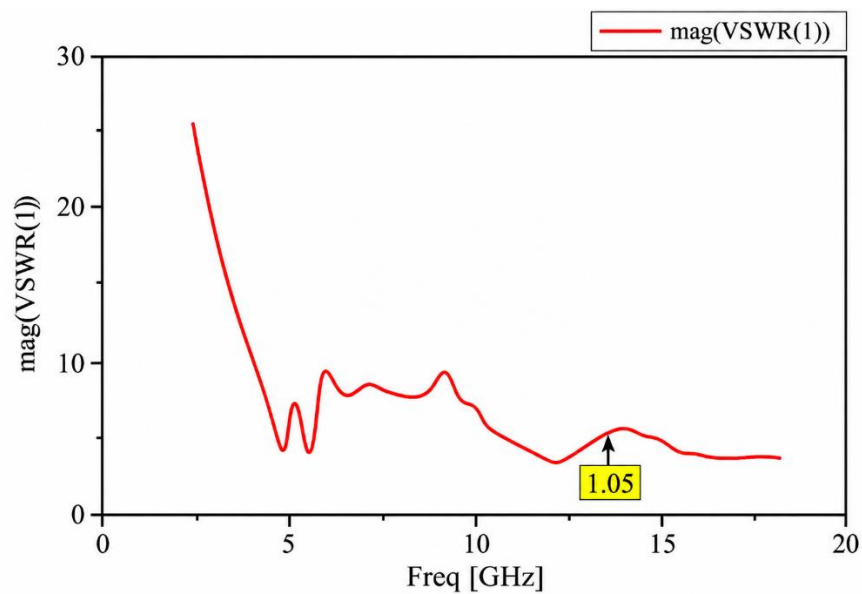


Fig. 7 Voltage standing wave ratio of the proposed antenna

Table 2. Performance comparison of the proposed antenna in various stages

Design	Frequency	Return Loss	VSWR	GAIN
Single Port Hexagonal Antenna	11.5 GHz	-26 dB	1.31	1.7 dB
Dual Port Hexagonal MIMO Antenna	11.6 GHz	-26 dB	1.12	4.7 dB
Proposed Antenna	10.5 GHz	-31 dB	1.05	5.3 dB

7. Fabricated and Simulated Results

Performance analysis has been done using High Frequency Structure Software (HFSS) v20 for the recommended antenna. The Agilent E5071C Vector Network Analyzer is utilized for measurements under an anechoic chamber. The antenna parameters for the working frequency range of 800 MHz to 18 GHz can be measured by the anechoic chamber, which has dimensions of 5 m × 3 m × 2.6 m. Important antenna parameters such as radiation pattern, bandwidth, gain, Voltage Standing Wave Ratio (VSWR), and reflection coefficient (S11) are covered in this section. FR4 substrate is used in the construction of the suggested antenna. The FR4 substrate has a relative permittivity of 4.4 and a thickness of 1 mm. Figure 9 (a) and (b) show the front and back views of the fabricated antenna, respectively. The

antenna configuration in an anechoic chamber is depicted in Figure 9(c). Figure 10(a) and (b) show the comparison of the simulated and measured reflection coefficient and VSWR. The developed antenna has a resonance frequency of 10.5 GHz and a return loss of -31.3 dB in simulation.

During measurement, it is found that the suggested hexagonal MIMO antenna resonates at 9.3 GHz with a return loss of -34.5 dB across the frequency range. The measured VSWR 1.23 across the operating bands shows that the impedance of the antenna and the microstrip line are well matched. Figures 11(a) and (b) represent the proposed antenna's radiation pattern in the E- and H-planes, respectively. The antenna exhibits an omnidirectional pattern in the E and H planes at the operating frequencies.

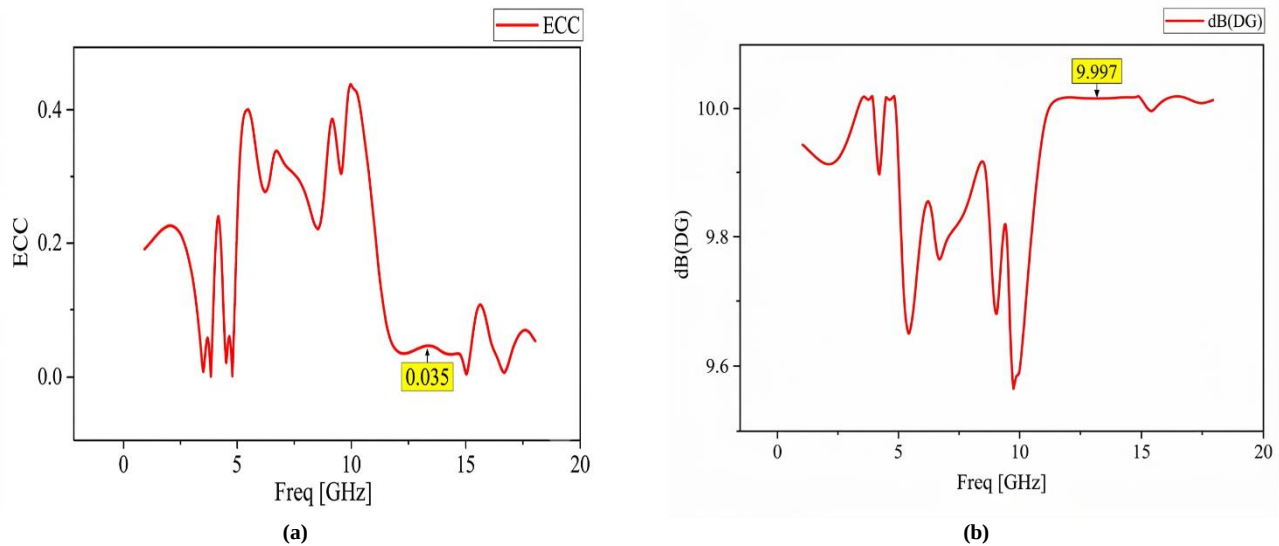


Fig. 8(a) Envelope Correlation Coefficient of the proposed antenna, and (b) Diversity gain of the proposed antenna.

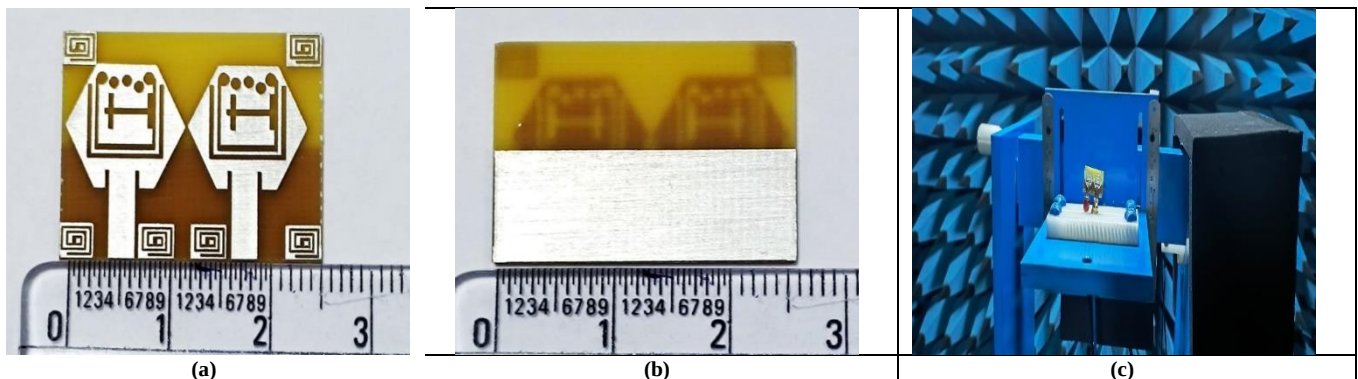


Fig. 9(a) Front view of fabricated antenna, (b) Back view of fabricated antenna, and (c) Fabricated antenna in anechoic chamber.

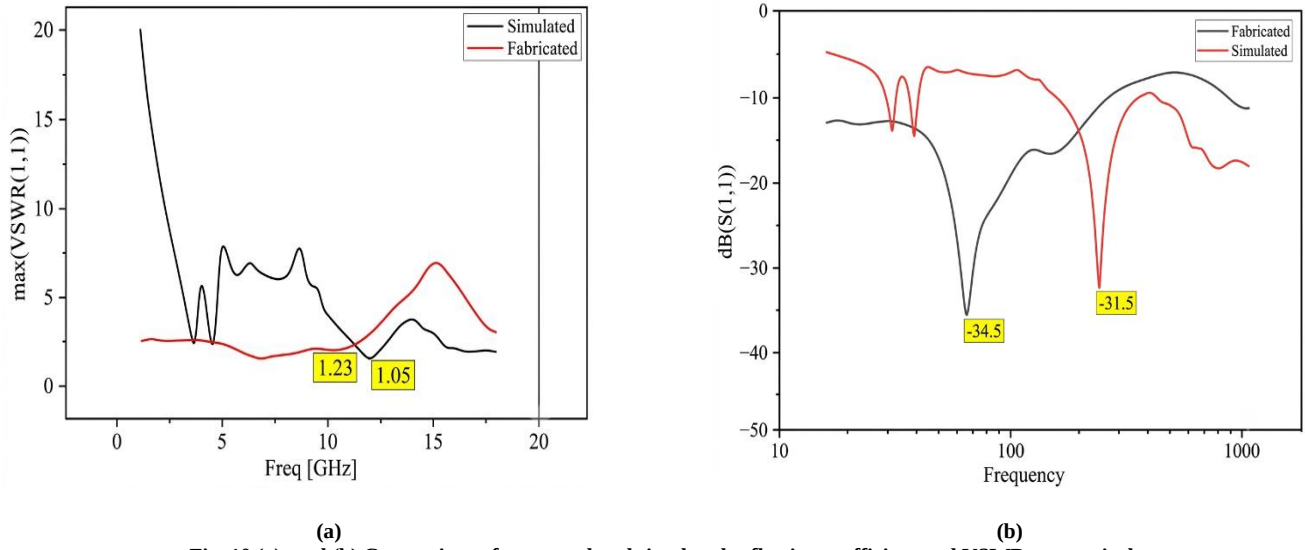


Fig. 10 (a), and (b) Comparison of measured and simulated reflection coefficient and VSWR, respectively.

From Table 4, it is evident that the proposed antenna achieves increased gain and enhanced return loss, even in its miniature size, which renders it highly suitable for satellite communication applications. The integration of FR4 substrate

in the antenna design not only makes it cost-effective but also simplifies the fabrication process. The results of the proposed antenna support the use of the design modifications and show enhanced performance compared to the other antenna designs.

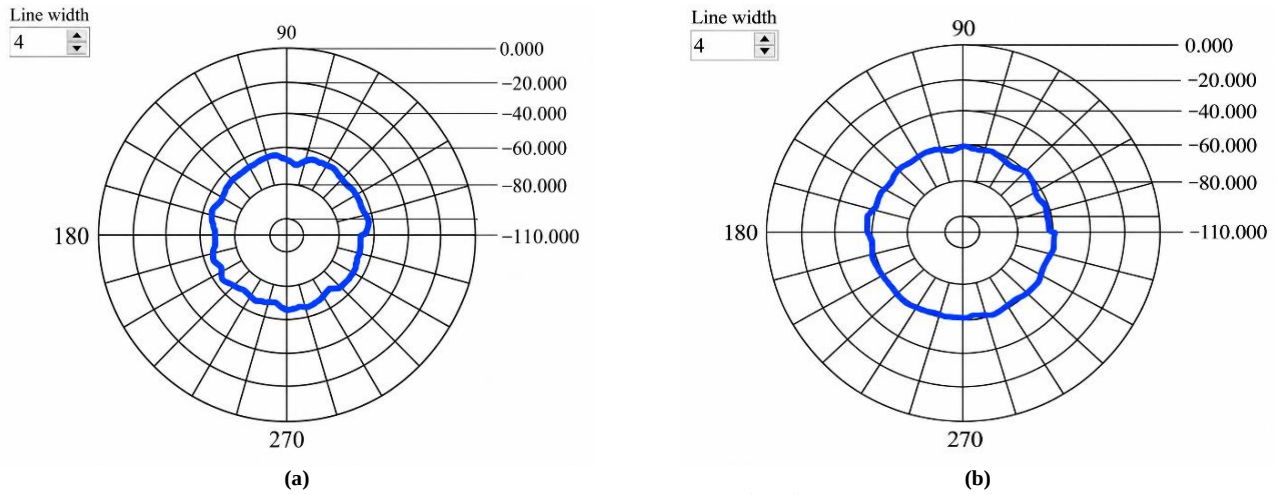


Fig. 11 (a) and (b) represent the E and H planes of the fabricated antenna.

Table 3. Performance comparison between the stimulated and fabricated antenna

Antenna	Frequency	VSWR	Return loss	Gain
Simulated Antenna	10.5 GHz	1.05	-31 dB	5.3 dB
Fabricated Antenna	9.33 GHz	1.23	-34 dB	4.4 dB

Table 4. Performance comparison of the proposed antenna with the literature

Existing antenna	Dimensions(mm)	Substrate	Resonance frequency	Gain
SIGW MIMO antenna [2]	1.5 x 1.5	Rogers 3850	13.3-13.8 GHz	9dB
X-Band horn antenna [8]	6.9 x 4.5	-	7 - 9 GHz	1dB
Wideband MIMO antenna [10]	19 x 12	Rogers T5870	28GHz`	7.5dB
X conformal SAA [16]	130 x 80 x 0.8	FR4 substrate	9.65GHz	13.2dB
Proposed Antenna	19 x 26 x 1	FR4 Substrate	10.5GHz	5.3 dB

8. Conclusion

In conclusion, this paper offers an analysis and design of a MIMO antenna with hexagonal slots that demonstrates significant advancements in high-frequency antenna technology. By integrating a unit cell metasurface, slotted features, and the geometric advantages of the hexagonal patch, the proposed antenna offers excellent impedance matching, high gain, good return loss, and enhanced performance characteristics.

The proposed antenna is fabricated and measured. In conclusion, the fabricated antenna is operational with a return loss of 9.3 GHz at -31dB, it offers a gain of 4.4 dB with ECC of 0.03 and diversity gain of 9.99. The antenna exhibits an omnidirectional pattern in the E and H planes at the operating

frequencies. The results of the proposed antenna support the use of the design modifications and show enhanced performance compared to the other antenna designs.

The integration of slot characteristics on an FR4 substrate enhances the antenna's efficiency and widens its scope for use in modern wireless communication systems. This antenna is a fantastic choice for use in modern communication systems because of its tiny size, powerful gain, and outstanding impedance matching, which emphasize its potential for satellite applications.

Conflicts of Interest

"The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper."

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