Circular microstrip antenna with defected ground structure for bandwidth enhancement at 2.4 GHz

Muhammad Nur Fadly[1], Deri Latika Herda[2], Popy Maria[3]
[1,2,3]Telecommunication Engineering, Politeknik Negeri Padang, Indonesia

**Corresponding Author: muhammadnurfadly600@gmail.com*

ABSTRACT

This study proposes an optimized circular microstrip patch antenna integrated with a stepped-slot Defected Ground Structure (DGS) for 2.4 GHz WLAN applications. The objective of this work is to improve the bandwidth and gain performance of conventional microstrip antennas, which are typically limited by narrow bandwidth and low radiation efficiency. The main contribution of this study is the development of a novel stepped-slot DGS configuration combined with a circular patch geometry to achieve simultaneous enhancement of bandwidth and gain. The proposed antenna is designed on an FR-4 substrate with a dielectric constant of 4.3 and a thickness of 1.6 mm, and analyzed using CST Microwave Studio. A parametric optimization of the DGS dimensions is performed to obtain optimal antenna performance. Simulation results show that the bandwidth increases significantly from 70.4 MHz to 298.8 MHz, representing more than a fourfold improvement. In addition, the antenna gain improves from 2.72 dBi to 3.87 dBi after the implementation of the DGS structure. These results confirm that the proposed stepped-slot DGS effectively enhances impedance bandwidth and radiation performance without increasing antenna complexity. Therefore, the proposed antenna is suitable for practical WLAN applications requiring compact size and improved performance. The findings of this study also provide useful insights for the design of high-performance microstrip antennas using DGS techniques in future wireless communication systems.

Keywords: Bandwidth enhancement; DGS; Gain improvement; Microstrip antenna; WLAN 2.4 GHz

ABSTRAK

Penelitian ini mengusulkan antena mikrostrip patch berbentuk lingkaran yang dioptimasi dengan mengintegrasikan Defected Ground Structure (DGS) berbentuk stepped-slot untuk aplikasi WLAN pada frekuensi 2,4 GHz. Tujuan utama penelitian ini adalah untuk meningkatkan bandwidth dan gain antena mikrostrip konvensional yang umumnya memiliki keterbatasan berupa bandwidth sempit dan efisiensi radiasi yang rendah. Kontribusi utama penelitian ini adalah pengembangan konfigurasi DGS stepped-slot yang baru yang dikombinasikan dengan geometri patch lingkaran untuk mencapai peningkatan bandwidth dan gain secara simultan. Antena yang diusulkan dirancang menggunakan substrat FR-4 dengan konstanta dielektrik 4,3 dan ketebalan 1,6 mm, serta dianalisis menggunakan CST Microwave Studio. Optimasi parameter dimensi DGS dilakukan untuk memperoleh performa antena yang optimal. Hasil simulasi menunjukkan bahwa bandwidth meningkat secara signifikan dari 70,4 MHz menjadi 298,8 MHz, atau lebih dari empat kali lipat. Selain itu, gain antena juga meningkat dari 2,72 dBi menjadi 3,87 dBi setelah penerapan struktur DGS. Hasil ini menunjukkan bahwa konfigurasi DGS stepped-slot yang diusulkan efektif dalam meningkatkan bandwidth impedansi dan performa radiasi tanpa menambah kompleksitas antena secara signifikan. Oleh karena itu, antena yang diusulkan sangat potensial untuk diaplikasikan pada perangkat WLAN yang membutuhkan ukuran kompak dengan performa yang lebih baik. Temuan penelitian ini juga memberikan wawasan penting dalam pengembangan antena mikrostrip berbasis DGS untuk sistem komunikasi nirkabel di masa depan.

Kata kunci: Antena mikrostrip; DGS; Peningkatan bandwidth; Peningkatan gain; WLAN 2.4 GHz

Manuscript Received 09 April. 2026; Revised 19 April. 2026; Accepted 01 May. 2026..

1. INTRODUCTION

Wireless communication technology has experienced rapid development in recent years due to the increasing demand for high-speed and reliable data connectivity [1]. One of the most widely adopted wireless communication technologies is the Wireless Local Area Network (WLAN), which operates in the 2.4 GHz frequency band. This frequency band is extensively used in various wireless devices such as WiFi routers, Internet of Things (IoT) devices, and other communication systems due to its wide coverage and compatibility [2], [3].

In wireless communication systems, antennas play a crucial role as they are responsible for converting electrical signals into electromagnetic waves that propagate through free space, and vice versa [4]. Among various types of antennas, the microstrip antenna is widely used due to its compact size, lightweight structure, and compatibility with printed circuit board (PCB) fabrication technology [2], [5]. A typical microstrip antenna consists of three main components: a radiating patch, a dielectric substrate, and a ground plane. The radiating patch is located on the top surface of the substrate, while the ground plane is placed on the bottom layer, enabling efficient integration into modern wireless devices [4].

Despite these advantages, microstrip antennas inherently suffer from limitations such as narrow bandwidth and relatively low gain, which restrict their performance in broadband wireless communication systems [2], [6], [7]. To overcome these limitations, various techniques have been proposed, including the use of slot structures, parasitic elements, and Defected Ground Structures (DGS) [6], [8].

Among these techniques, the Defected Ground Structure (DGS) has gained significant attention due to its effectiveness in modifying current distribution and electromagnetic characteristics on the ground plane. By introducing slots or defects in the ground plane, DGS can enhance impedance matching, increase bandwidth, and improve radiation performance [6], [8], [9]. In general, the DGS structure can be modeled as an equivalent LC circuit, where the slot introduces inductive effects while the gap contributes capacitive effects, leading to improved antenna performance.

Several previous studies have successfully applied DGS techniques to improve microstrip antenna performance. However, most of these works focus on rectangular or other common patch geometries, and limited attention has been given to circular patch antennas combined with optimized stepped-slot DGS configurations. Furthermore, existing studies often emphasize bandwidth enhancement without thoroughly addressing the simultaneous improvement of both bandwidth and gain, particularly for 2.4 GHz WLAN applications.

Based on these challenges, this study focuses on the design and analysis of a circular microstrip antenna operating at 2.4 GHz using CST Microwave Studio. The circular patch geometry is selected due to its symmetrical structure, which provides uniform current distribution, reduced edge diffraction effects, and more stable radiation characteristics compared to other geometries such as rectangular or triangular patches. Additionally, circular patches can achieve a more compact size for a given resonant frequency, making them suitable for compact wireless devices.

This study aims to investigate the effect of a stepped-slot Defected Ground Structure on antenna performance by comparing the characteristics before and after DGS implementation. The evaluated parameters include return loss (S11), bandwidth, and antenna gain.

The main contributions of this study are:

1. A novel circular microstrip antenna design integrated with a stepped-slot Defected Ground Structure.
2. A systematic parametric optimization of DGS dimensions to significantly enhance bandwidth performance.
3. A comprehensive performance evaluation comparing conventional and DGS-based antennas in terms of return loss, bandwidth, and gain for 2.4 GHz WLAN applications.

ISSN : 2964-2655

2. RESEARCH METHOD

In this research, a circular microstrip patch antenna operating at a frequency of 2.4 GHz was designed and analyzed using the electromagnetic simulation software CST Microwave Studio. Microstrip antennas are widely employed in modern wireless communication systems due to their compact dimensions, lightweight structure, and simple fabrication process using printed circuit board (PCB) technology [2], [5]. To provide a clear understanding of the research procedure, the overall methodology is illustrated in the form of a flowchart, as shown in Figure 1.

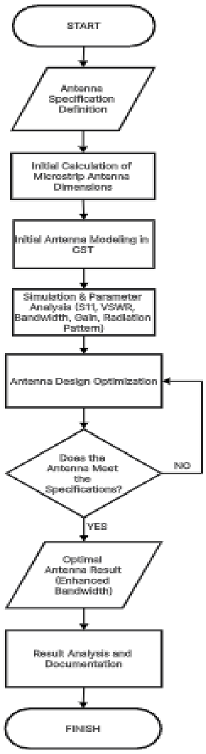

Figure 1. Flowchart of the proposed antenna design methodology

The overall research methodology is illustrated in Figure 1 in the form of a flowchart. The process begins with the specification of antenna requirements, including the operating frequency of 2.4 GHz for WLAN applications and the selection of the FR-4 substrate material.

In the next step, a conventional circular microstrip patch antenna is designed using initial analytical calculations based on the cavity model. The calculated parameters, such as patch radius and feedline dimensions, are then implemented and simulated using CST Microwave Studio.

After obtaining the baseline performance of the conventional antenna, a Defected Ground Structure (DGS) is introduced on the ground plane in the form of a stepped-slot configuration. Subsequently, a parametric optimization process is carried out by varying key DGS dimensions, particularly Wdgs and Ldgs, using the parameter sweep feature in CST.

The simulation results are then evaluated in terms of return loss (S11), bandwidth, and antenna gain. If the performance does not meet the desired criteria, the design parameters are adjusted iteratively until optimal results are achieved.

Finally, the optimized antenna design is compared with the conventional antenna to analyze the performance improvement achieved through the implementation of the DGS. The process ends with drawing conclusions based on the obtained results.

Generally, a microstrip antenna consists of three main components: the radiating patch, the dielectric substrate, and the ground plane [4]. The patch, which acts as the radiating element, is typically made of a thin conductive material placed on the top surface of the dielectric substrate, while the ground plane is located on the opposite side. This configuration provides a

low-profile structure that can be easily integrated with various wireless communication devices such as WLAN and Internet of Things (IoT) systems [2].
In this study, the antenna design process was divided into two main stages:
1. Designing a conventional antenna without a Defected Ground Structure (DGS).
2. Designing an antenna with a modified ground plane incorporating the DGS technique.

The primary objective of this work is to evaluate the effect of the Defected Ground Structure technique on antenna performance, particularly in terms of return loss (S11) and antenna gain.

The proposed antenna is designed using an FR-4 substrate, which is commonly used in microstrip antenna design due to its low cost and easy availability [2], [5].

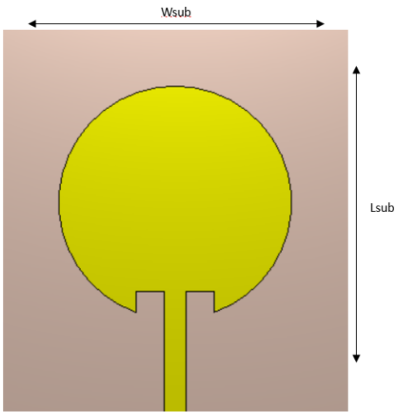

Figure 2. Geometry of the proposed microstrip antenna PCB.

Figure 2 illustrates the basic structure of the printed circuit board (PCB) used as the substrate of the microstrip antenna. The substrate has dimensions of 50 mm × 55 mm with a thickness of 1.6 mm and is made of FR-4 material as the dielectric layer. This substrate thickness is commonly used in microstrip antenna designs operating within the frequency range of approximately 2–3 GHz.

The radiating patch and the feedline are fabricated using copper with a thickness of 0.035 mm. Copper is selected due to its high electrical conductivity, which helps improve the radiation efficiency of the antenna.

2.1. Conventional Circular Patch Design

The first step in this research is the design of a conventional circular microstrip patch antenna with an unmodified ground plane. This initial configuration serves as a reference model to analyze the antenna performance prior to applying the Defected Ground Structure (DGS) technique.

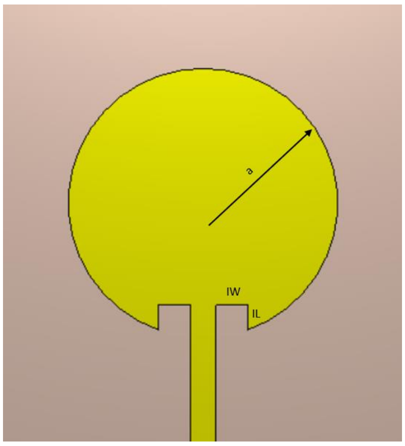

Figure 3. Geometry of the circular microstrip patch antenna.

The radius of the circular patch is calculated based on the cavity model using the following equations:

$$F = \frac{8.791\times10^9}{fr\sqrt{\mathcal{E}r}} \quad (1)$$

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

The feedline width is determined using the transmission line model as follows:

$$W_f = \frac{2h}{\pi}\left[B-1-\ln(2B-1)+\frac{\epsilon_{r-1}}{2\epsilon_r}\left(\ln(B-1)+0.39-\frac{0.61}{\epsilon_r}\right)\right]$$

(3)

$$B = \frac{60\pi 2}{z_0\times\sqrt{\epsilon_r}}$$

(4)

Where:

$a \;= radius\ of\ the\ circular\ patch\ (mm)$

$F \;= intermediate\ parameter\ for\ radius\ calculation$

$fr = resonant\ frequency\ (Hz)$

$\mathcal{E}r = dielectric\ constant\ of\ the\ substrate$

$h \;= substrate\ thickness\ (mm)$

$W_f = feedline\ width\ (mm)$

$B \;= intermediate\ parameter\ used\ in\ feedline\ width\ calculation$

$z_0 = characteristic\ impedance\ (typically\ 50\ \Omega)$

a is the radius of the circular patch, εr is the dielectric constant of the substrate, h is the substrate thickness, fr is the resonant frequency, and Wf is the feedline width. These equations are based on the cavity model approach for circular microstrip antenna design [4].

Figure 2 illustrates the geometry of the circular patch antenna used in this study. The radiating patch is designed in a circular shape with a radius of 17.2 mm and is positioned on the top surface of the FR-4 substrate. The patch is placed at the center of the substrate to maintain symmetrical current distribution, which helps produce a stable radiation pattern at the antenna's resonant frequency.

The circular patch configuration provides uniform current distribution and stable radiation characteristics compared to other patch geometries. The calculation of the patch radius in this work follows the cavity model approach [4], which is commonly applied in the design of circular microstrip patch antennas.

Table 1. Antenna design parameters

Parameters	Value (mm)
h	1.6
a	17.2
W_{feed}	3.1
IL	4
IW	4
W_{sub}	50
L_{sub}	55

After determining the initial antenna dimensions as presented in Table 1, an optimization process was carried out to achieve the best antenna performance at the operating frequency of 2.4 GHz. Several key design parameters were optimized, including the patch radius, feedline width, and inset feed dimensions. The optimization was performed iteratively using the parameter sweep feature in CST Microwave Studio until the configuration yielding the lowest return loss (S11) and stable resonance at the desired frequency was obtained.

The simulation results are presented systematically in terms of return loss (S11) and antenna gain, with a clear comparison between the conventional antenna and the antenna incorporating the Defected Ground Structure (DGS). The results demonstrate a significant improvement in antenna performance, where the implementation of the DGS leads to a substantial increase in bandwidth and a noticeable enhancement in gain.

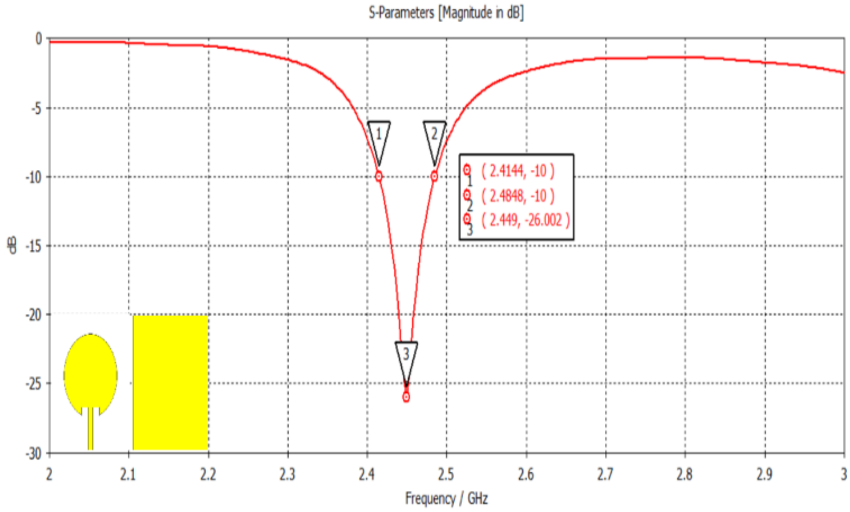

Figure 4. Simulated return loss (S11) of the conventional antenna without DGS.

Figure 4 illustrates the simulated return loss (S11) characteristics of the conventional circular microstrip antenna without the Defected Ground Structure. The antenna exhibits a resonant frequency around 2.462 GHz with a return loss value lower than −10 dB. The effective operating frequency range spans from 2.4144 GHz to 2.4848 GHz, which corresponds to a bandwidth of 70.4 MHz.

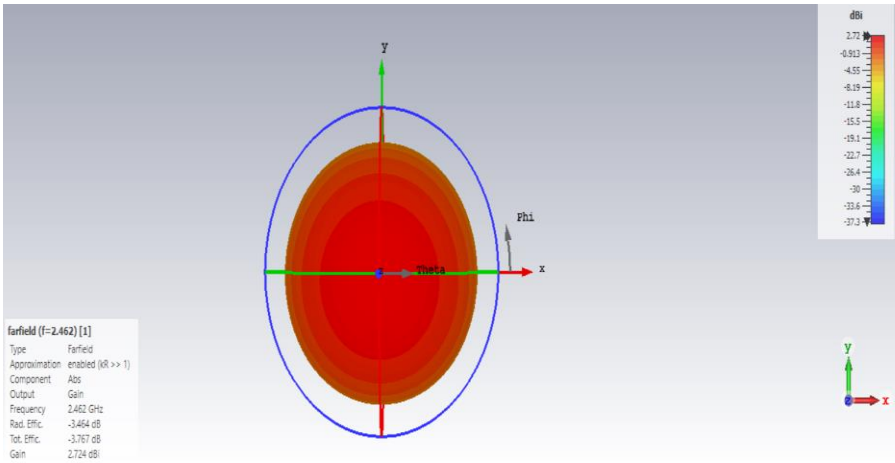

Figure 5. Simulated gain of the conventional antenna without DGS.

Figure 5 illustrates the simulated gain of the conventional circular microstrip antenna without the application of the Defected Ground Structure. The antenna achieves a maximum gain of 2.72 dBi at a resonant frequency near 2.462 GHz. This relatively low gain is commonly observed in conventional microstrip antenna designs.

2.2. Defected Ground Structure Design

Once the conventional antenna design was established, a Defected Ground Structure (DGS) was introduced on the ground plane. The DGS technique involves introducing slots or defects in the ground plane to modify the surface current distribution and electromagnetic characteristics of the antenna, which can enhance important performance parameters such as bandwidth and gain [6], [9]. In this work, a rectangular stepped slot configuration is employed as the DGS and is located at the center of the ground plane.

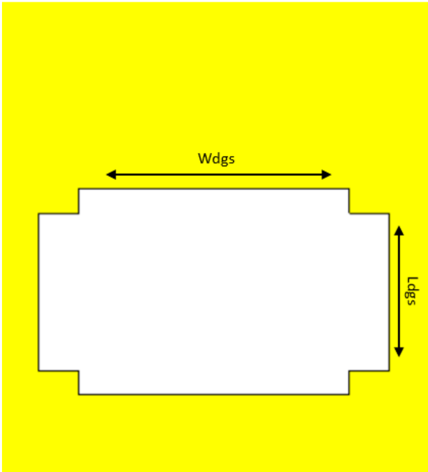

Figure 6. Geometry of the Defected Ground Structure applied to the ground plane.

Figure 6 presents the geometry of the Defected Ground Structure implemented on the antenna ground plane. The DGS is designed as a rectangular stepped slot positioned at the center of the ground plane. The primary slot measures 30.8 mm × 23.5 mm and is accompanied by two symmetrical side slots with dimensions of 4.5 mm × 18 mm. The symmetrical arrangement ensures a balanced distribution of surface currents on the ground plane. The relative location of the DGS with respect to the radiating patch is determined by the position parameter $Y_{dgs} = -6$.

The presence of slots on the ground plane effectively extends the surface current path compared to a conventional ground plane configuration. This modification changes the electromagnetic characteristics of the antenna, which contributes to bandwidth enhancement and improved radiation efficiency [10], [11], [12].

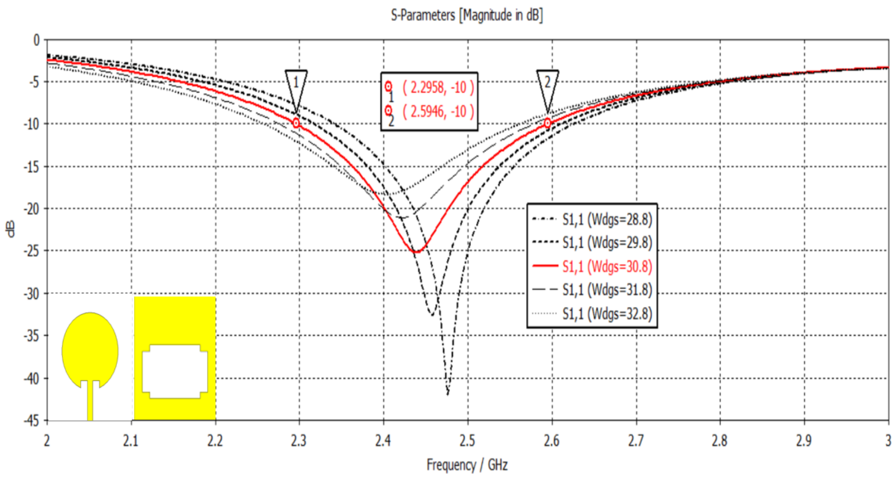

Figure 7. Parameter sweep optimization of W_{dgs} from 28.8 mm to 32.8 mm.

Figure 7 illustrates the parametric optimization of the DGS dimensions. To obtain the optimal antenna performance, a parametric study was conducted on the dimensions of the Defected Ground Structure (DGS), particularly the width W_{dgs} and length L_{dgs}. The optimization range for W_{dgs} was varied from 28.8 mm to 32.8 mm with a step size of 1 mm, while L_{dgs} was maintained around its initial design value based on preliminary simulations.

The selected parameter range was determined based on initial analytical estimation and iterative simulations to ensure that the antenna resonance remains within the 2.4 GHz WLAN frequency band. Variations outside this range were observed to significantly shift the resonant frequency away from the desired operating band.

The optimization process was carried out using the parameter sweep feature in CST Microwave Studio, where each parameter variation was evaluated based on return loss (S11), bandwidth, and resonance stability. The optimal value of W_{dgs} = 30.8 mm was selected as it provided the best impedance matching and the widest bandwidth.

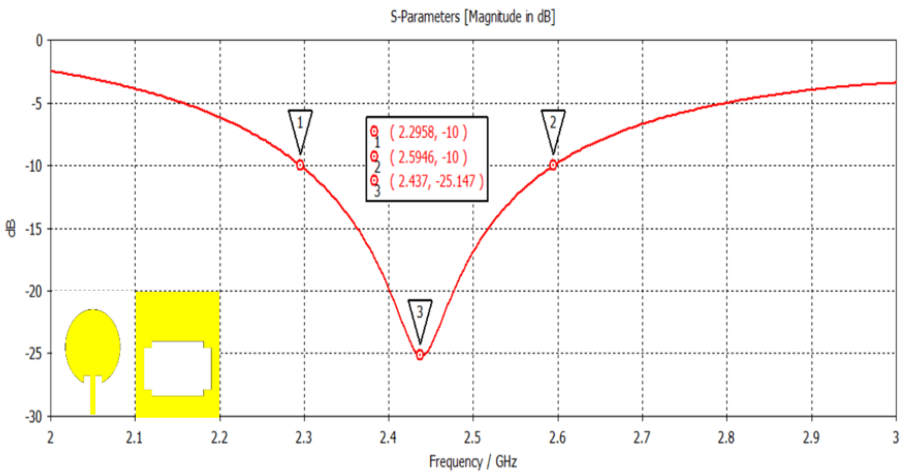

Figure 8. Simulated return loss of the antenna after applying the optimized DGS.

Figure 8 illustrates the simulated return loss characteristics of the antenna after applying the optimized Defected Ground Structure. The antenna exhibits a resonant frequency around 2.462 GHz with a return loss below −10 dB. The effective operating frequency range spans from 2.2958 GHz to 2.5946 GHz, resulting in a bandwidth of 298.8 MHz. This improvement confirms that the optimization and the introduction of the DGS structure successfully enhance the bandwidth performance compared to the conventional antenna configuration.

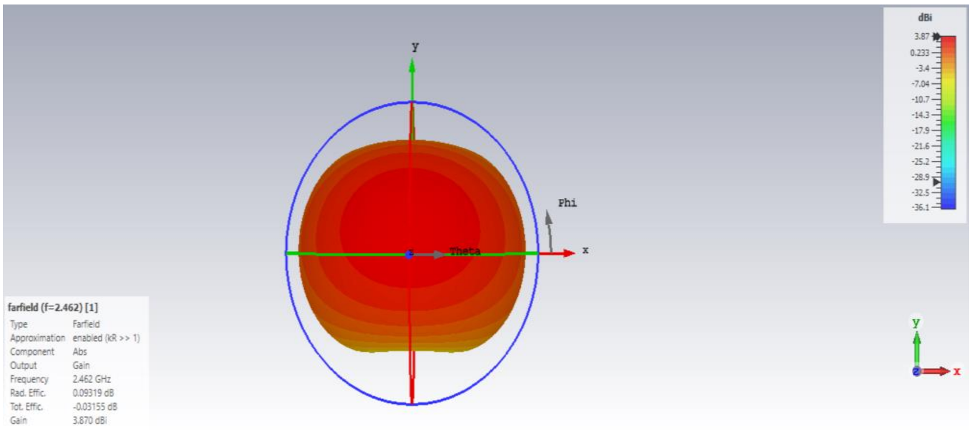

Figure 9. Simulated gain of the antenna after DGS optimization.

Figure 9 presents the simulated gain characteristics of the antenna after the implementation of the Defected Ground Structure and the optimization process. The antenna achieves a maximum gain of 3.87 dBi at a resonant frequency close to 2.462 GHz. This gain value is higher than that of the conventional antenna without DGS, which provides a gain of 2.72 dBi.

The observed gain improvement indicates that the ground plane modification and parameter optimization contribute to enhanced radiation efficiency.

3. RESULTS AND DISCUSSION

This section presents a comprehensive analysis of the performance of the circular microstrip patch antenna designed using CST Microwave Studio. The evaluation is conducted by comparing the characteristics of the conventional antenna without the Defected Ground Structure (DGS) and the antenna incorporating the DGS modification.

The antenna performance is analyzed in terms of resonant frequency, bandwidth, and antenna gain. A systematic comparison between both configurations is carried out to clearly identify the impact of the DGS on the overall antenna performance.

The Defected Ground Structure (DGS) can be represented by an equivalent LC circuit model, where the slot structure introduces additional inductance (L) due to the elongation of the surface current path, while the gap between the slots contributes to capacitance (C). This LC resonance behavior plays a significant role in modifying the input impedance and enhancing the bandwidth of the antenna.

Specifically, the stepped-slot geometry increases the effective current path length, leading to higher inductance, while the slot gaps create capacitive coupling effects. The interaction between these inductive and capacitive elements produces multiple resonant modes (multi-resonance behavior), which overlap and result in a significantly wider impedance bandwidth.

Based on the simulation results, the conventional antenna without DGS resonates at 2.462 GHz and provides a bandwidth of 70.4 MHz, which is relatively narrow and represents a common limitation of conventional microstrip antennas [2], [6].

After introducing the Defected Ground Structure on the ground plane, the antenna performance improves significantly. Although the resonant frequency remains stable at 2.462 GHz, the bandwidth increases substantially to 298.8 MHz, representing more than a fourfold improvement. This significant enhancement confirms the effectiveness of the DGS in generating additional resonant modes and improving impedance matching.

In addition to bandwidth enhancement, the antenna gain also increases from 2.72 dBi to 3.87 dBi after applying the DGS structure. This improvement indicates enhanced radiation efficiency due to the modified surface current distribution.

The improvement in bandwidth and gain occurs because the DGS modifies the surface current distribution on the ground plane, effectively extending the current path [6]. This modification alters the electromagnetic characteristics of the antenna and improves its radiation performance [10], [13], [14].

Table 2 presents the comparison of antenna performance before and after the implementation of the Defected Ground Structure (DGS). The results confirm that the proposed antenna design successfully covers the entire 2.4 GHz WLAN frequency band while achieving significant improvements in both bandwidth and gain.

Table 2. Comparison of antenna performance with and without DGS

Parameters	Without DGS	With DGS
Resonant Frequency	2.462 GHz	2.462 GHz
Bandwidth	70.4 MHz	298.8 MHz
Gain	2.72 dBi	3.87 dBi

The enhancement in both bandwidth and gain achieved by the antenna with the DGS configuration is attributed to the alteration of the surface current distribution on the ground plane. The slots incorporated in the DGS structure extend the current path and modify the electromagnetic characteristics of the antenna, generating additional inductive effects within the ground plane. Consequently, the electromagnetic characteristics of the antenna are modified, leading to improved bandwidth and better radiation efficiency.

4. CONCLUSION

From the design and simulation of the circular microstrip patch antenna operating at 2.4 GHz, it can be concluded that the implementation of the stepped-slot Defected Ground Structure (DGS) significantly enhances antenna performance. The proposed antenna achieves a substantial bandwidth improvement from 70.4 MHz to 298.8 MHz, representing more than a fourfold increase compared to the conventional design. In addition, the antenna gain is improved from 2.72 dBi to 3.87 dBi, indicating enhanced radiation efficiency.

The performance improvement is attributed to the modification of the surface current distribution on the ground plane, where the stepped-slot DGS introduces additional inductive and capacitive effects that improve impedance matching and generate multiple resonant modes. This confirms that the proposed DGS configuration is an effective and practical technique for achieving simultaneous bandwidth and gain enhancement in microstrip antenna design.

Overall, the proposed antenna successfully covers the 2.4 GHz WLAN frequency band while maintaining a compact structure and simple configuration. These characteristics make it highly suitable for practical wireless communication applications, particularly for compact WLAN devices requiring improved performance without increasing design complexity. Furthermore, this study provides a valuable design reference for future development of high-performance microstrip antennas using DGS techniques.

For future work, experimental validation through antenna fabrication and measurement is recommended to verify the simulation results. In addition, further investigation on alternative DGS geometries and advanced optimization techniques can be explored to achieve even higher performance improvements.

REFERENCES

[1] I. F. Akyildiz, A. Kak, and S. Nie, “6G and Beyond: The Future of Wireless Communications Systems,” IEEE Access, vol. 8, pp. 133995–134030, 2020, doi: 10.1109/ACCESS.2020.3010896.

[2] M. S. Rana et al., “A review on microstrip patch antenna for wireless communication systems at 3.5 GHz,” Aug. 01, 2024, Institute of Advanced Engineering and Science. doi: 10.11591/eei.v13i4.5941.

[3] N. L. Nhlengethwa and P. Kumar, “Fractal microstrip patch antennas for dual-band and triple-band wireless applications,” International Journal on Smart Sensing and Intelligent Systems, vol. 14, no. 1, pp. 1–9, Feb. 2021, doi: 10.21307/IJSSIS-2021-007.

[4] C. A. Balanis, “ANTENNA THEORY,” 2016.

[5] T. Omoleye, J. Ojo, and O. Faromika, “Development of Microstrip Patch Antenna through Variant Shapes Technique for 5G Application and Future Wireless Communication Systems,” 2025, pp. 51–66. doi: 10.2991/978-94-6463-644-4_6.

[6] M. K. Khandelwal, B. K. Kanaujia, and S. Kumar, “Defected ground structure: Fundamentals, analysis, and applications in modern wireless trends,” 2017, Hindawi Limited. doi: 10.1155/2017/2018527.

[7] M. S. Shishkin, “Bandwidth Enhancement Methods Analysis for High-Gain Stacked Microstrip Antenna,” Progress In Electromagnetics Research B, vol. 107, pp. 19–31, 2024, doi: 10.2528/PIERB24052703.

[8] M. L. El Issawi, D. Konditi, and A. 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, Mar. 2024, doi: 10.37391/ijeer.120143.

[9] P. Haryanto, D. W. Astuti, M. Alaydrus, A. Firdausi, D. Rusdiyanto, and H. A. Majid, “An ultra-broadband microstrip antenna using a triple dumbbell-shaped defected ground structure,” Sinergi (Indonesia), vol. 30, no. 1, pp. 79–90, 2026, doi: 10.22441/sinergi.2026.1.008.

[10] P. Pushadapu, G. S. Rao, P. Thota, P. Parisa, and V. Indhu, “A Multiband High-Performance L-Shaped Microstrip Patch Antenna with DGS For 5G Applications,” International Journal of Innovative Research in Engineering and Management, vol. 12, no. 2, pp. 75–76, May 2025,

doi: 10.55524/ijirem.2025.12.2.12.
[11] D. Rusdiyanto, C. Apriono, D. W. Astuti, and M. Muslim, "BANDWIDTH AND GAIN ENHANCEMENT OF MICROSTRIP ANTENNA USING DEFECTED GROUND STRUCTURE AND HORIZONTAL PATCH GAP," SINERGI, vol. 25, no. 2, p. 153, Feb. 2021, doi: 10.22441/sinergi.2021.2.006.
[12] R. V. H. Prasad, D. Vakula, and M. Chakravarthy, "A New Approach in Realisation of DGS Microstrip Patch Antennas With Fractal Geometry," Def. Sci. J., vol. 73, no. 4, pp. 468–474, 2023, doi: 10.14429/dsj.73.18561.
[13] A. Tsegaye, X. Q. Lin, H. Liu, and H. S. Abubakar, "A Compact Monopole Wideband Antenna Based on DGS," Electronics (Switzerland), vol. 14, no. 12, Jun. 2025, doi: 10.3390/electronics14122311.
[14] G. K. Soni, D. Yadav, A. Kumar, P. Jain, and M. V. Yadav, "Design and optimization of flexible DGS-based microstrip antenna for wearable devices in the Sub-6 GHz range using the nelder-mead simplex algorithm," Results in Engineering, vol. 24, Dec. 2024, doi: 10.1016/j.rineng.2024.103470.