Compact Microstrip Patch Antenna with Rectangular DGS for Wi-Fi Applications

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Abstract: Over the past several years, antenna miniaturization has become a key focus of research for engineers specializing in antenna design. In this paper, an inset-fed microstrip patch antenna incorporating a rectangular slot etched in the ground plane is presented. The proposed design utilizes the Defected Ground Structure (DGS) concept to achieve antenna miniaturization. A parametric analysis is conducted to determine the optimal length, width, and placement of the rectangular slot on the ground plane. The antenna is constructed using an FR-4 substrate with dimensions of 0.1816λ_0 × 0.216λ_0 × 0.0128λ_0, where λ_0 denotes the free-space wavelength corresponding to a frequency of 2.4 GHz. Simulation outcomes indicate that the proposed antenna achieves an impedance bandwidth of 4.77% (5.12 GHz to 5.37 GHz) when no DGS is used, whereas incorporating a rectangular DGS results in an impedance bandwidth of 5.34% (2.37 GHz to 2.5 GHz). Using the proposed method, a size reduction of up to 67.05% is achieved compared to the conventional antenna. The antennas were simulated and optimized using CST Microwave Studio, and the fabricated prototypes were evaluated with a Rohde & Schwarz ZVL13 VNA. Both simulation and experimental results confirm that the proposed antenna operates within the 2.4 GHz Wi-Fi band.

Keywords: *Compact; Inset Fed; Microstrip Antenna; DGS; Slot; Miniaturization.*

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I. INTRODUCTION

Modern wireless communication has seamlessly integrated into our daily routines, driven by the widespread adoption of compact, portable, and handheld devices. This has led to the development of miniaturized antennas that can fit inside such devices. Compact microstrip antennas have recently attracted significant interest due to the increasing demand for small antennas across various communication applications.

For antenna miniaturization, several methods have been proposed in the literature, such as introducing slots on the patch, Defected Ground Structure (DGS), the fractal method [1], metamaterial structures [2], or a combination of these techniques. Among all available methods for antenna miniaturization, the Defected Ground Structure is the most popular. DGS is realized by etching either a single or a number of periodic and aperiodic shapes into the ground plane. The DGS shape may be simple or complex. The natural resonance characteristics of this defect disrupt the shielding current distribution in the ground plane. The defect's shape and dimensions determine the distribution of the shielding current [3–9]. DGS is considered a simple and effective method for reducing antenna size, while also enabling the excitation of additional resonant modes [9]. A variety of slot geometries etched into the ground plane for different applications have been reported in the literature.

There are many publications discussing various slot geometries etched into the ground plane for different applications. In addition to antenna miniaturization, DGS can enable reductions in crosspolarization, harmonic suppression, performance improvements in power dividers and couplers, reduction of sidelobes in phased arrays, and antenna beam steering [6]. Microstrip antennas with square DGS and truncated corners [9], square slots [10], and rectangular slots [11, 12] are used to achieve circular polarization along with dual-band operation. In [3], the effect of a rectangular-shaped defective ground structure implemented on two, four, and eight element hybrid microstrip array antennas is presented. With an I-shaped slot integrated into the ground plane, size miniaturization of 54% was achieved by shifting the resonant frequency from 5.2 GHz to 3.5 GHz [4]. Using a DGS structure composed of six concentric rings along with a rectangular slot, a miniature microstrip patch antenna was

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developed, shifting the resonance frequency from 10 GHz to 3.5 GHz [5]. A compact, reconfigurable square slot antenna with a modified radiating element for UWB applications and band-notch functionality has also been demonstrated [13–16]. In [17], a 33% size reduction was achieved by bending both the feed line and the ground slot of the antenna. By employing a U-shaped slot with shorted ends and two L-shaped slots with open ends etched in the ground plane, frequency reconfiguration was achieved along with a size reduction of 32.5% [18]. Antenna miniaturization of 91% was achieved by introducing both a slot on the patch and DGS [19]. Introduction of a single slot in the ground plane, along with the proper position of the feeding point, yielded a size reduction of about 90% and improvement in impedance bandwidth [20].

To study how the size and location of the rectangular DGS affect frequency, this research describes a compact microstrip patch antenna utilizing rectangular DGS, along with a parametric investigation. The rectangular DGS was used to shift the antenna's resonant frequency from 5.25 GHz to 2.4 GHz while maintaining its original size. The antenna achieves a size reduction of approximately 67.05% compared to a conventional microstrip patch antenna.

The remainder of the paper is structured as follows: Section 2 provides an overview of the proposed antenna design. Section 3 presents the parametric analysis aimed at identifying the optimal location and dimensions of a rectangular ground slot. Section 4 examines the simulation and measurement results. The paper concludes in Section 5 with a summary of findings.

II. ANTENNA DESIGN

A low-cost FR-4 substrate with a dielectric constant (ε_r) of 4.4, a loss tangent (tanδ) of 0.02, and a thickness of 1.6 mm was selected for the antenna. The rectangular patch is fed by a 50 Ω microstrip feed line. To achieve impedance matching with the feed line, the inset feed technique is employed, providing effective impedance control within a planar feed configuration. Fig. 1 illustrates the antenna geometry, with dimensions $L_g \times W_g \times H_s$ measuring 22.7 mm, 27 mm, and 1.6 mm, respectively.

The antenna parameters for 5.25 GHz were calculated using standard design equations [21–23]. For the miniaturized antenna design, the Defected Ground Structure (DGS) concept is utilized. DGS refers to an intentional defect introduced into the ground plane to modify the antenna's effective capacitance, inductance, and resistance. The size, shape, and position of this defect relative to the feed point result in shifting the resonance frequency of the reference antenna toward a lower frequency [5, 7, 9].

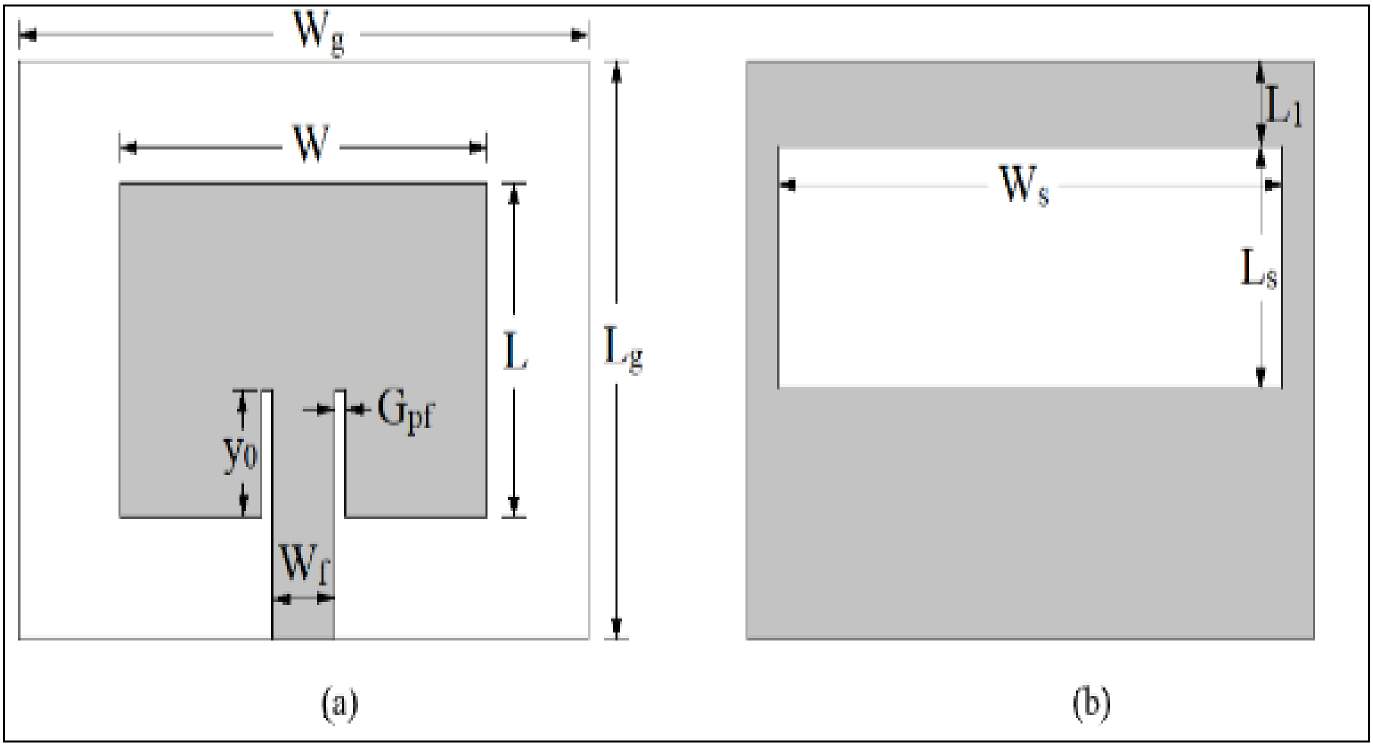

Fig 1 Geometry of the Proposed Antenna (a) Top View and (b) Bottom View.

Antenna miniaturization is achieved by etching a rectangular slot with dimensions $L_s \times W_s = 9.5 \times 24\ mm^2$ on the ground plane. The integration of the Defected Ground Structure (DGS) alters the antenna's surface current distribution, resulting in a resonant frequency shift from 5.25 GHz (without DGS) to 2.4 GHz. Table 1 provides the optimized design parameter values.

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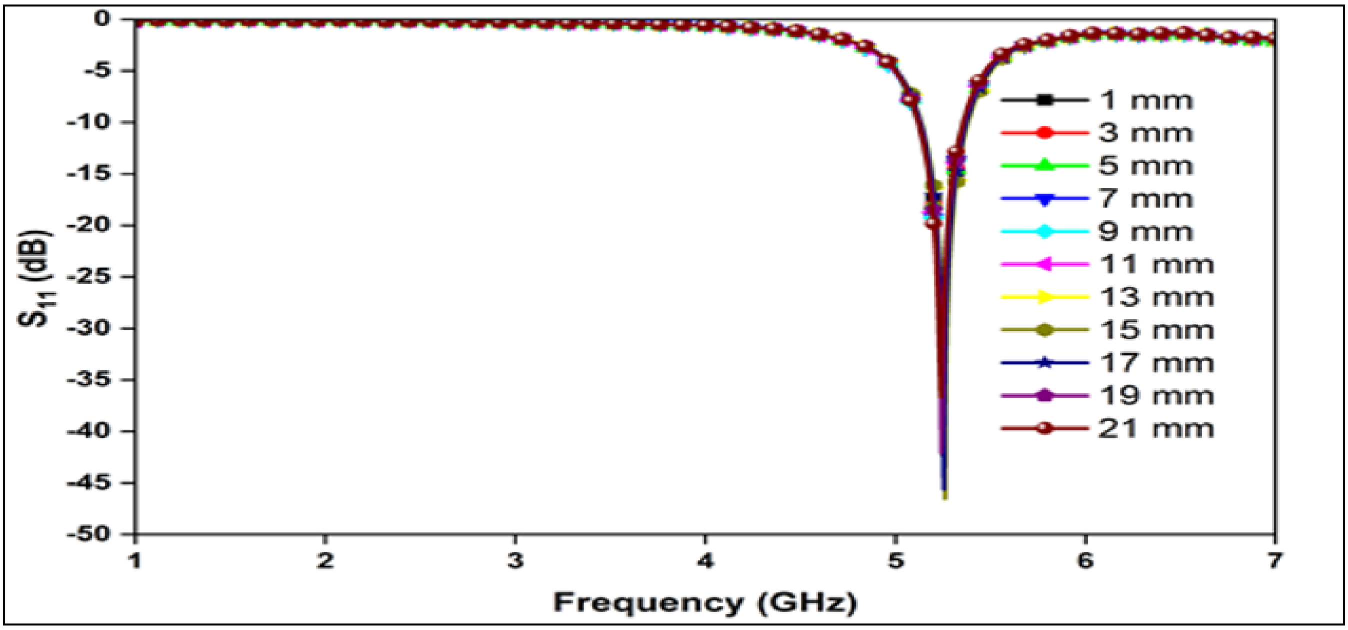
Table 1 Optimized Values of Design Parameters (Mm).

Parameter	Size	Parameter	Size
L	13.1	W	17.4
L_g	22.7	W_g	27
L_s	9.5	W_s	24
L_1	3.35	W_f	3
y_0	5	G_{pf}	0.2

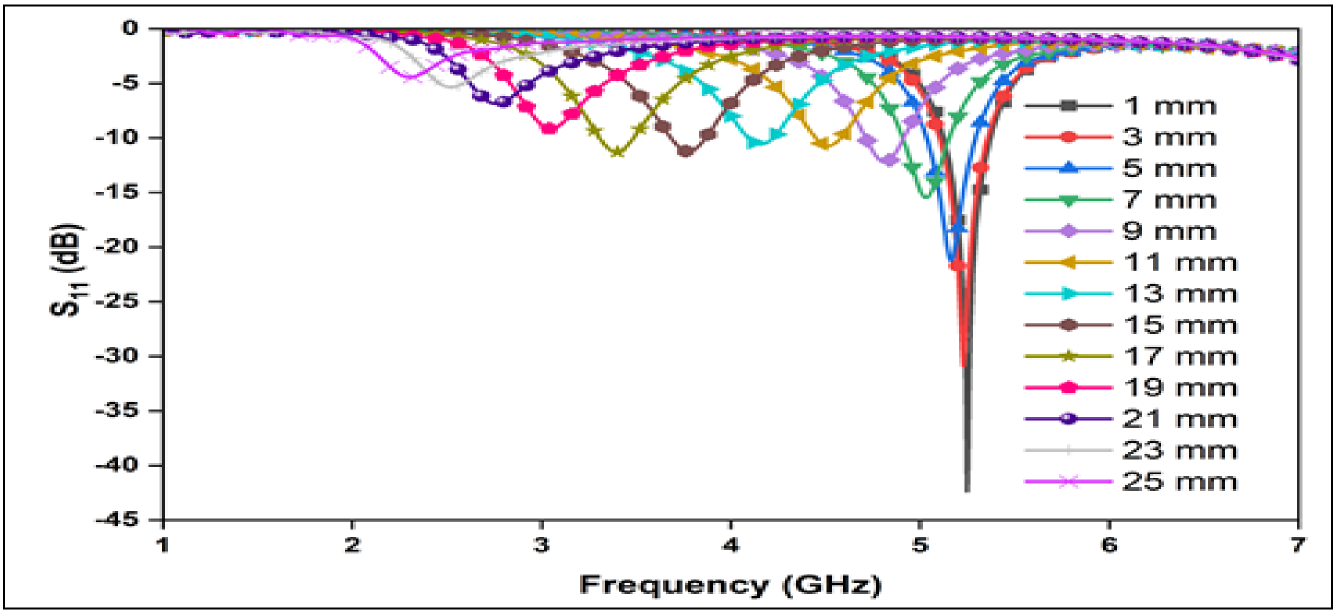
III. PARAMETRIC INVESTIGATION

In this section, a comprehensive analysis of various design parameters is conducted to fine-tune the location and dimensions of the rectangular Defected Ground Structure (DGS). This thorough investigation ensures that the antenna reliably radiates at 2.4 GHz, achieving an S_{11} value of ≤ –10 dB.

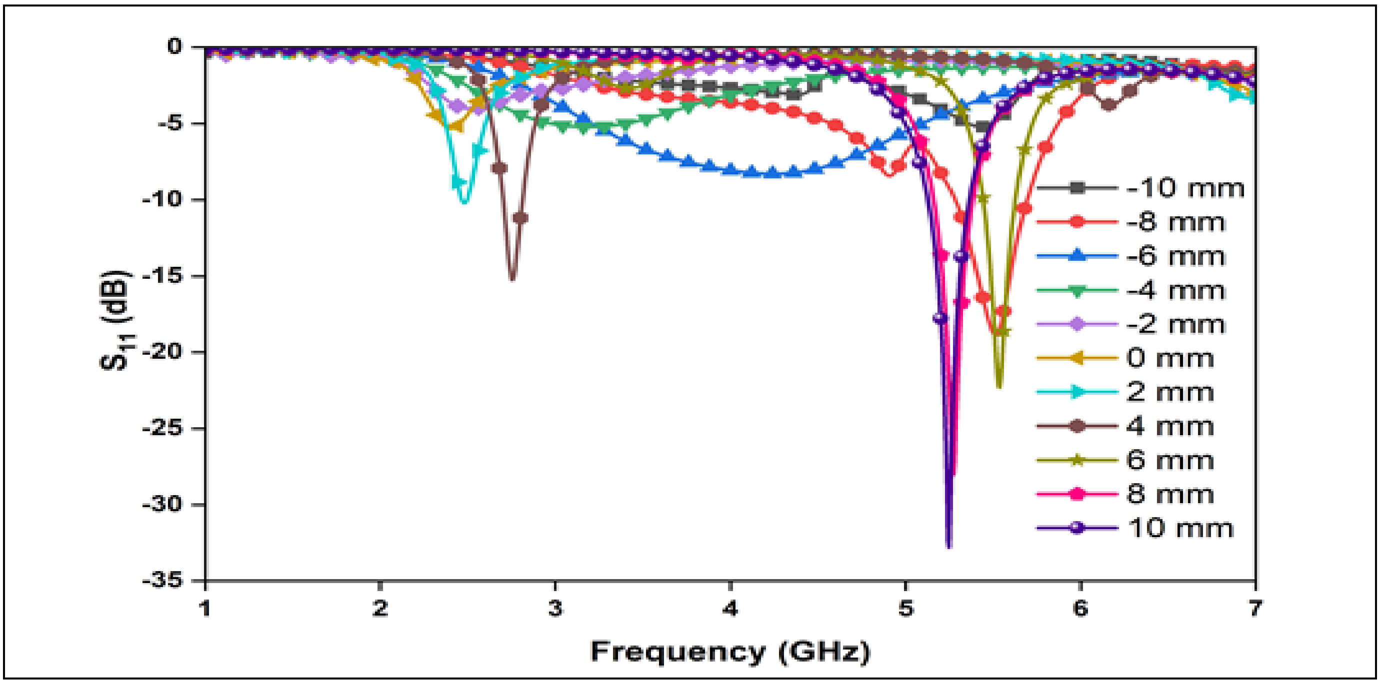
The study is carried out by placing the slot at the center of the ground plane, while the slot length (L_s) is symmetrically adjusted about the central horizontal axis. The slot width (W_s) is maintained at 1 mm, and the slot length (L_s) is incrementally extended from 1 mm to 21 mm in appropriate steps. When the slot is centered on the ground plane, no significant changes in the antenna's resonant frequency or bandwidth are observed, as depicted in Fig. 2(a).



(a)



(b)



(c)

Fig 2 Parametric Analysis of Slot Dimensions, (A) L_s, (B) W_s and (C) Slot Position.

Keeping the slot at the center position, the slot width (W_s) is varied symmetrically about the central vertical axis. The slot width (W_s) is increased from 1 mm to 25 mm while keeping the slot length (L_s) constant at 1 mm. Altering the slot width modifies both the resonant frequency and the reflection coefficient, as shown in Fig. 2(b).

Fig. 2(c) illustrates the impact of the slot position on the resonant frequency and bandwidth. The study is conducted by shifting the slot upward and downward from the antenna's center while maintaining the slot width (W_s) and slot length (L_s) fixed at 24 mm and 1 mm, respectively. The resonant frequency decreases as the slot is moved from the bottom edge of the ground plane toward the middle, but it increases again when the slot is shifted further upward toward the top edge. The resonant frequency reaches its minimum when the slot is positioned exactly at the center. It is also observed that the slot position influences the reflection coefficient.

Thus, the antenna's resonant frequency and reflection coefficient are affected not only by the appropriate length and width of the rectangular DGS but also by its precise location. These parameters collectively determine the antenna's ability to radiate efficiently at lower frequencies.

IV. RESULTS AND DISCUSSIONS

CST Microwave Studio is used as the simulation tool for antenna design. As shown in Fig. 3, the reference antenna (without DGS) operates at a resonant frequency of 5.25 GHz, with an S_{11} of –40.62 dB and a –10 dB impedance bandwidth ranging from 5.12 GHz to 5.37 GHz, covering a total bandwidth of 250 MHz. The antenna with DGS resonates at 2.4 GHz, with an S_{11} of –37 dB and a –10 dB impedance bandwidth extending from 2.37 GHz to 2.5 GHz, covering a total bandwidth of 130 MHz. Table 2 provides the comparison between simulated and measured parameters of the antenna.

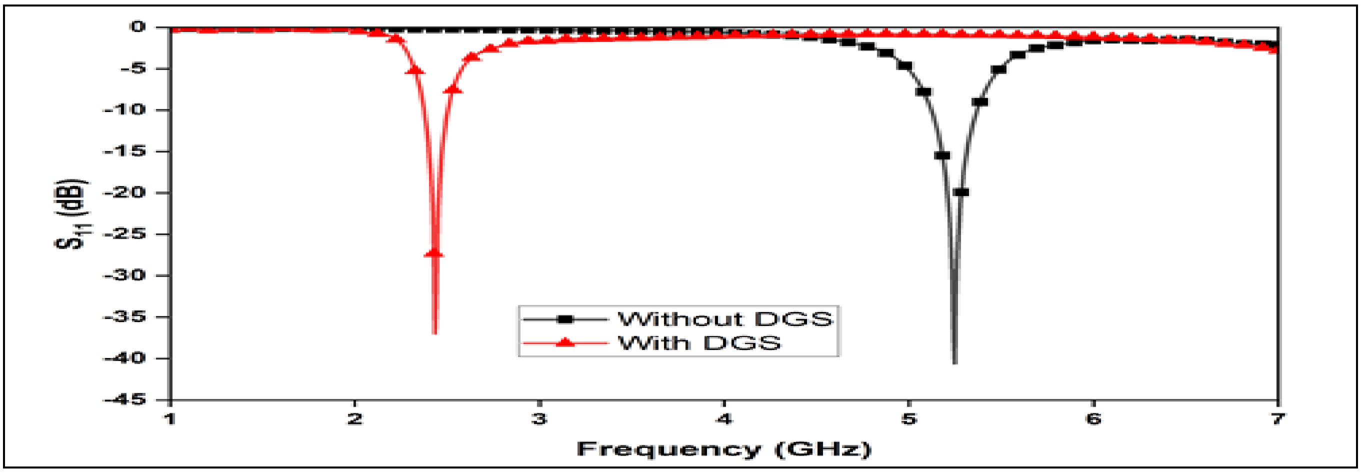


Fig 3 Simulated S_{11} of the Antenna.

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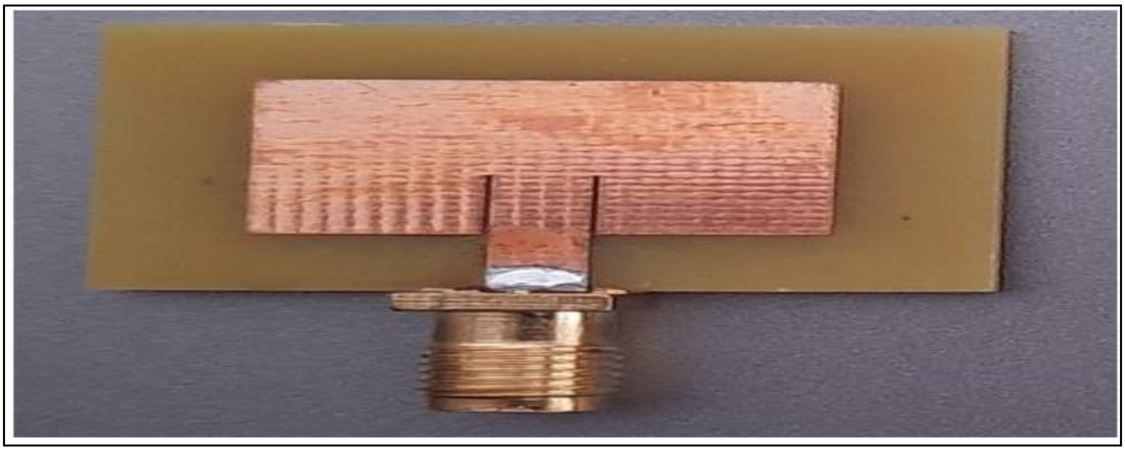
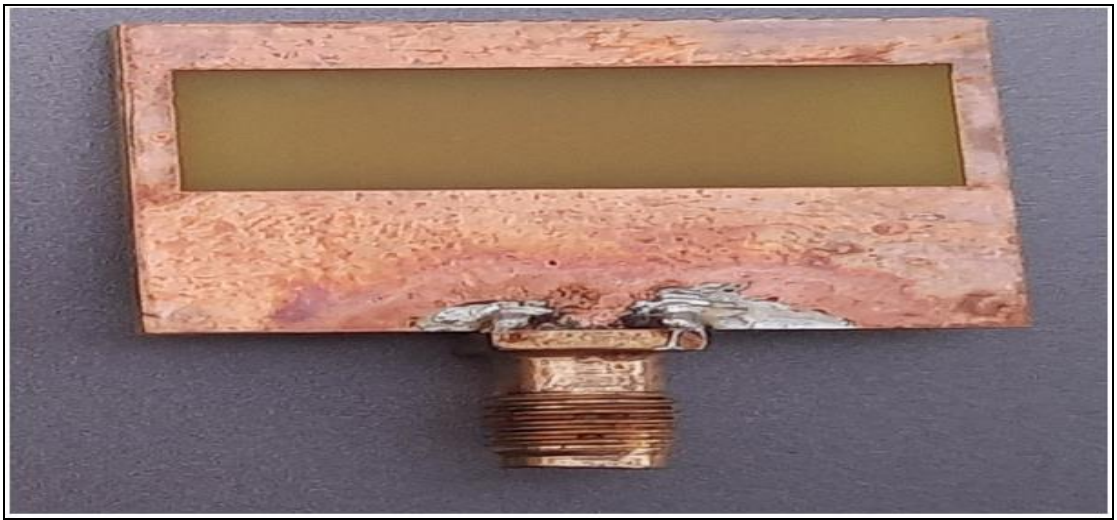
Table 2 Comparison Between Simulated and Measured Parameters of the Antenna.

	Antenna Parameters	Antenna Without DGS	Antenna With DGS
Simulated Results	**Resonance frequency (GHz)**	5.25	2.43
	Reflection coefficient (dB)	-40.62	-37
	Percentage Bandwidth	4.77%	5.34%
Measured Results	**Resonance frequency (GHz)**	5.11	2.44
	Reflection coefficient (dB)	-27.14	-20.25
	Percentage Bandwidth	8.95%	8.26%



(a)

(b)



(c)

Fig 4 Photograph of the Fabricated Antenna (A) Top View, (B) Bottom View Without DGS and (C) Bottom View with DGS.

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To confirm the simulation outcomes, antenna prototypes were constructed and tested. Fig. 4 displays the fabricated prototypes of the antenna, both with and without the rectangular Defected Ground Structure (DGS). The reflection coefficient (S_{11}) was measured using a Rohde & Schwarz Vector Network Analyzer (Model: ZVL13). As illustrated in Fig. 5, excellent agreement is achieved between the simulated and measured S_{11} results, which validates the design and confirms the effectiveness of the implemented DGS in achieving the desired antenna performance.

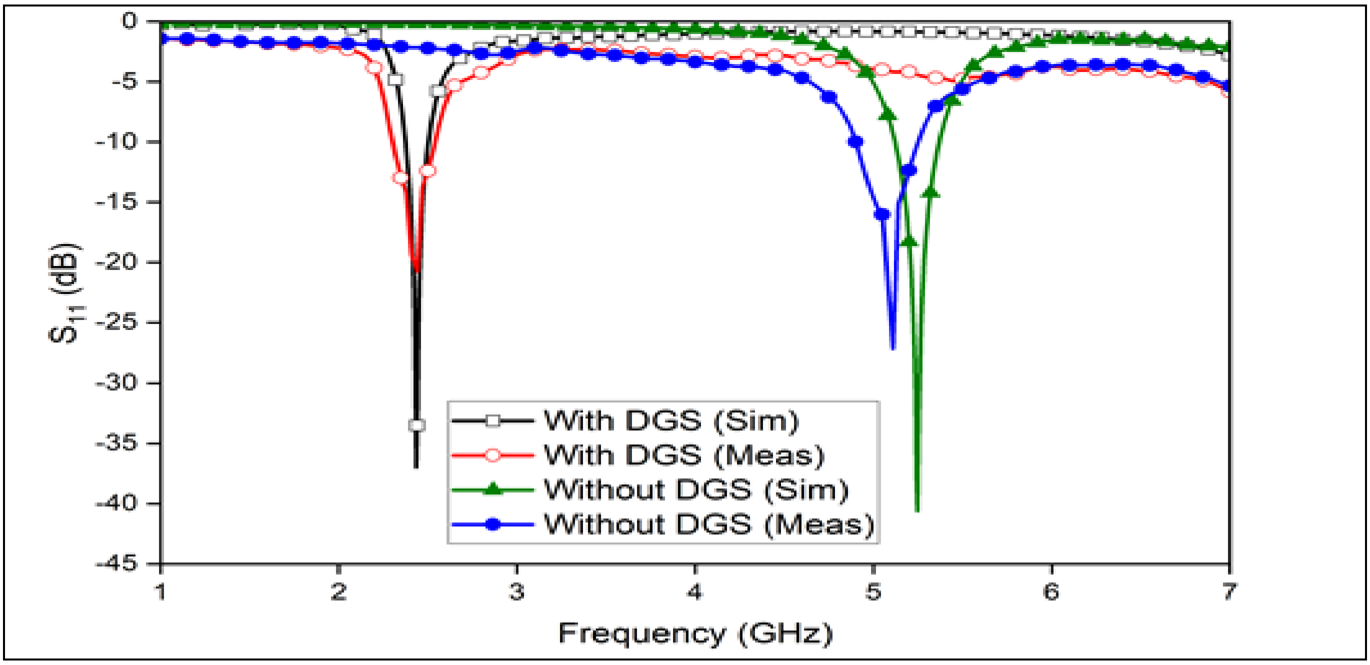


Fig 5 Comparison of Simulated and Measurement Results of the Antenna.

To delve deeper into how the rectangular Defected Ground Structure (DGS) contributes to antenna miniaturization, a detailed analysis of the antenna's surface current distribution was conducted both without and with the DGS. Fig. 6 and 7 illustrate the surface current distributions for these two scenarios, respectively. As shown in Fig. 6, the surface current is primarily concentrated on the patch itself. In contrast, Fig. 7 reveals that when the rectangular DGS is present, the surface current predominantly concentrates around the DGS area. This redistribution of the surface current due to the rectangular DGS leads the microstrip patch antenna to exhibit a bidirectional radiation pattern.

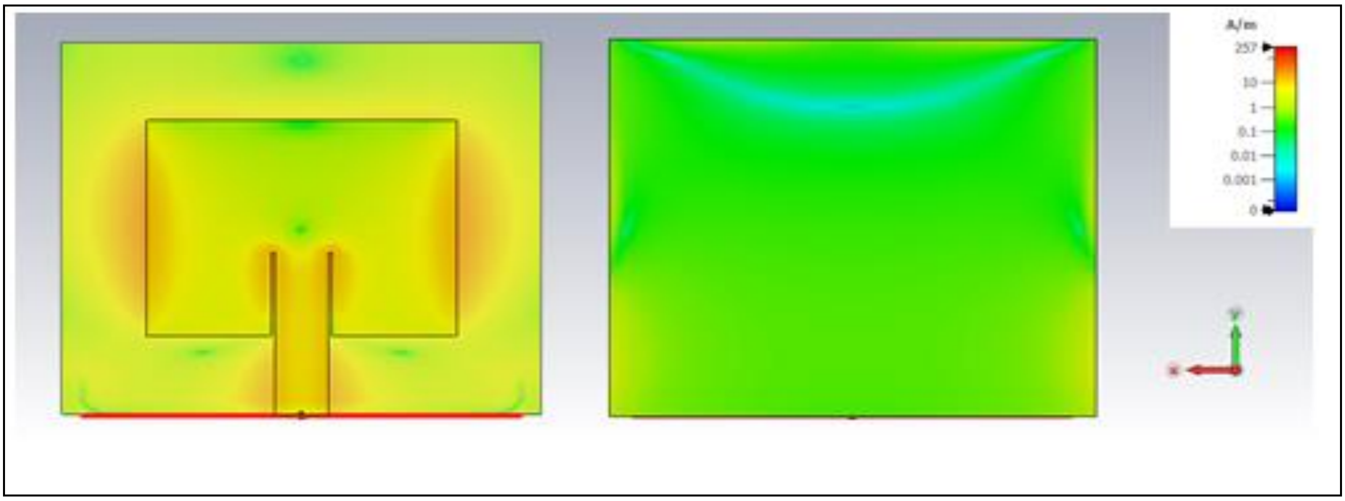


Fig 6 Distribution of Surface Current at 5.25 Ghz.

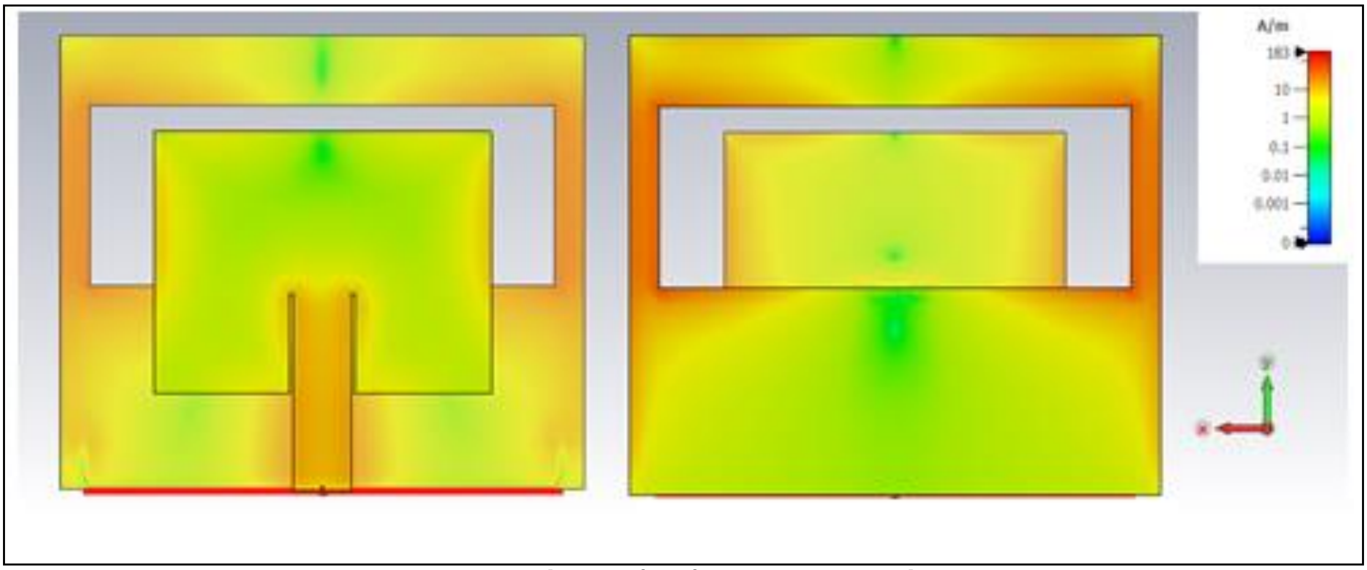
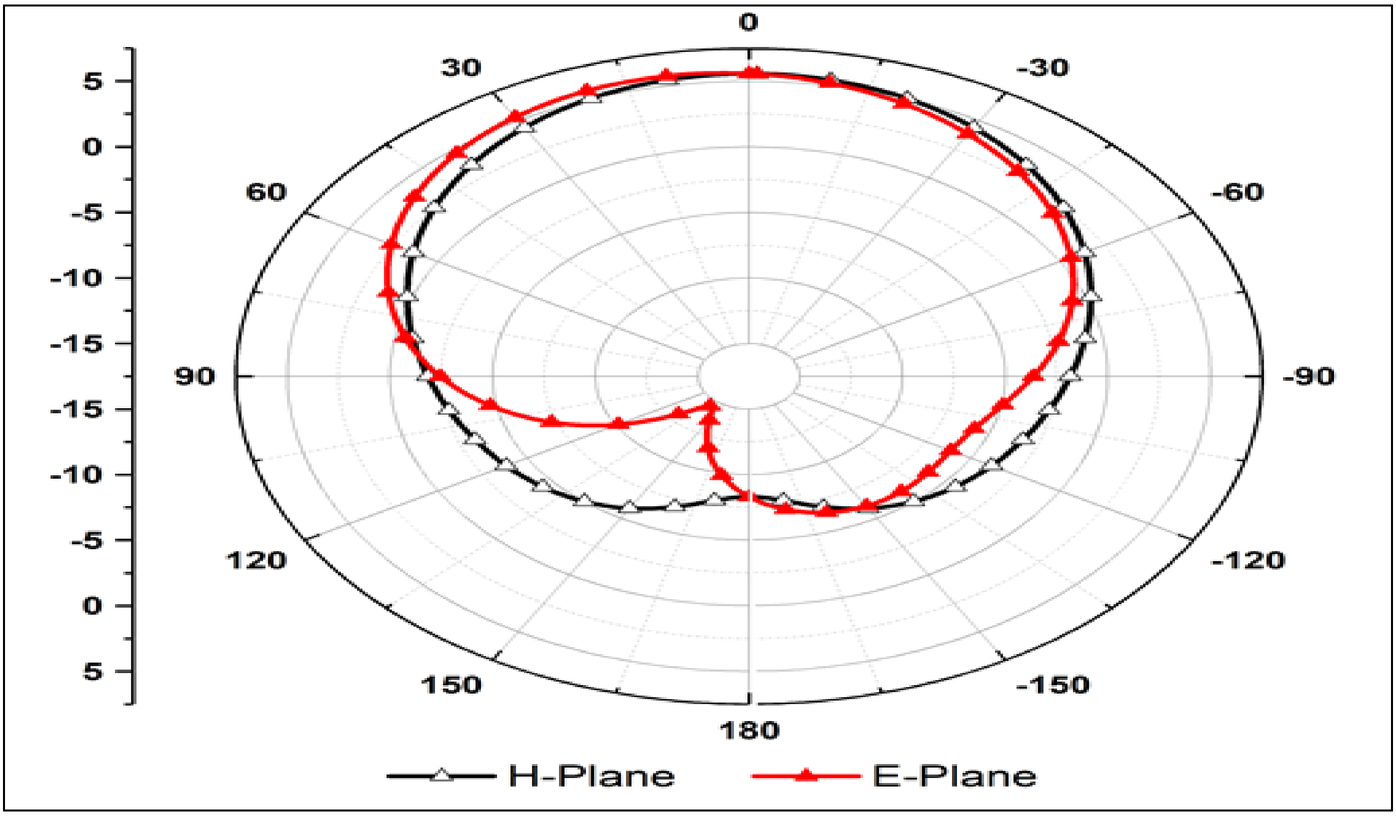


Fig 7 Distribution of Surface Current at 2.4 Ghz.

Fig. 8(a) presents the simulated radiation pattern of the antenna without the Defected Ground Structure (DGS), highlighting its behavior in both the E-plane and H-plane. In this configuration, the antenna exhibits a directional radiation pattern in each plane, achieving a directivity of 5.73 dBi. In contrast, Fig. 8(b) depicts the simulated radiation pattern when the rectangular DGS is integrated. With the DGS, the antenna produces a bidirectional radiation pattern in the E-plane and an omnidirectional pattern in the H-plane at 2.4 GHz, with a directivity of 2.84 dBi.

The percentage radiation efficiency and gain of the antenna with and without the rectangular Defected Ground Structure (DGS) are shown in Fig. 9. The introduction of the rectangular DGS improves the antenna's radiation efficiency across the operating band. Specifically, the antenna without DGS exhibits a gain of 2.33 dBi at 5.25 GHz, whereas the DGS-loaded antenna achieves a gain of 1.28 dBi at 2.43 GHz. The reduced gain at 2.43 GHz is attributed to the antenna's compact size resulting from the DGS implementation.



(a)

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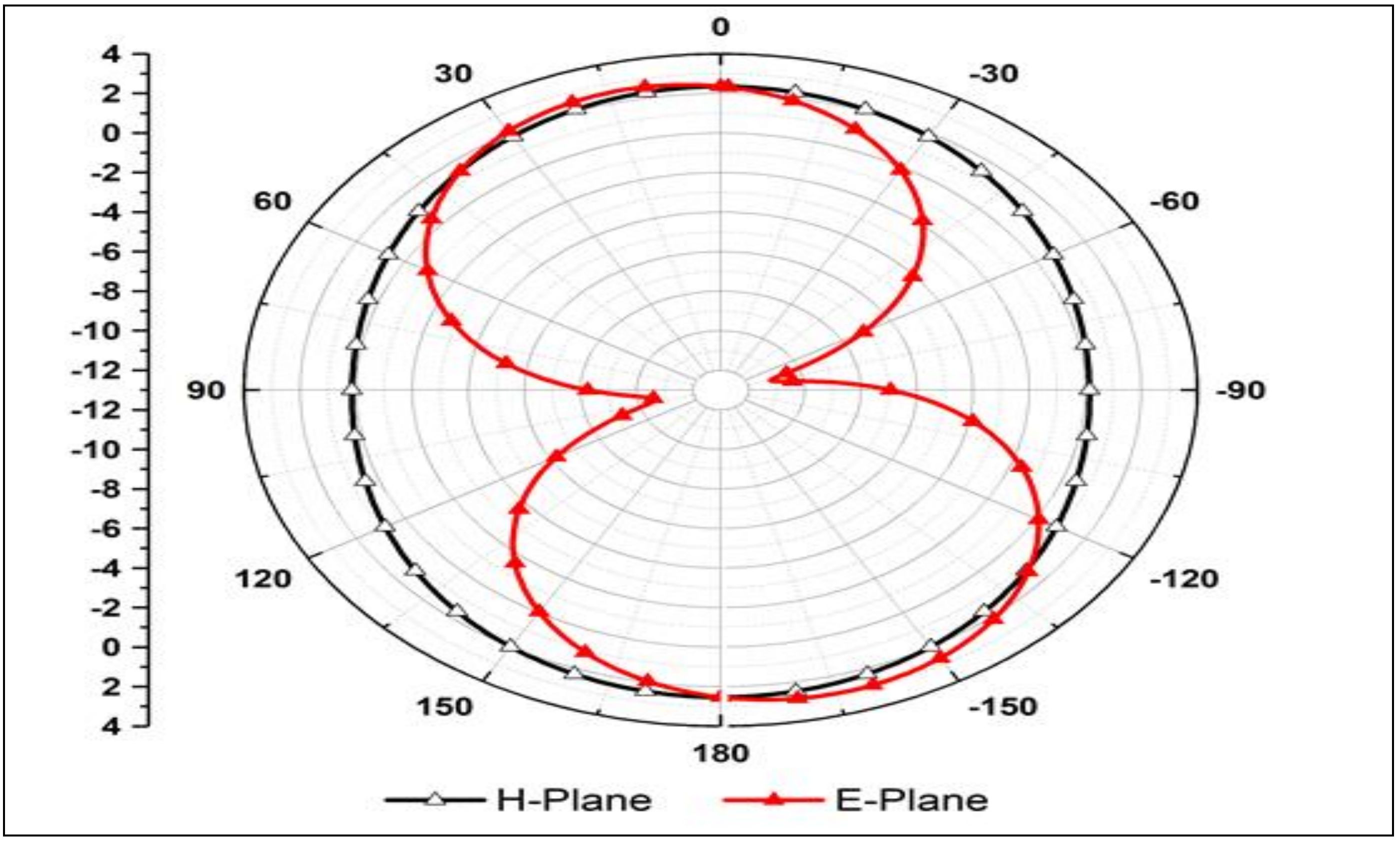

(b)

Fig 8 Simulated Antenna Radiation Patterns (A) 5.25 Ghz and (B) 2.4 Ghz.

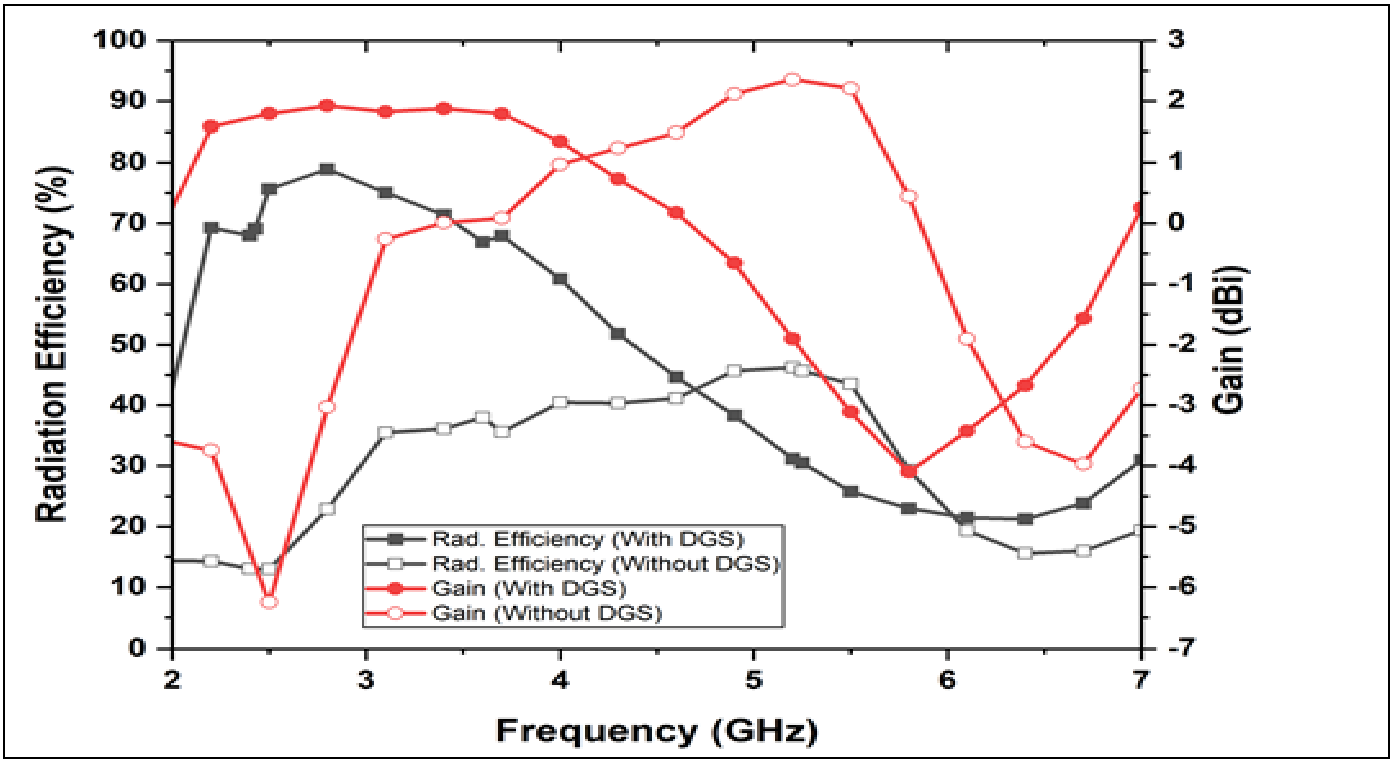

Fig 9 Simulated Radiation Efficiency and Gain (IEEE) of the Proposed Antenna with and Without DGS.

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V. CONCLUSIONS

A compact and highly efficient microstrip patch antenna featuring a rectangular Defected Ground Structure (DGS) is proposed. The antenna is miniaturized by etching a rectangular slot into its ground plane. This study examines how variations in the slot's length, width, and position influence the overall antenna performance. Notably, the placement and specific dimensions of the DGS significantly affect the resonant frequency, enabling the antenna to operate effectively at lower frequencies. With overall dimensions of 22.7×27 mm^2, the proposed design achieves a size reduction exceeding 67% compared to conventional microstrip patch antennas operating at 2.4 GHz. Both simulation and experimental results corroborate the antenna's performance. Consequently, the proposed antenna represents an excellent candidate for Wi-Fi applications in the 2.4 GHz band.

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