I.J. Wireless and Microwave Technologies, **2024, 5, 44-58**
Published Online on October 8, 2024 by MECS Press (http://www.mecs-press.org/)
DOI: 10.5815/ijwmt.2024.05.04

Design and Analysis of Microstrip Patch Antennas with Polygonal and Rectangular Defected Ground Structures for Sub-6GHz Applications

Padmasree Ramineni*
Department of ECE, Rajiv Gandhi University of Knowledge and Technologies, Basar, Telangana, 504107, India
E-mail: r.padmasree3@gmail.com
ORCID ID: https://orcid.org/0009-0006-2351-7274
*Corresponding Author

Abhinay Nimmala
Department of ECE, Rajiv Gandhi University of Knowledge and Technologies, Basar, Telangana, 504107, India
E-mail: abhinaynimmalaa@gmail.com
ORCID ID: https://orcid.org/0009-0006-9843-8554

Received: 25 May, 2024; Revised: 28 June, 2024; Accepted: 26 July, 2024; Published: 08 October, 2024

Abstract: Microstrip Patch Antennas (MPAs) play a critical role in modern wireless communication systems due to their compact size, easy integration, and capability to ensure reliable communication across wide frequency ranges. This paper introduces enhanced designs of rectangular MPAs aimed at overcoming the narrow bandwidth limitation commonly found in traditional designs. Three innovative configurations are proposed: one featuring a simple rectangular slot on the ground plane, another integrating polygonal Defected Ground Structures (DGS), and a third utilizing rectangular DGS. These antennas are optimized at a frequency of 4 GHz using High Frequency Structural Simulator (HFSS) software to significantly improve antenna performance. The MPA without DGS showed a return loss of -21.124 dB at a resonant frequency of 4 GHz, with a Voltage Standing Wave Ratio(VSWR) of 4.8038 and a gain of 3.88 dBi. In contrast, the MPA with Polygonal DGS exhibited significant improvements, achieving a return loss of -26.87 dB at a resonant frequency of 4.1 GHz, along with a VSWR of 1.3721 and a gain of 4.38 dBi. Similarly, the MPA with Rectangular DGS demonstrated superior characteristics, with a return loss of -27.08 dB, resonance at 3.825 GHz, a VSWR of 1.4399, and a gain of 4.00 dBi. These results underscore the effectiveness of DGS in broadening the bandwidth and improving the performance of MPAs for applications below 6 GHz, making them highly suitable for next-generation wireless communication systems.

Index Terms: Antenna Performance, Bandwidth Enhancement, Defected Ground Structures, High Frequency Structural Simulator, Microstrip Patch Antennas, Sub-6GHz Applications.

1. Introduction

In recent years, advancements in microwave circuitry have been significantly driven by innovative techniques aimed at improving performance. One prominent method is the implementation of defected ground structures (DGS) [1], where intentional alterations are made to the ground plane beneath microstrip circuits. This approach optimizes the operational characteristics of microwave components without significantly altering their physical dimensions. DGS is particularly effective in addressing challenges such as narrow bandwidth, unwanted radiation patterns, and surface wave suppression, which are commonly encountered in traditional microstrip antennas. By modifying the electromagnetic properties of the structure, DGS can significantly enhance critical parameters such as gain, bandwidth, efficiency, and radiation pattern control. Engineers can strategically design the ground plane to tailor antennas for specific applications, ensuring optimal performance in diverse scenarios including mobile communication, satellite technology, radar systems, and Radio frequency identification (RFID) applications.

Microstrip Patch Antennas (MPAs) [2], consisting of a conducting patch on a dielectric substrate with a ground plane on the opposite side [3], have long been valued for their versatile design. They allow customization of specifications such as frequency range, bandwidth, and radiation pattern, making them widely applicable in mobile and satellite communications, RFID systems, and radar technology. MPAs are recognized for their seamless integration, cost-effectiveness, and straightforward manufacturing [4]. However, they face challenges in achieving adequate bandwidth and maintaining optimal radiation efficiency across different frequencies. Despite these challenges, MPAs [5] remain crucial in enabling reliable wireless communication and electronic devices, significantly contributing to advances in miniaturization and technology integration.

The integration of DGS with microstrip antennas involves embedding specific patterns or geometries into the ground plane to interact with the antenna's electromagnetic fields [6]. These engineered structures manipulate electromagnetic wave propagation, thereby improving antenna performance and mitigating undesired effects. Practical implementation often utilizes simulation tools like High Frequency Structural Simulator (HFSS) or CST Microwave Studio to refine designs and achieve desired enhancements in performance. DGS provides an effective solution to enhance microstrip antenna designs by addressing critical limitations and advancing capabilities in terms of bandwidth, radiation efficiency, and overall performance. As wireless technologies evolve, DGS [7] continues to play a vital role in optimizing the reliability and functionality of modern antenna systems.

Defected Ground Structures come in various forms, each designed to enhance antenna and microwave circuit performance [8]. Common types include:

Rectangular DGS: Simple and widely used, it consists of a rectangular slot to improve bandwidth and return loss.

Circular DGS: Circular slot to enhance bandwidth and reduce mutual coupling in antenna arrays.

Elliptical DGS: Elliptical slot for dual-band or wideband applications, offering design flexibility.

H-Shaped DGS: Two connected rectangular slots forming an "H" shape, effective for multiple resonances and harmonic suppression.

U-Shaped DGS: "U" shaped slot providing band-stop filtering to eliminate unwanted frequencies.

V-Shaped DGS: "V" shaped defect enhancing gain and bandwidth while maintaining a compact design.

Meandered DGS: Meandered slot pattern creating additional resonances, improving bandwidth, and reducing antenna size.

Spiral DGS: Spiral-shaped defect for miniaturizing antennas and improving impedance matching.

Interdigital DGS: Parallel slots creating high impedance surfaces, enhancing bandwidth and radiation efficiency.

Cross-Shaped DGS: Cross-shaped slot for multiple resonant frequencies, boosting bandwidth and overall performance.

Dumbbell-Shaped DGS: Two defects connected by a narrow slot, suppressing harmonics and improving bandwidth.

Periodic DGS: Periodic defects creating electromagnetic bandgap properties to control surface wave propagation and improve performance.

Polygonal DGS: Distinguished by its polygonal shape with a defined number of sides, employed to enhance antenna performance by improving bandwidth, minimizing mutual coupling, and optimizing radiation characteristics across various applications.

Each DGS type offers unique benefits tailored to specific performance enhancements in antenna design, making them a powerful tool in modern microwave and antenna engineering. Despite the extensive research and development in this field, there remains a significant gap in addressing the narrow bandwidth limitation in traditional MPA designs. This paper introduces advanced designs of rectangular MPAs aimed at overcoming these limitations through the integration of innovative DGS configurations, thereby providing a novel approach to enhance antenna performance and efficiency.

2. Literature Review

Microstrip Patch Antennas are crucial in modern wireless communications due to their compact size, straightforward manufacturing, and compatibility with microwave systems. Despite these benefits, MPAs often face limitations due to their narrow bandwidth. Recent research has investigated various strategies to enhance the bandwidth of MPAs, with DGS emerging as a significant technique. This review explores the latest advancements and alternative methods for increasing bandwidth, highlighting key findings from recent studies.

DGS have emerged as an important method for improving Microstrip patch antenna(MPA) bandwidth. Research by Ali et al. [9] examined the use of an Inverted-F shaped DGS to expand the bandwidth of microstrip patch antennas. Their findings indicate that this DGS configuration enhances impedance matching and reduces surface wave effects, thereby widening the operational bandwidth. This approach represents a notable advancement in overcoming the bandwidth limitations of conventional microstrip antennas.

Metamaterials and Advanced Substrates offer another effective method for increasing antenna bandwidth. Vammi et al. [10] explored the use of double-layered substrates combined with metamaterials. Their study showed that this technique leverages the unique electromagnetic properties of metamaterials to achieve significant bandwidth enhancement. Integrating these materials with advanced substrate designs provides valuable insights into overcoming bandwidth challenges in MPAs, thereby improving overall antenna performance.

Electromagnetic Bandgap (EBG) Structures also present a viable solution for boosting bandwidth. Patil et al. [11] investigated a low-profile microstrip antenna featuring an elliptical EBG structure. Their results demonstrated that the EBG structure enhances both bandwidth and polarization characteristics while maintaining a compact design. This research highlights the effectiveness of EBG structures in addressing bandwidth issues and enhancing antenna performance.

Stacked and Parasitic Patch Configurations provide another approach for bandwidth improvement. Bondarik et al. [12] introduced a gridded parasitic patch stacked microstrip array antenna designed for the 60 GHz band. Their study illustrated how stacking multiple patches and integrating parasitic elements can significantly increase bandwidth. This focus on high-frequency applications offers valuable insights into advanced antenna designs that effectively address bandwidth constraints and improve performance.

Meander Line Slot Antennas offer a novel method for addressing bandwidth limitations. Let et al. [13] developed an asymmetric microstrip-fed meander line slot antenna for 5.6 GHz applications. Their design utilizes meander line slots to effectively tackle bandwidth constraints, presenting an innovative solution for achieving broader bandwidth in specific frequency ranges. Slot and Meander Line Techniques have been shown to introduce additional resonances, thus improving bandwidth. According to Bhuvaneswari et al. [14], incorporating slots or meander lines into antenna designs not only enhances bandwidth but also helps reduce the overall size of the antenna, offering a valuable approach for designing compact antennas with improved bandwidth.

Advances in Material Science also play a critical role in enhancing bandwidth. Rambe et al. [15] emphasized that using high-permittivity and anisotropic substrates can significantly boost bandwidth. By choosing materials with specific electromagnetic properties, antennas can achieve broader operational bandwidths and better performance.

A comparative analysis of bandwidth enhancement techniques, including DGS, metamaterials, EBG structures, and meander line designs, highlights their distinct advantages, each catering to specific application needs. DGS improves impedance matching and reduces surface wave effects, while metamaterials and advanced substrates provide significant bandwidth increases. Emerging trends point to advancements in material science and fabrication techniques, with ongoing research focusing on adaptive materials and integrated circuit technologies to further boost performance. Challenges remain in balancing bandwidth improvements with other factors such as antenna size, gain, and efficiency, leading to future research exploring hybrid techniques and novel materials. Practical applications of these methods span mobile communications, satellite technology, and radar systems, each offering tailored benefits. The historical evolution from early microstrip designs to sophisticated structures with advanced materials provides context for understanding current advancements. Theoretical insights into these techniques involve fundamental electromagnetic principles like impedance matching and wave propagation, essential for developing effective solutions.

3. Antenna Design

A microstrip patch antenna comprises essential components that work together to facilitate wireless communication and other applications. The primary components of this antenna are as follows:

Patch: It is typically made of copper and shaped as rectangular or circular, acts as the antenna's radiating element. When stimulated by an RF signal, it emits electromagnetic waves into space, with its dimensions (length and width) determining fundamental antenna characteristics such as operating frequency, radiation pattern, and impedance [16].

Substrate: It serves as the base on which the patch is mounted. Usually composed of dielectric materials like FR4 or specialized high-frequency substrates such as Rogers materials, the substrate provides structural support for the patch [17] and influences key electrical properties like impedance bandwidth, efficiency, and radiation behaviour.

Ground Plane: Beneath the substrate lies the ground plane**,** an extended conductive surface. It plays a pivotal role in reflecting emitted electromagnetic waves, thereby enhancing the antenna’s radiation efficiency and controlling its radiation pattern. Additionally, the ground plane establishes a reference for radiation and mitigates back radiation towards the feeding structure [18].

Microstrip Feedline: Connecting the patch to the RF feed source or transmission line is the microstrip feed line, a narrow conductor strip on the substrate’s surface. This feed line delivers the RF signal to the patch for radiation. Precisely designed in terms of width and length [19], the feed line ensures optimal impedance matching, crucial for efficient power transfer and bandwidth performance.

A microstrip patch antenna integrates these components to achieve compact size, ease of fabrication using printed circuit board (PCB) technology, and versatility across various wireless communication applications. Each component plays a crucial role in determining the antenna's operational characteristics, ensuring efficient RF signal transmission and radiation performance [20].

3.1 Microstrip Antenna Design Specifications

Designing a microstrip antenna requires taking into account several crucial parameters that influence the antenna's performance. The primary parameters needed for designing a microstrip antenna [21] are as follows:

Operating Frequency(f_o): This is the frequency at which the antenna is designed to operate and it dictates the physical dimensions of the patch and the overall size of the antenna. The operating frequency of proposed antenna is 4GHz.

Dielectric constant of the Substrate(ε_r): The relative permittivity of the dielectric material used for the substrate affects the wavelength within the substrate and influences the patch dimensions, bandwidth, and efficiency. For the proposed antenna, the relative permittivity is 4.4.

Height of the substrate(h): The thickness of the dielectric substrate affects impedance bandwidth and radiation efficiency. Thicker substrates can increase bandwidth but may also cause surface wave losses. For the proposed antenna, the substrate height is 1.6 mm.

Patch Dimensions: Patch dimensions in a microstrip antenna denote the physical measurements of the radiating element, often a rectangular or circular metallic conductor adhered to a dielectric substrate. These dimensions encompass both the length (L_P) and width (W_p) of the patch. During the design phase, these dimensions are determined according to the target operating frequency and the relative permittivity of the substrate material. The formulas used to compute the width and length of the patch are expressed in equations 1 and 2.

$$W_p = \frac{C}{2f_0}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

Where,
C is Velocity of light,
f_0 is desired Resonant frequency,
ε_r is the relative permittivity of the substrate

$$L_p = \frac{C}{2f_0\sqrt{\varepsilon_{eff}}} - 2\,\Delta L \tag{2}$$

Where,
ε_{eff} is effective dielectric constant of an antenna
ΔL is patch length extension

To find the patch length, it's necessary to compute the effective dielectric constant of the antenna and the extension in patch length, utilizing the formulas presented in equations 3 and 4.

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\left(\frac{h}{w_p}\right)\right]^{-\frac{1}{2}} \tag{3}$$

Where,
h is substrate thickness,
w_p is patch width

$$\Delta L = h * 0.412\left[\frac{(\varepsilon_{eff}+0.3)\left(\left(\frac{W_p}{h}\right)+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\left(\frac{W_p}{h}\right)-0.8\right)}\right] \tag{4}$$

Substrate Dimensions: In a microstrip patch antenna, the substrate length and width are usually determined by enlarging the patch dimensions. This extension ensures adequate support for the patch and facilitates efficient radiation. The formulas for calculating the substrate's length (L_s) and width (W_s) are provided by equations 5 and 6, respectively. These calculations ensure the substrate extends beyond the patch, accommodating the ground plane and offering necessary structural support [22].

$$L_s = L_p + 6h \tag{5}$$

$$W_s = W_p + 6h \tag{6}$$

Feed point and Feedline Dimensions: The placement and dimensions of the feed line, whether a microstrip feed or coaxial probe, are crucial for impedance matching and effective power transfer. The feed point is typically adjusted to obtain the desired input impedance, generally set at 50 ohms. The various width and length dimensions are as follows:

Length of Quarter-wavelength Transformer(L_{qw}): It is the length of the microstrip transmission line segment crafted to equalize the impedance between the feed line and the patch antenna, functioning as a quarter-wavelength transformer. Its primary function is to ensure effective impedance matching, adjusting the feed point's impedance to align with the characteristic impedance (Z_o) of both the feed line and the patch antenna. This adjustment is critical for reducing reflection losses and maximizing the efficiency of power transmission.

Width of Quarter-wavelength Transformer(W_{qw}): The width of the microstrip transmission line used for the quarter-wavelength transformer section in the antenna design determines the characteristic impedance and the impedance transformation ratio. It plays a critical role in achieving proper impedance matching, tailored to the substrate material properties and specific requirements for impedance transformation.

Width of the feed (W_f): It denotes the width of the microstrip transmission line forming the feed line within the antenna structure. Its role lies in defining the characteristic impedance of the feed line and affecting how well impedance is matched between the source and the patch antenna. This parameter is critical for minimizing losses in the transmission line and ensuring effective power transfer to the antenna.

Length of the Feed(L_f)*:* It represents the actual length of the microstrip transmission line linking the feed point (where the RF signal enters the antenna) to the patch antenna. Its significance lies in its impact on the antenna's impedance properties. It must be precisely configured to attain impedance alignment with the source impedance (usually 50 ohms), thus optimizing power transfer efficiency and reducing signal losses.

The various parameters required to design the antenna, such as width of the substrate(W_s), length of the substrate(L_s), width of the patch(W_p), length of the patch(L_p), Length of Quarter-wavelength Transformer(L_{qw}), Width of Quarter-wavelength Transformer(W_{qw}),Width of the feed (W_f),Length of the Feed(L_f), height of the substrate(h) are depicted in the Figure 1. The corresponding values for these parameters are listed in Table 1, providing a detailed overview of the antenna's design specifications.

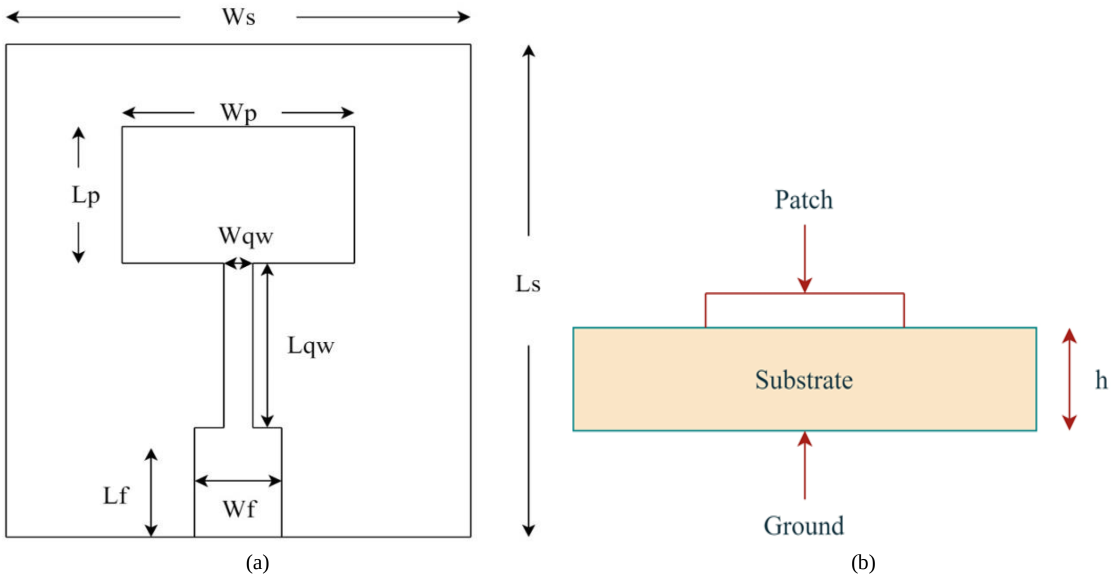

Fig. 1. (a) Top View of Microstrip antenna (b) Side View of Microstrip antenna

Table 1. Design Parameters for Microstrip Antenna with Dimensions

Antenna Design Parameters	Dimensions(mm)
Width of the substrate(W_s)	30.2
Length of the substrate(L_s)	32.8
Width of the patch(W_p),	15.5
Length of the patch(L_p)	16
Height of the substrate(h)	1.6
Length of Quarter-wavelength Transformer(L_{qw}),	9
Width of Quarter-wavelength Transformer(W_{qw}),	1
Width of the feed (W_f),	1.5
Length of the Feed(L_f)	3

Using the above dimensions, a microstrip antenna was designed and implemented in three different configurations using HFSS: one without a DGS, one with a rectangular DGS, and one with a polygonal DGS.

3.2 Simulation setup

The simulation of the Microstrip Patch Antennas was conducted using ANSYS HFSS software. The specific configuration and parameters used are critical for reproducibility and accurate results. The detailed antenna design parameters are provided in Table 1. In addition, the additional simulation parameters are listed in Table 2.

Table 2. Simulation Parameters and Settings

Parameters	Value
Substrate Material	FR4 Epoxy
Relative Permittivity(ε_r)	4.4
Loss Tangent	0.02
Frequency range	1 GHz- 6GHz
Frequency sweep	0.1 GHz steps
Boundary Conditions	Perfect Electric Conductor (PEC)
Excitation Source	Wave port, magnitude 1V
Meshing	Adaptive, max element size 0.1 mm
Radiation Boundary	λ/4 distance, open boundary
Solver Settings	Driven modal solution
Convergence Criterion	Maximum Delta S of 0.02
Number of Passes	Minimum 10, Maximum 20
Adaptive Meshing	Enabled, refinement per pass

The procedure involved creating the initial design of the microstrip patch antenna, including the DGS, using the HFSS design interface. Material properties, boundary conditions, and excitation sources were defined as specified. The geometry was meshed using adaptive techniques to ensure accuracy, and the simulation was run with the outlined solver settings to obtain Scattering parameters or S-Parameters, gain, and Voltage Standing Wave Ratio(VSWR). The results were analyzed to determine performance enhancements due to the DGS, including improvements in bandwidth, gain, and impedance matching. This detailed description ensures the methodology is clear and reproducible.

3.3 Proposed Microstrip Antenna Designs

A standard microstrip patch antenna operating at a frequency of 4 GHz was initially developed for a comprehensive comparative assessment against the proposed antennas featuring Defected Ground Structures. The design of this standard MPA is shown in Figure 2. This standard MPA serves as a baseline to evaluate and contrast the performance enhancements introduced by integrating rectangular and polygonal DGS configurations into the antenna design.

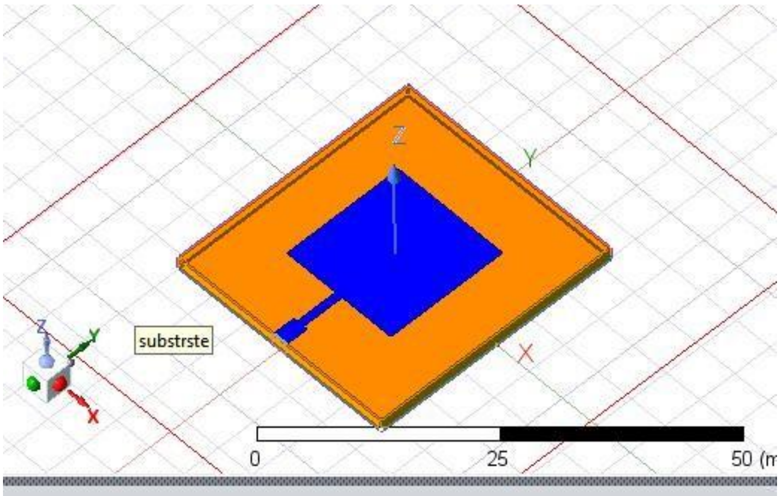

Fig. 2. Design of Standard Microstrip Patch Antenna without Defected Ground structures

To enhance the performance of the basic microstrip patch antenna design, a rectangular slot is incorporated onto the ground plane as shown in Figure 3. This Defected Ground Structure measures 24mm × 1.7mm, significantly improving bandwidth and return loss. The antenna includes a purple ground plane with modified patterns and a blue radiating patch. The white feed line connects the Radio frequency(RF) signal to the patch for radiation.

The DGS alters current distribution to enhance antenna parameters like bandwidth, return loss, VSWR, gain, and efficiency compared to a conventional MPA. Specific dimensions and patterns are tailored for optimal performance at the operating frequency. This configuration will be evaluated against designs without DGS and with different patterns to assess overall performance improvement.

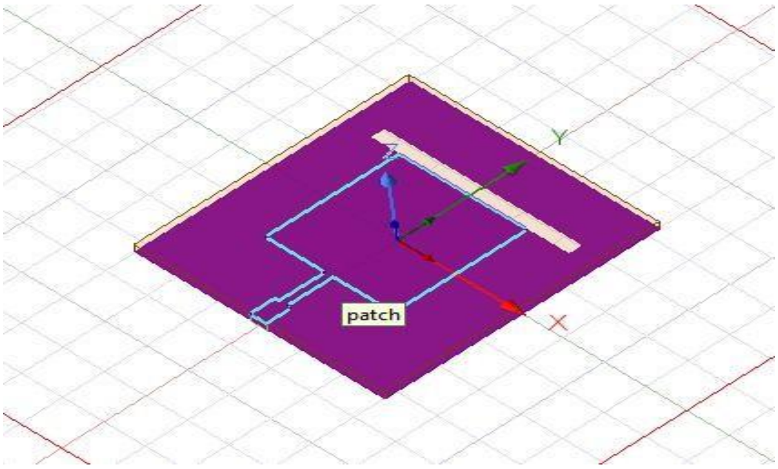

Fig. 3. Design of Microstrip Patch Antenna with Rectangular Defected Ground structures

To further improve antenna parameters, a new design featuring polygonal Defected Ground Structures has been introduced for the microstrip patch antenna. In this iteration, Figure 4 illustrates the integration of three polygons, each with 12 sides, onto the ground plane. One polygon has a radius of 3 mm, and the other two polygons have radii of 4 mm. These polygons are strategically placed to alter the current distribution on the ground plane, with the goal of enhancing antenna performance metrics such as bandwidth, return loss, and efficiency.

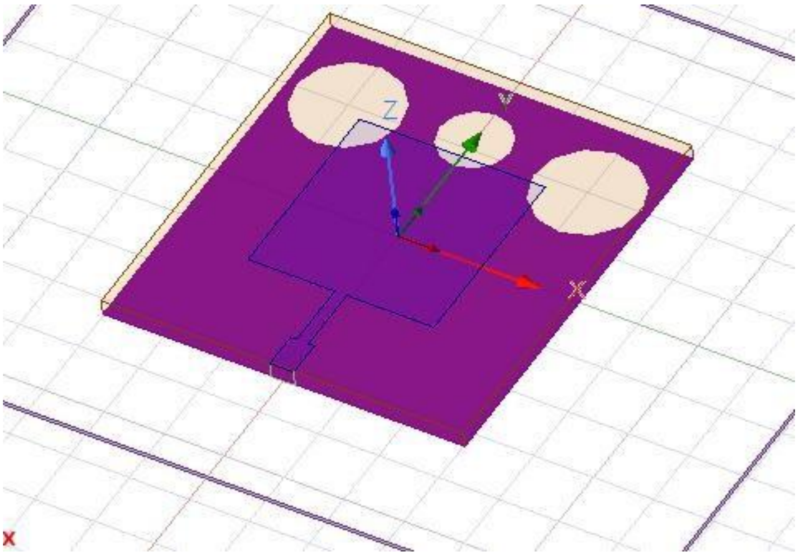

Fig. 4. Design of Microstrip Patch Antenna with Polygonal Defected Ground structures

The three designed antennas in HFSS are evaluated for various parameters such as VSWR, scattering parameters, and Gain. These metrics are critical in assessing the antenna's performance across its operating frequency range.

3.4 Evaluated Antenna Parameters

The proposed three antenna configurations were evaluated across various parameters to ensure a comprehensive understanding and reproducibility, as these parameters are defined below.

Antenna Gain: It is a measure of the directional performance of the antenna, quantifying how well it radiates or receives power in a particular direction compared to an isotropic radiator. Gain is usually expressed in decibels (dB). Higher gain indicates that the antenna can focus energy more effectively in a specific direction, leading to improved performance in that direction. Gain is crucial for applications requiring targeted signal coverage or increased signal strength.

Voltage standing Wave Ratio(VSWR): It is a measure of the efficiency of the antenna’s impedance matching. It is the ratio of the maximum voltage to the minimum voltage along the transmission line, resulting from the reflections of signal waves. A VSWR of 1:1 indicates perfect impedance matching, while higher ratios indicate increasing levels of mismatch. A VSWR below 2:1 is typically acceptable, indicating that the antenna is effectively matched and minimizes reflected power.

Scattering Parameters: These parameters are crucial for analyzing the electrical behavior of radio frequency networks, including antennas. They describe how RF signals are reflected or transmitted through a device, such as an antenna. Key S-parameters include:

S_{11}(Reflection Coefficient): This parameter quantifies the amount of the incident signal that is reflected back towards the source due to impedance mismatch.

S_{21} (Transmission Coefficient): This measures the portion of the signal that is transmitted from port 1 to port 2 of the device.

Since a microstrip antenna is a single-port device, it has only the reflection coefficient and does not have a transmission coefficient. S-parameters are vital for evaluating antenna performance, offering insights into the effectiveness of signal transmission and reception. They help in understanding impedance matching, signal loss, and the overall efficiency of the antenna.

Return Loss: It quantifies the amount of power reflected back from the antenna due to impedance mismatches. It is derived from the ratio of reflected power to incident power and is usually expressed in decibels (dB). A higher return loss signifies better impedance matching between the antenna and the transmission line, resulting in reduced reflected power and more effective energy transfer. Typically, a return loss greater than 10 dB is deemed satisfactory for most applications, indicating that less than 10% of the power is reflected. The Return loss for the designed Microstrip antennas can be calculated from the reflection coefficient using the equation (7) given as:

$$Return\ loss(dB) = -20\ log_{10}|\,S_{11}| = -20\ log_{10}|\,\Gamma| \quad (7)$$

4. Results and Discussions

The microstrip antenna designs, featuring polygonal DGS, rectangular DGS, and a standard configuration without DGS, were thoroughly simulated using HFSS. These simulations were conducted to evaluate a range of performance parameters, including S-parameters, gain, VSWR, and Return loss. Each configuration was analyzed to understand the impact of different DGS shapes on the antenna's overall performance.

Figures 5, 6, and 7 depict the gain of microstrip antennas across three configurations: without DGS, with a polygonal DGS, and with a rectangular DGS, respectively. These figures offer a comparative analysis of the effects of different DGS shapes on antenna gain. The microstrip antenna without DGS serves as a baseline, while the configurations featuring polygonal and rectangular DGSs showcase the influence of these structures on the antenna's gain characteristics.

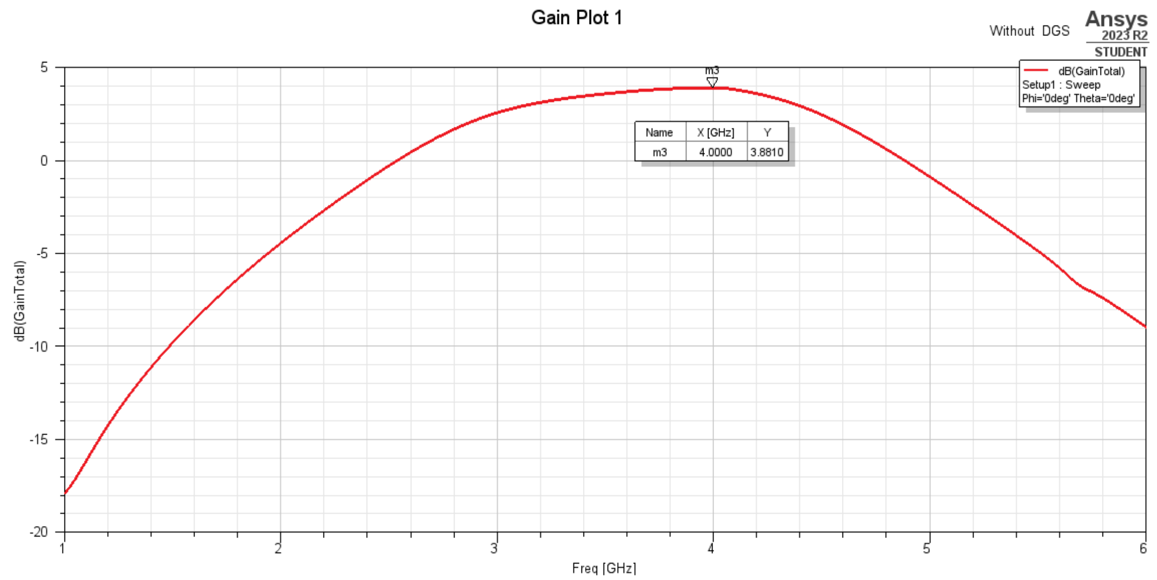

Fig. 5. Gain characteristics of the Microstrip antenna design without Defected Ground structures

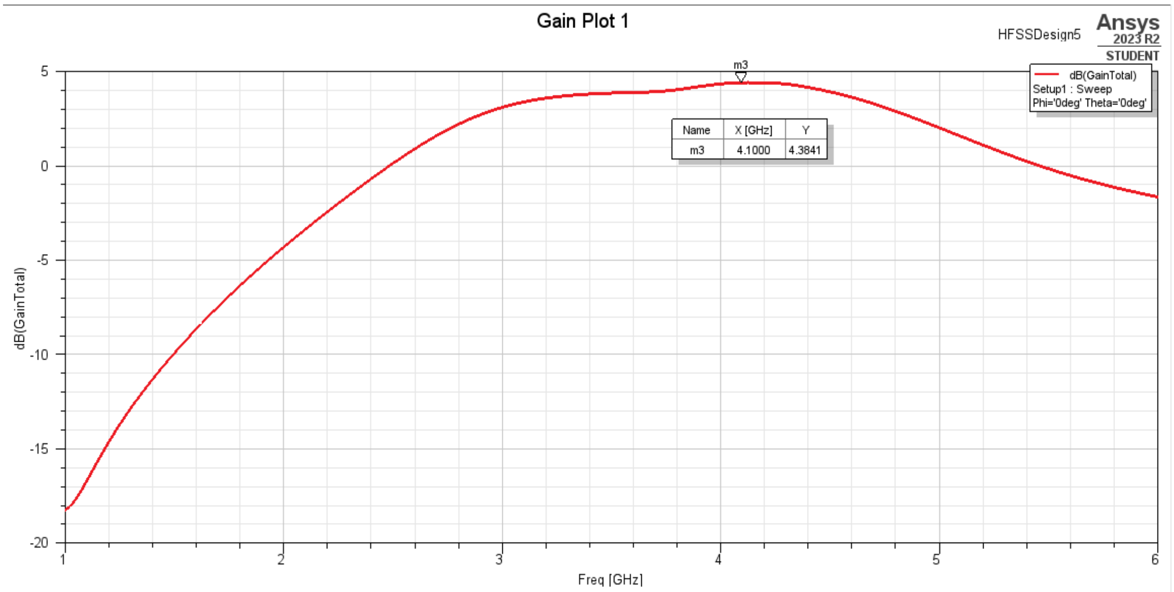

Fig. 6. Gain characteristics of the Microstrip antenna design with Polygonal Defected Ground structures

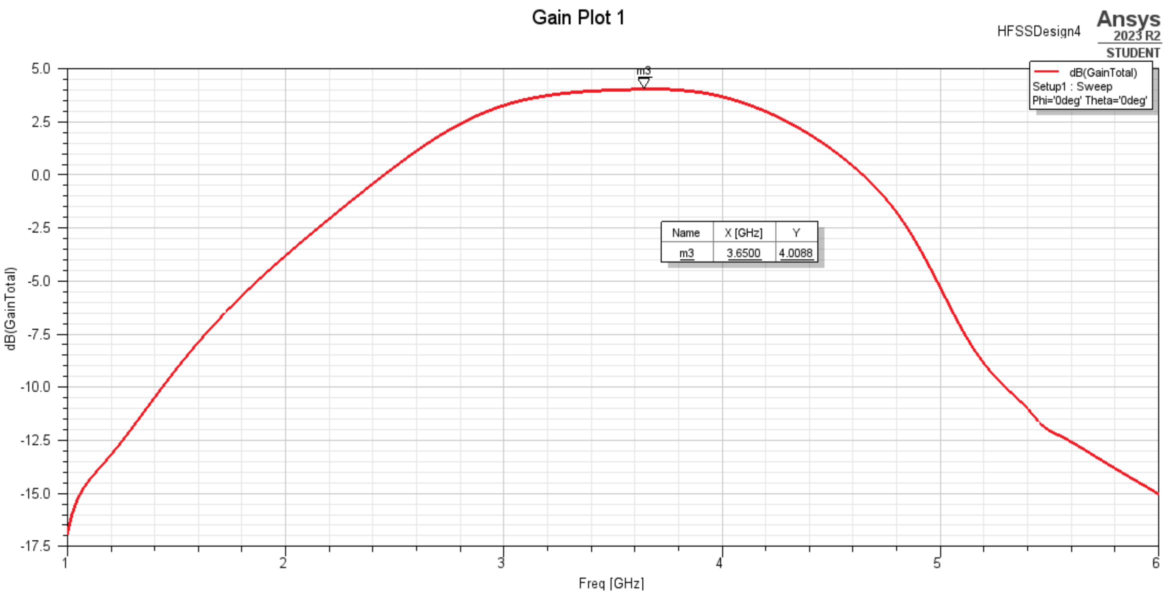

Fig. 7. Gain characteristics of the Microstrip Antenna design with Rectangular Defected Ground structures

From the figures, it is observed that gain measurements show that the inclusion of DGS positively impacts antenna performance. The antenna without DGS has a gain of 3.88 dBi, reflecting moderate performance in signal transmission and reception. The gain increases to 4.38 dBi with the polygonal DGS and to 4.00 dBi with the rectangular DGS. This improvement indicates that both DGS configurations enhance the antenna's ability to transmit and receive signals more effectively, with the polygonal DGS providing the highest gain.

Figures 8,9, and 10 depict the Voltage Standing Wave Ratio (VSWR) of microstrip antennas in three configurations: without DGS, with a polygonal DGS, and with a rectangular DGS, respectively. These figures compare variation of VSWR across different antenna setups. The microstrip antenna without DGS serves as a baseline, showing typical VSWR characteristics. Meanwhile, antennas with polygonal and rectangular DGSs demonstrate how these specific DGS shapes influence VSWR, highlighting their impact on impedance matching and potential enhancements in bandwidth and overall performance.

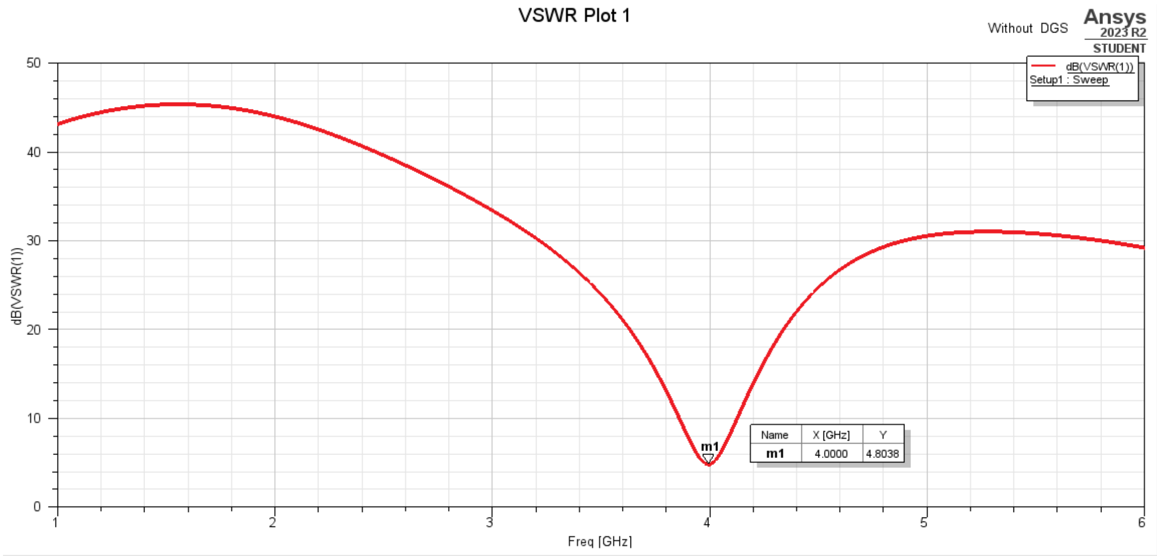

Fig. 8. Voltage Standing Wave Ratio of the Microstrip Antenna without Defected Ground structures

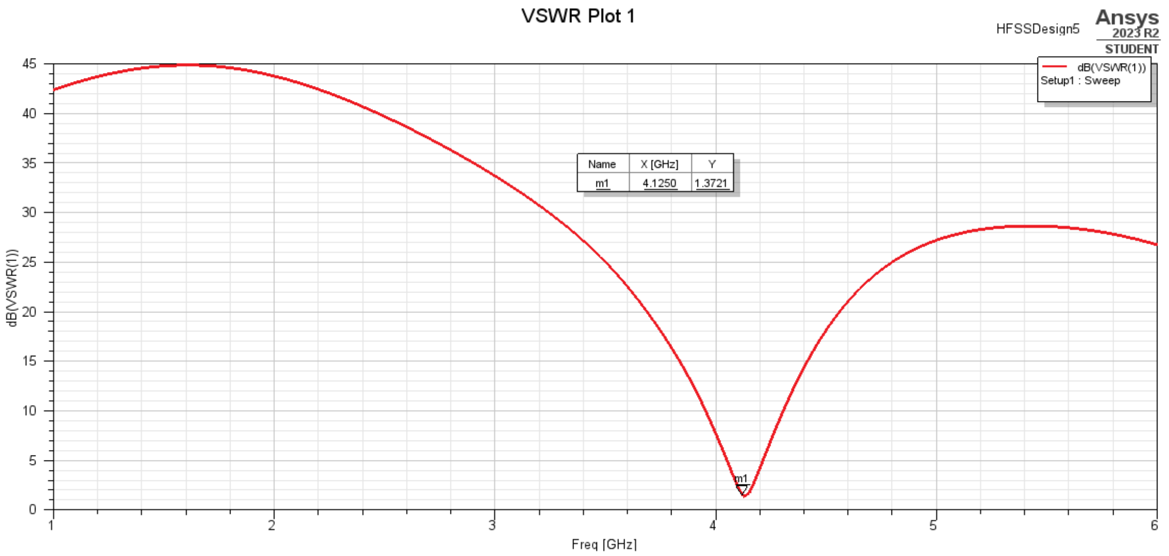

Fig. 9. Voltage Standing Wave Ratio of the Microstrip Antenna with Polygonal Defected Ground structures

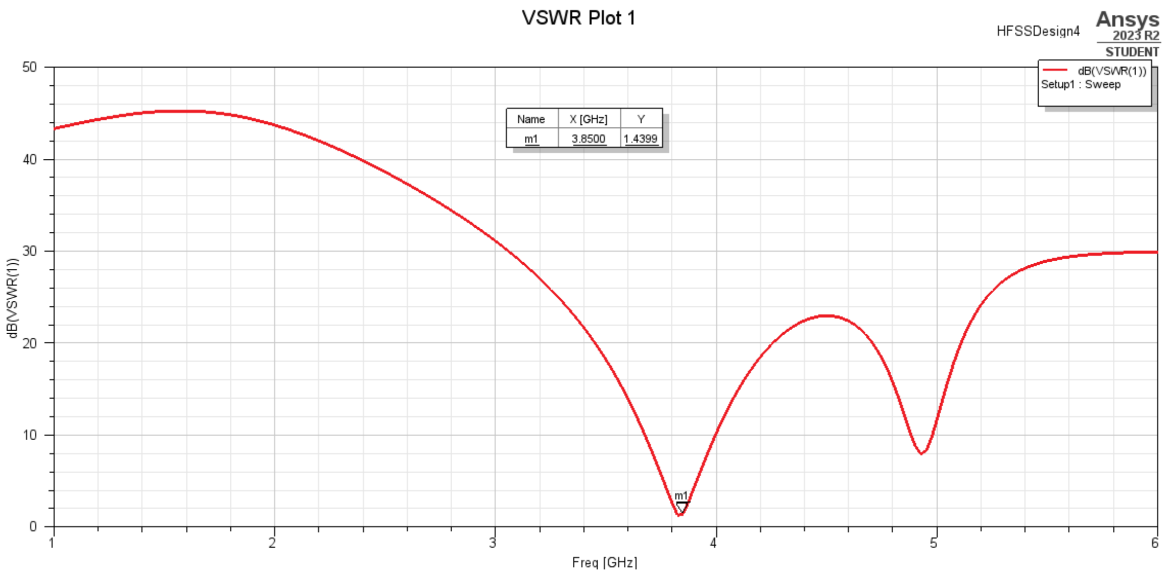

Fig. 10. Voltage Standing Wave Ratio of the Microstrip Antenna with Rectangular Defected Ground structures

From the figures, it is observed that the VSWR values for the antenna configurations reveal significant differences in impedance matching efficiency. The antenna without DGS shows a high VSWR of 4.8038, indicating poor impedance matching and substantial signal reflection. Conversely, the antennas with polygonal and rectangular DGS exhibit much lower VSWR values of 1.3721 and 1.4399, respectively. These lower values signify better impedance matching, leading to more efficient signal transmission with minimal reflection.

Figures 11, 12, and 13 show the S-parameters of microstrip antennas in three setups: without DGS, with a polygonal DGS, and with a rectangular DGS, respectively. These figures compare the differences in S-parameters across various antenna configurations. The microstrip antenna without DGS acts as a reference, demonstrating typical S-parameter behavior. In contrast, antennas with polygonal and rectangular DGSs illustrate how these specific DGS shapes affect impedance characteristics and the efficiency of signal transmission.

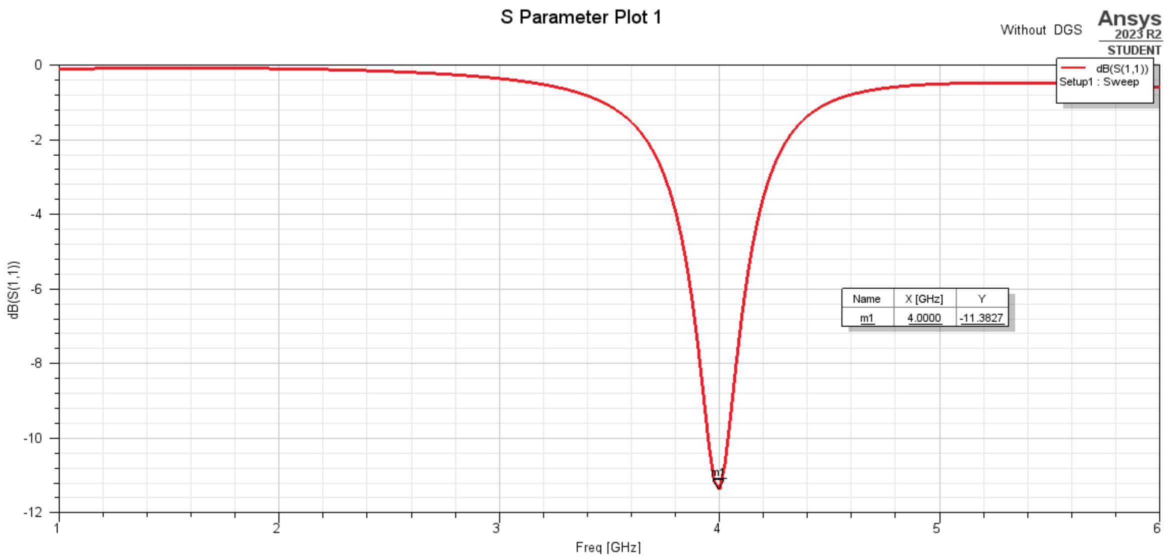

Fig. 11. Scattering Parameters of the Microstrip Antenna without Defected Ground structures

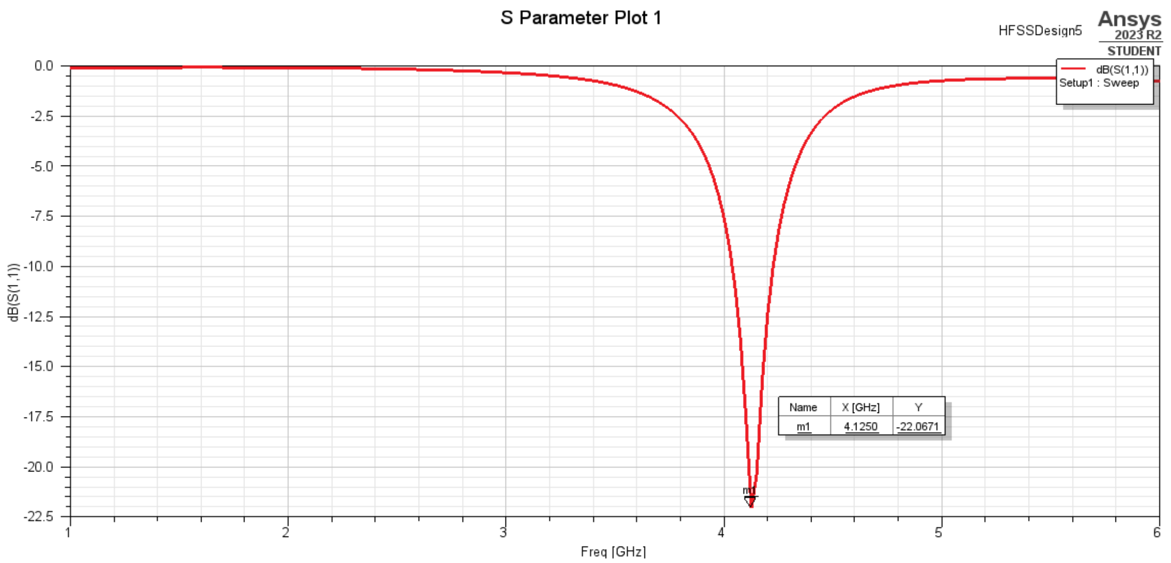

Fig. 12. Scattering Parameters of the Microstrip Antenna with Polygonal Defected Ground structures

For a single-port device like a microstrip antenna, S_{11} directly represents the reflection coefficient (**Γ**). This makes it straightforward to interpret the reflection characteristics of the device from its S-parameter plot. From the figures, it is observed that the reflection coefficient values underscore the effectiveness of DGS in reducing signal reflection. The antenna without DGS has a reflection coefficient of -11.3827 dB, indicating significant signal reflection. With the introduction of polygonal and rectangular DGS, the reflection coefficients improve markedly to -22.067 dB and -22.5969 dB, respectively. These lower values demonstrate enhanced impedance matching and reduced reflection, with the rectangular DGS configuration showing the least amount of signal reflection.

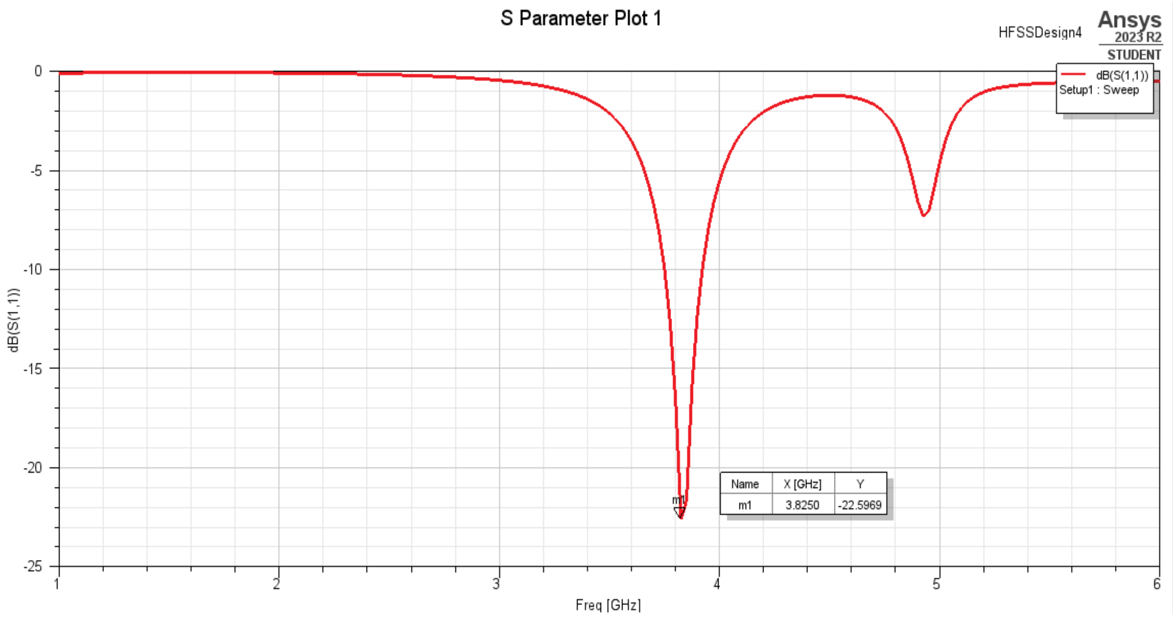

Fig. 13. Scattering Parameters of the Microstrip Antenna with Rectangular Defected Ground structures

By using Equation 7, return loss can be calculated from the reflection coefficient. The microstrip antenna without DGS exhibits a return loss of -21.124 dB, indicating a moderate level of signal returning to the source. With the addition of DGS, the return loss improves to -26.87 dB for the polygonal DGS and further to -27.08 dB for the rectangular DGS. These measurements underscore the effectiveness of DGS configurations in minimizing signal return, with the rectangular DGS demonstrating superior performance in return loss reduction.

From the figures, it is observed that the resonant frequency analysis highlights the tuning effects of DGS on the antenna. The antenna without DGS resonates at the designed frequency of 4 GHz. However, the polygonal DGS shifts the resonant frequency slightly to 4.1 GHz, while the rectangular DGS shifts it to 3.825 GHz. These shifts indicate that DGS not only impacts performance parameters like VSWR, gain, reflection coefficient, and return loss but also fine-tunes the operating frequency, with the rectangular DGS having a more pronounced effect.

The parameters assessed for all three microstrip antenna configurations, including the Microstrip antenna without DGS, the Microstrip antenna with polygonal DGS, and the Microstrip antenna with rectangular DGS, are summarized in Table 3.

Table 3. Evaluated Parameters of Microstrip Antenna Configurations

Microstrip Antenna Designs	**Evaluated Antenna Parameters**				
	VSWR	**Gain (dBi)**	**Reflection Coefficient(dB)**	**Return Loss (dB)**	**Resonant frequency(GHz)**
Microstrip antenna Without DGS	4.8038	3.88	- 11.3827	- 21.124	4
Microstrip antenna with Polygonal DGS	1.3721	4.38	- 22.067	- 26.87	4.1
Microstrip antenna with Rectangular DGS	1.4399	4.00	- 22.5969	- 27.08	3.825

The microstrip antenna without DGS exhibits a relatively high VSWR and lower gain, reflecting its limited bandwidth and less effective impedance matching, which results in significant signal reflection. In contrast, the polygonal DGS configuration shows marked improvements, with a significant reduction in VSWR indicating better impedance matching. This configuration also achieves higher gain and notably improved reflection coefficient and return loss, demonstrating more efficient energy transfer. The higher resonant frequency with the polygonal DGS suggests enhanced bandwidth capability due to its complex resonant behavior. Similarly, the rectangular DGS configuration enhances performance compared to the baseline, with lower VSWR and improved reflection coefficient and return loss. Although its gain is slightly lower than that of the polygonal DGS, it remains superior to the baseline setup, and the resonant frequency shift reflects the impact of DGS on tuning the antenna's operational bandwidth. Overall, the inclusion of DGS significantly improves antenna performance, with the polygonal DGS providing slightly better gain and VSWR, while the rectangular DGS offers superior return loss and reflection coefficient.

The observed performance enhancements with the DGS configurations, including both rectangular and polygonal types, can be attributed to their impact on surface wave suppression, impedance matching, and resonant frequency adjustments. The distinctive shapes of the DGS effectively suppress surface waves by causing specific perturbations in the ground plane, which reduces wave propagation and improves overall performance. Additionally, the DGS structures enhance impedance matching between the antenna and the feed network, as indicated by the lower VSWR values, which suggest reduced signal reflection and more efficient energy transfer. The introduction of DGS also alters resonant frequencies by adding extra resonant modes. The polygonal DGS, in particular, introduces more complex resonant behavior than the rectangular DGS, leading to increased bandwidth and higher gain. The shift in resonant frequency observed with the DGS configurations underscores their effect on modifying the antenna's operational bandwidth and performance.

The simulated parameters of the proposed antenna configurations are compared with those of previously designed antennas, and the corresponding values are listed below in Table 4.

Table 4. Comparison of Simulated Parameters between Proposed and Previous Antenna Designs

Ref.	Size of antenna (mm)	Operating frequency(GHz)	Gain (dBi)	Return loss (dB)
[23]	30 x 24	2.8	1.89	- 15.4
[24]	41 x 50	2.8	1.09	- 20.6
[25]	40 x 16	2.8	1.9	- 7.9
[26]	100 x 28.5	2.8	1.3	- 34
[27]	30 x 70	1.94	1.4	- 20
[28]	37.23 x 28.8	1.9 & 2.8	3	- 20.2 & - 13.12
[29]	37.23 x 28.8	1.9 & 2.89	3.16 & 4	- 18 & - 13.7
Proposed Antenna	30.2 x 32.8	4	4.38 (Polygonal DGS) 4 (Rectangular DGS)	- 26.87 (Polygonal DGS) - 27.08 (Rectangular DGS)

Enhanced MPAs have various practical applications. In wireless communication systems, they can significantly enhance mobile communication by improving signal reception and transmission, leading to better connectivity and faster data rates. Their compact size and efficient high-frequency operation make them suitable for satellite communication, boosting signal quality and coverage. In radar systems, enhanced MPAs can offer improved resolution and detection capabilities, increasing the accuracy of object tracking and imaging. For wireless sensor networks, high-performance MPAs can extend the range and reliability of data transmission, resulting in better network coverage and data accuracy.

The benefits of enhanced MPAs include improved bandwidth, enabling higher data transmission rates and more efficient communication. They also offer better impedance matching, reducing signal reflections and losses, which leads to more effective energy transfer and improved overall performance. The small size of MPAs makes them ideal for integration into compact devices and systems, saving space and allowing for more versatile applications. Furthermore, enhanced MPAs with higher gain provide stronger signal strength and coverage, essential for maintaining robust connections in various communication systems.

Nevertheless, there are potential limitations to consider. Advanced designs and materials might increase the cost and complexity of manufacturing MPAs, which could impact their feasibility for some applications. Integrating enhanced MPAs into existing systems might require additional modifications or considerations, affecting deployment timelines and costs. Additionally, performance may vary with environmental conditions such as temperature and humidity, potentially impacting the reliability of enhanced MPAs in some applications.

5. Conclusion

This research has comprehensively evaluated the performance of three microstrip antenna configurations: without DGS, with polygonal DGS, and with rectangular DGS, using HFSS for simulations and analysis. The assessment focused on key parameters such as VSWR, gain, reflection coefficient, return loss, and resonant frequency.

From the results, it is evident that the introduction of DGS significantly enhances the performance of microstrip antennas. The microstrip antenna without DGS exhibited a moderate performance with a return loss of -21.124 dB, a gain of 3.88 dBi, and a VSWR of 4.8038 at a resonant frequency of 4 GHz. These values indicate a reasonable performance but also highlight areas where improvements can be made, particularly in terms of return loss and VSWR.

The polygonal DGS configuration showed marked improvements, with a return loss of -26.87 dB, a gain of 4.38 dBi, and a VSWR of 1.3721 at a slightly shifted resonant frequency of 4.1 GHz. These results suggest that the polygonal DGS effectively enhances signal quality by reducing the amount of signal returning to the source, thereby improving overall antenna performance.

The rectangular DGS configuration provided the best performance among the three configurations. It achieved a return loss of -27.08 dB, a gain of 4.00 dBi, and a VSWR of 1.4399 at a resonant frequency of 3.825 GHz. These results demonstrate the superior effectiveness of the rectangular DGS in minimizing signal return and optimizing signal transmission.

The evaluation confirms that incorporating DGS into microstrip antenna designs can significantly enhance performance metrics, particularly in terms of return loss and VSWR. The choice between polygonal and rectangular DGS configurations should be guided by specific application requirements, with the rectangular DGS offering slightly better performance in the parameters evaluated.

Future research should focus on several key areas to enhance microstrip antenna performance. Exploring alternative DGS shapes and configurations, such as fractal or irregular designs, could yield improvements in bandwidth and impedance matching. Real-world testing of simulated antenna designs is crucial to validate their performance in practical conditions, ensuring reliability and effectiveness. Integrating these optimized designs into actual communication systems, like mobile or satellite networks, will provide insights into their practical applications. Additionally, investigating advanced materials and manufacturing techniques, including metamaterials and high-permittivity substrates, could further improve antenna performance and expand their applicability. Future work should also include continued optimization of DGS designs and the practical application of these findings to real-world wireless communication systems. Using HFSS for simulation and analysis remains an effective method for assessing and refining antenna performance.

Acknowledgment

The author(s) have no acknowledgements to declare.

References

[1] M. Khandelwal, B. Kanaujia, and S. Kumar, "Defected Ground Structure: Fundamentals, Analysis, and Applications in Modern Wireless Trends," *International Journal of Antennas Propagation*, vol. 2017, pp. 1-22, 2017, doi: 10.1155/2017/2018527.

[2] T. Dey and S. Mandal, "Design and Analysis of 28 GHz Microstrip Patch Antenna for 5G Network," in *Data Science and Communication*, 2024, pp. 773-784, doi: 10.1007/978-981-99-5435-3_57.

[3] D. Saha, S. Mandal, and K. Purkait, "Design of Rectangular Slotted Microstrip Patch Antenna for 5G Applications at 27GHz," *in 2022 International Conference on Intelligent Innovations in Engineering and Technology (ICIIET)*, 2022, pp. 15-19, doi: 10.1109/ICIIET55458.2022.9967679.

[4] K. Fante and M. Gemeda, "Broadband Microstrip Patch Antenna at 28GHz for 5G Wireless Applications," *International Journal of Electrical and Computer Engineering*, vol. 11, no. 3, pp. 2238-2244, 2021, doi: 10.11591/ijece. v11i3.pp2238-2244.

[5] A. Lozada, A. Piedrahita, and G. Russi, "Design and study of a microstrip slot antenna operating at 2.8/3.1/3.6/4.7/5.4 GHz," *MATEC Web Conf*erence, vol. 125, p. 03003, 2017, doi: 10.1051/matecconf/201712503003.

[6] S. Shivangi, Chandan Ashutosh Kumar and H. Yadav, "A compact microstrip patch antenna with DGS for WiFi/WiMAX/WLAN," *i-manager's Journal of Communication Engineering and Systems*, vol. 12, no. 1, p. 1, 2023, doi: 10.26634/jcs.12.1.19756.

[7] B. Balaji, V. Yasaswini, R. R. Reddy, and B. Spandana, "Rectangle Patch Antenna with Slots and Defective Ground Structure for C-band Applications," in *2024 IEEE Wireless Antenna and Microwave Symposium (WAMS*), 2024, pp. 1-5, doi: 10.1109/WAMS59642.2024.10527952.

[8] R. V. Prasad, D. Vakula, and M. Chakravarthy, "A New Approach in Realisation of DGS Microstrip Patch Antennas with Fractal Geometry," *Defence Science J*ournal, vol. 73, no. 4, pp. 468-474, 2023, doi: 10.14429/dsj.73.18561.

[9] H. Ali, N. Sherif, and G. Saady, "Bandwidth Enhancement of a Microstrip Patch Antenna Using Inverted-F Shaped Defected Ground Structure," *American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS)*, vol. 54, no. 1, pp. 20-29, 2019.

[10] S. Vammi, K. V. V. S. Redd, and A. M. Prasad, "Bandwidth Enhancement of Metamaterial Loaded Microstrip Antenna Using Double Layered Substrate*," Indonesian Journal of Electrical Engineering and Computer Science*, vol. 5, no. 3, pp. 661-665, 2017. doi: 10.11591/ijeecs. v5. i3. pp661-665.

[11] S. Patil, A. Verma, A. Kumar Singh, B. K. Kanaujia, and S. Kumar, "A Low-Profile Circularly Polarized Microstrip Antenna Using Elliptical Electromagnetic Band Gap Structure*," International Journal of Microwave and Wireless Technologies*, vol. 14, no. 8, pp. 1009-1018, 2022. doi: 10.1017/S1759078721001367.

[12] A. Bondarik and D. Sjöberg, "Gridded Parasitic Patch Stacked Microstrip Array Antenna for 60 GHz Band," *IET Microwaves, Antennas & Propagation*, vol. 14, 2020. doi: 10.1049/iet-map.2018.5916.

[13] G. Let, S. Rekha, and B. Pratap, "Asymmetric Microstrip Fed Meander Line Slot Antenna for 5.6 GHz Applications," *Materials Today: Proceedings*, vol. 58, 2022. doi: 10.1016/j.matpr.2022.01.045.

[14] B. Bhuvaneswari, V. Aruna, R. Monisha, and E. Pooja, "Design of Multiband, Reconfigurable Coplanar Meander Antenna for WLAN Applications," *Journal of High-Frequency Communication Technologies*, vol. 01, pp. 102-110, 2023. doi: 10.58399/PLYH6400.

[15] A. Rambe, M. Sitopu, and S. Suherman, "Bandwidth Enhancement of Rectangular Patch Microstrip Antenna Using Left Handed Metamaterial at 2.4 GHz," *IOP Conference Series: Materials Science and Engineering*, vol. 420, 2018. doi: 10.1088/1757-899X/420/1/012054.

[16] H. Hadiuzzaman, M. Rahman, and M. Shakib, "Design and Analysis of High Gain Microstrip Antenna Array for 5G Wireless Communications," in *2024 International Conference on Advances in Computing, Communication, Electrical, and Smart Systems (iCACCESS*), 2024, pp. 1-4, doi: 10.1109/iCACCESS61735.2024.10499530.

[17] B. Mazumdar, A. De, S. Karmakar, J. Dey, S. Rana, and D. Bar, "Microstrip patch antenna designed for 5G implementations," *International Journal of Multidisciplinary Research and Growth Evaluation*, vol. 5, no. 2, pp. 909-911, 2024, doi: 10.54660/IJMRGE.2024.5.2.909-911.

[18] G. Namineni, S. Das, N. Koppala, C. Prasanna, and B. Naik, "DGS based Slotted Microstrip Patch Antenna for Mm-Wave and 5G Applications," *NeuroQuantology*, vol. 20, no. 7, pp. 1539-1549, 2022, doi: 10.14704/nq.2022.20.7. NQ33192.
[19] M. Joshi and V. Gond, "Inverted T-Shaped DGS loaded nearly square microstrip patch antenna for wireless applications," *Australian Journal of Electrical and Electronics Engineering*, vol. 20, no. 1, pp. 1-7, 2022, doi: 10.1080/1448837X.2022.2115670.
[20] M. L. El Issawi, D. Konditi, and A. D. Usman, "Design of Enhanced Wide Band Microstrip Patch Antenna Based on Defected Ground Structures (DGS) for Sub-6 GHz Applications," *International Journal of Electrical and Electronics Research*, vol. 12, no. 1, pp. 315-321, 2024, doi: 10.37391/IJEER.120143.
[21] W. M. Abdulkawi, A. F. A. Sheta, I. Elshafiey, and M. A. S. Alkanhal, "Design of Low-Profile Single- and Dual-Band Antennas for IoT Applications," *Electronics*, 2021.
[22] A. S. Elkorany et al., "Implementation of a Miniaturized Planar Tri-Band Microstrip Patch Antenna for Wireless Sensors in Mobile Applications," *Sensors*, vol. 22, 2022.
[23] N. Sharma and V. Sharma, "A design of Microstrip Patch Antenna using hybrid fractal slot for wideband applications," *Ain Shams Engineering Journal*, vol. 9, no. 4, 2017, doi: 10.1016/j.asej.2017.05.008.
[24] Y. Khraisat, "Increasing Microstrip Patch Antenna Bandwidth by Inserting Ground Slots," *Journal of Electromagnetic Analysis and Applications*, vol. 10, no. 1, pp. 1-11, 2018, doi: 10.4236/jemaa.2018.101001.
[25] A. Amir Anton Jone, John Paul. J, Shajin Prince, K. Martin Sagayam and Samson Immanuel. J, "Folded Shorted Patch Antenna with Slots for Wireless Applications," *International Journal of Engineering and Advanced Technology (IJEAT)*, vol. 9, no. 1, pp. 1437-1441, Oct. 2019, doi: 10.35940/ijeat. A1245.109119.
[26] A. Ammar, N. Mahmoud, M. Ali, and A. Hussein, "Efficient Diplexer with High Selectivity and Low Insertion Loss Based On SOLR and DGS for Wimax," *Progress in Electromagnetics Research C*, vol. 116, pp. 171-180, 2021, doi: 10.2528/PIERC21090104.
[27] S. Santhanam and T. Palavesam, "Comparative characterization of microstrip patch antenna array with defected ground structure for biomedical application," *Bulletin of Electrical Engineering and Informatics*, vol. 11, no. 1, pp. 346-353, 2022, doi: 10.11591/eei. v11i1.3459.
[28] P. Goyal, P. K. Singhal, P. Sahoo, and D. K. Parsediya, "Dual Band U Shape Slot Rectangular Microstrip Patch Antenna with Defected Ground Structure," *International Journal of All Research Education and Scientific Methods (IJARESM)*, vol. 10, no. 7, July 2022.
[29] P. Goyal, P. K. Singhal, P. Sahoo, and D. Parsediya, "Modified E-Shape Rectangular Microstrip Patch Antenna with DGS for Wireless Communication," *International Journal of Electrical and Electronics Research*, vol. 11, no. 3, pp. 814-818, 2023, doi: 10.37391/ijeer.110327.

Authors' Profiles

Padmasree Ramineni is currently serving as an Assistant Professor in the Department of Electronics and Communication Engineering (ECE) at Rajiv Gandhi University of Knowledge and Technologies, Basar. Alongside her teaching responsibilities, she is pursuing a part-time Ph.D. in Wireless Communications at Osmania University, Hyderabad. She obtained her M. Tech degree in Digital Electronics and Communication Systems (DECS) from Jawaharlal Nehru Technological University (JNTU) Hyderabad, following her undergraduate studies in Electronics and Communications Engineering (ECE) from the same institution. she has contributed significantly to her field and has published several papers internationally. Her research interests lie in the interdisciplinary fields of Wireless Communication, Advanced Microcontrollers-Embedded Systems, Wireless Sensor Networks, Antenna Designs, and Machine Learning. she is actively engaged in both teaching and research, contributing to the advancement of knowledge in her areas of expertise.

Abhinay Nimmala is currently pursuing a Bachelor of Technology (B. Tech) degree in Electronics and Communication Engineering (ECE) at Rajiv Gandhi University of Knowledge and Technologies (RGUKT), Basar. His areas of interest include wireless communication, antenna design, and machine learning.

How to cite this paper: Padmasree Ramineni, Abhinay Nimmala, "Design and Analysis of Microstrip Patch Antennas with Polygonal and Rectangular Defected Ground Structures for Sub-6GHz Applications", International Journal of Wireless and Microwave Technologies(IJWMT), Vol.14, No.5, pp. 44-58, 2024. DOI:10.5815/ijwmt.2024.05.04