International Journal of Computational Science and Engineering Research
ISSN: 3107 - 8605 (Online) , http://www.ijcser.com/
Regular Issue , Vol. 3, Issue. 2 (April– June) , 2026 , Pages: 1 - 5
Received: 18 June 2025 ; *Accepted:* 29 March 2026 ; *Published:* 07 April 2026
https://doi.org/10.63328/IJCSER-V3RI2P1
Original Paper : Applied Research – Experimental Research Paper

Design and Parametric Analysis of a Broadband Elliptical Slot Antenna with Defected Ground Structure for Multi-Band Applications

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Abstract: This paper deals with the design and parametric study of a miniaturized elliptical slot microstrip antenna with defect ground structure (DGS). The antenna is fabricated on a FR4 substrate with dimensions of 40 × 40 × 1.6 mm³. The systematic design of the antenna involves incorporating slots into the radiating patch and altering the ground plane structure. The parameters considered include slot ratio effect and the effect of ground defects on the resonant frequency, return loss, bandwidth, and gain. The original design of the antenna is characterized by dual bands with narrow bandwidth. When successive changes are made to the slots, the antenna becomes a multiband antenna. The inclusion of DGS greatly improves the performance of the antenna with an ultrawide bandwidth of 6.33 GHz, good return loss of −37.45 dB, and gain 4.9 dBi.

Keywords: Elliptical Slot Antenna, DGS, Broadband Antenna, Multi-band, Microstrip Antenna.

1. Introduction

Microstrip antennas find extensive applications in wireless communications because of their small size, relatively inexpensive construction and ease of fabrication. However, traditional microstrip antennas have inherent drawbacks, such as limited bandwidth and low gain. In order to improve upon these drawbacks, several approaches have been explored that include slot loading, and DGS. The use of slots alters the current density pattern, enabling multi-band operation and improved impedance matching. Similarly, defects introduced in the ground plane help in increasing bandwidth and gain by limiting surface waves. Among different geometrical shapes, elliptical slot antennas prove to be very effective for wide band and multi-band applications. This study focuses on the design of an elliptical slot antenna in a series of stages. The initial stage involves design of a simple elliptical patch antenna that undergoes further enhancements based on slots and DGS approach.

2. Literature Review

Microstrip antennas are well-studied due to their small size, thin profile, and ease of manufacturing. Nonetheless, problems associated with these antennas such as their narrow bandwidths and low gains led scientists to come up with different methods for optimizing them. Classic books on antennas such as Antenna Theory: Analysis and Design by C. A. Balanis [1] and Compact and Broadband Microstrip Antennas by K. L. Wong [2] discuss design principles and the need for bandwidth enhancement in microstrip antennas [3]. One common way to enhance antenna performance is through Defected Ground Structures (DGS) [4]. The study carried out by Weng et al. [5] gives an insight into DGS by revealing how the method optimizes the inductance and capacitance of the ground plane resulting in enhanced impedance bandwidth and rejection of spurious modes. Likewise, Yeo et al. [10] present a novel technique for size and bandwidth optimization of microstrip antennas using DGS technology.

Bandwidth optimization using slot loading technique has also been extensively explored [6]. According to Abdelaziz [6], the creation of slots in the radiating patch enhances the impedance bandwidth by altering the current distribution [7]. Furthermore, Oraizi and Hedayati used both slot loading and DGS to develop an ultra-wideband microstrip antenna [8]. This clearly shows that applying both techniques is more effective than applying each method

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individually. Dual band or multi-band antennas have recently become highly important in wireless communication applications. For instance, Acıkaya and Yıldırım [9] developed a dual band microstrip antenna working at 2.45 GHz and 5 GHz frequencies for WLAN applications with optimized impedance matching and radiation characteristics.

On the other hand, Ramineni [8] proposed a dual-band antenna design operating below 6 GHz with enhanced reflection coefficient and gain, using HFSS. The latest trend in antennas is combining different geometries and DGS to enhance performance [9]. For example, according to the results obtained from your previous research [3], the implementation of F-shape geometry with DGS enabled dual band operation at 2.375 GHz and 5.325 GHz frequencies with return losses of −30.6 dB and −41.85 dB, respectively.

Moreover, beyond DGS, the use of metamaterials has become an effective means to enhance antenna performance [10]. The idea of metamaterials was proposed by Engheta and Ziolkowsk. These materials possess unusual electromagnetic properties, such as negative permittivity and permeability, that allow for better control of electromagnetic waves' behavior [12].

In your previous study [4], you designed a metamaterial-loaded antenna based on Split Ring Resonators (SRRs), which exhibited multi-band functionality in Ku-band, providing a 18.8 dBi gain enhancement and a 2.33 GHz bandwidth enhancement [13]. Additionally, Guha and Antar [9] highlighted recent developments in printed antennas and noted that contemporary designs should incorporate hybrid techniques such as slot loading, DGS, and metamaterials to achieve compact size, high performance, and enhanced functionality.

The literature is clear that although each technique individually contributes to antenna effectiveness, their combined use results in a marked improvement in bandwidth and gain. Based on the results of research in this field, this work aims to develop an antenna with elliptical slot loading and DGS for broadband and multi-band operations [14].

3. Antenna Design and Methodology

A broadband and multiband antenna is proposed and designed using a systematic design technique. The antenna is fabricated using FR4 substrate with dielectric constant (εr) of 4.4 and thickness of 1.6 mm, with overall size of 40×40 mm² as illustrated in Fig.1. Design development is done in several stages, including slot loading and DGS design to improve impedance bandwidth and return loss, illustrated in Fig.2, along with gain [15].

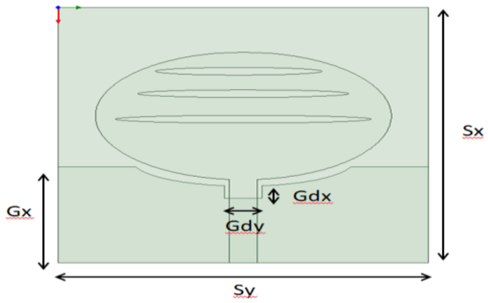

Figure.1 Elliptical Slot Antenna with DGS

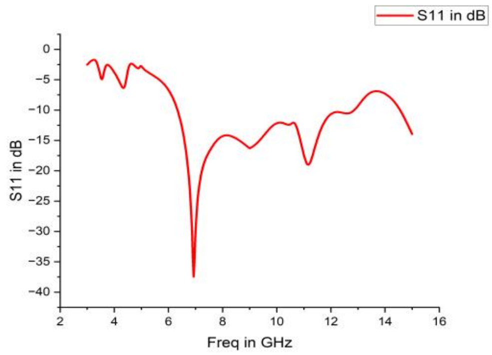

Figure.2 S11 plot of Elliptical Slot Antenna with DGS

3.1. Basic Elliptical Antenna Configuration

The first antenna uses an elliptical radiating patch of 10 mm radius that is mounted on the FR4 substrate, as illustrated in Fig.3. The microstrip feed line technique is applied to energize the antenna. This structure serves as the benchmark model for testing the essential performance characteristics [16]. The basic antenna design operates in two frequency bands, with resonances at 8.37 GHz and 12.06 GHz, producing return losses of -23.21 dB and -21.22 dB, respectively, as depicted in Fig.4. The bandwidth values are 240 MHz and 460 MHz, respectively, with a gain of 4.2 dBi.

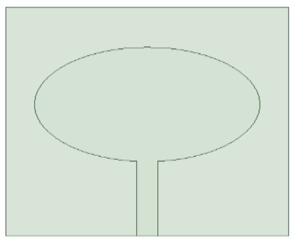

Figure.3 Basic elliptical Antenna

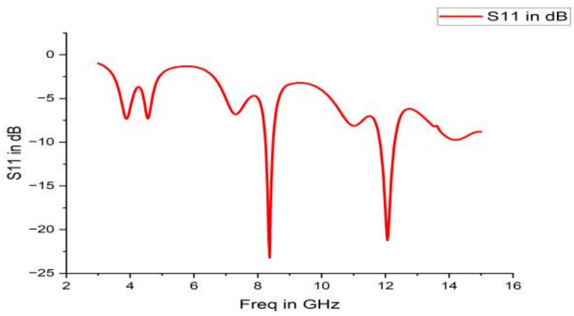

Figure.4 S11 plot of elliptical Antenna

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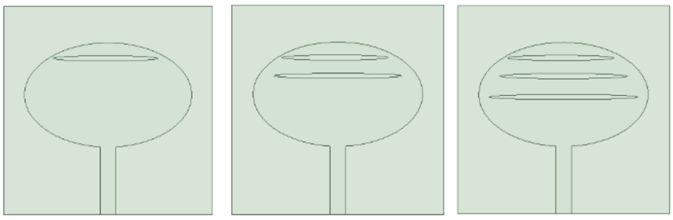
3.2. Elliptical Slot Loading

To enhance the antenna's efficiency, an elliptical slot is integrated into the radiating patch, as illustrated in Fig. 5(a). The slot's major axis length is 0.5 mm, while its ratio is altered for investigating the influence on antenna behavior [17]. The first slot ratio considered is 20 mm, for which three resonant frequencies occur at 5.01 GHz, 7.2 GHz, and 10.44 GHz. Return losses at those frequencies are −15.91 dB, −11.07 dB, and −19.51 dB, respectively. Bandwidths attained are 200 MHz, 150 MHz, and 660 MHz with a gain of 3.3 dBi. Subsequently, a parametric analysis is conducted by varying the slot ratio to 24 mm and 28 mm, as depicted in Fig. 5(b) & (c). If the slot ratio is set to 24 mm, then five resonance frequencies occur at 4.71 GHz, 5.7 GHz, 8.49 GHz, 10.26 GHz, and 12.15 GHz.



(a) (b) (c)

Figure.5 Optimized Elliptical Slot Antenna

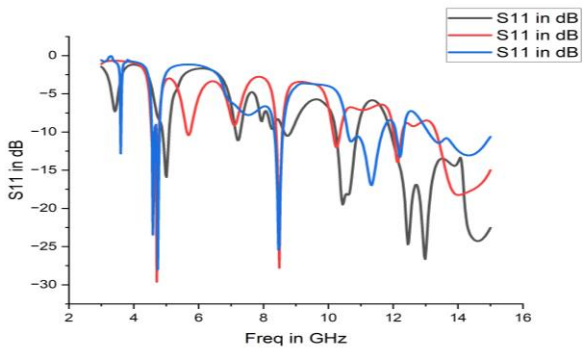


Figure.6 S11 plots of Optimized Elliptical Slot Antenna

Return losses are from −10.42 dB to −27.77 dB. Bandwidths range from 100 MHz to 280 MHz, with a gain of roughly 3 dBi. However, increasing the slot ratio to 28 mm improves antenna performance. The loss returns now range from as high as -27.95 dB as demonstrated in Fig. 6, and the gain rises up to about 4 dBi. By adding elliptical slots into the design, it is possible to increase the path length of the current and thus enable multiple frequencies to be generated [18].

3.3. Defected Ground Structure (DGS)

For further improvement in the operation of the antenna, a defected ground structure is incorporated into the ground plane as illustrated in Fig. 7. Specifically, a 40 × 15 mm² rectangular slot is etched under the radiating patch, thus distorting the current distribution and suppressing surface waves [19]. Upon using the defected ground structure, the antenna becomes resonant at frequencies of 5.22 GHz and 8.49 GHz, with return loss values of −36.57 dB and −14.95 dB, respectively, as presented in Fig. 8. The band-width is substantially increased to 560 MHz and 1.49 GHz, and the antenna gain is raised to 6.6 dBi.

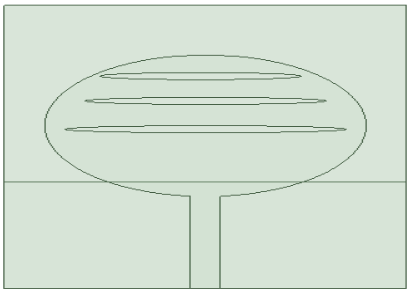


Figure.7 Elliptical Slot Antenna with Defected Ground Structure

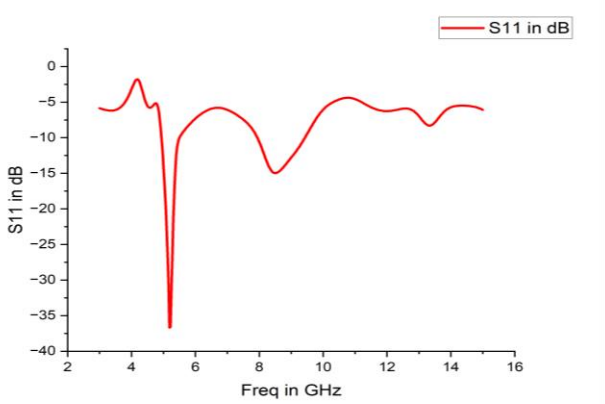
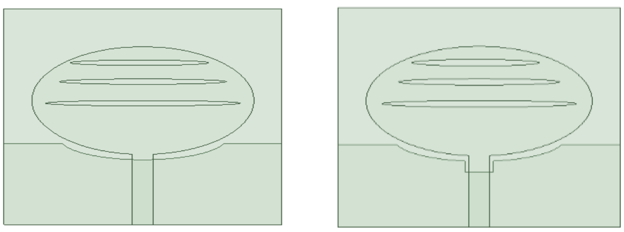


Figure.8 S11 plot of Defected Ground Structure

3.4. Ground Plane Slot Modification

Further bandwidth increase is achieved by introducing an elliptical slot into the ground plane, as depicted in Fig. 9(a) & 9 (b). The major axis of the slot is kept at 4 mm, while its ratio remains at 5 mm. As a result, increased coupling between the patch and the ground plane is achieved, which helps produce ultra-wideband properties in the antenna. The operating frequencies have now been shifted to 7.56 GHz and 11.79 GHz, which correspond to the return losses of −25.57 dB and −45.93 dB, respectively as illustrated in Fig.10. The bandwidth also becomes wider, being equal to 3.44 GHz and 2.71 GHz, respectively.



(a) (b)

Figure.9 Ground Slot Loaded DGS Antenna

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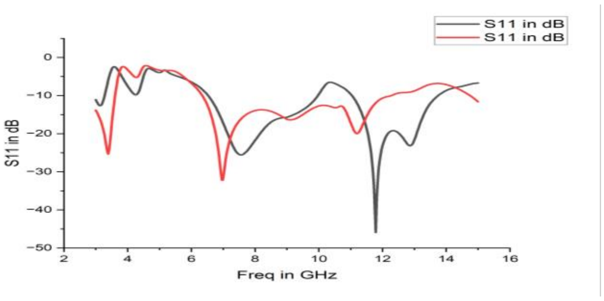

Figure.10 S11 plots of Ground Slot Loaded DGS Antenna

3.5. Parametric Optimization

Further, a comprehensive parametric study is performed using parameter variations including Sx (substrate width), Sy (substrate length), Gx (ground width), Gdx (ground dip width), and Gdy (ground dip length). These are optimized to optimize the performance of the antenna [4]. The resultant optimized antenna has high performance due to resonance occurring at 6.93 GHz and very good return loss of −37.45 dB. The ultra-wide bandwidth of 6.33 GHz is also achieved, a marked improvement over the first antenna design [5]. The antenna's gain remains consistent at 4.9-5.5 dBi. This optimized antenna clearly illustrates the advantage of incorporating the elliptical slot loading and the defected ground structure for high-performance operation. Slot loading provides multi-band performance, whereas the defects in the ground structure and ground slotting enhance bandwidth and improve gain.

4. Results and Discussion

The simulations show clear indications of gradual improvement in antenna performance at each design stage. First, the initial antenna shows narrow bandwidth (240-460 MHz) and moderately high gain (4.2 dBi). It means there is a need to enhance its performance by adding new elements. Introduction of elliptical slots turns the initial antenna into a multiband antenna by producing up to five frequencies within the same frequency range. However, the bandwidth remains narrow (100-660 MHz), and the gain decreases due to increased current paths [6].

The most significant achievement comes when a defected ground structure is introduced, increasing the bandwidth to 1.49 GHz while reducing the return loss to -36.57 dB. At the same time, the antenna reaches its maximum gain of 6.6 dBi. The addition of an elliptical slot to the ground plane creates ultra-wideband properties for the proposed antenna by increasing its bandwidth up to 3.44 GHz and 2.71 GHz while reaching the best value of return loss (-45.93 dB) [14]. It indicates that the engineering of ground planes increases the bandwidth.

The optimized design at last provides the ultra-wideband of 6.33 GHz, which shows substantial improvement from its earlier value as seen from Figure.11. With the return loss of −37.45 dB indicating high impedance matching [17], it can be noted that the gain stays constant at 4.9 dBi as seen in Figure.13. In summary, it can be seen that use of the elliptical slot loading and defected ground structure improves the antenna efficiency by providing wider bandwidth, better return loss, and constant gain.

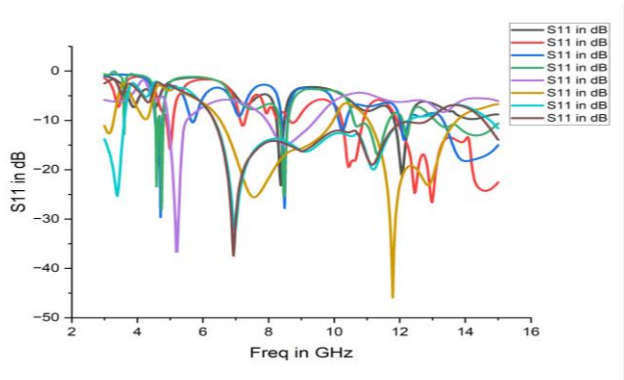

Figure. 11 reflection coefficient plots of all phase antennas

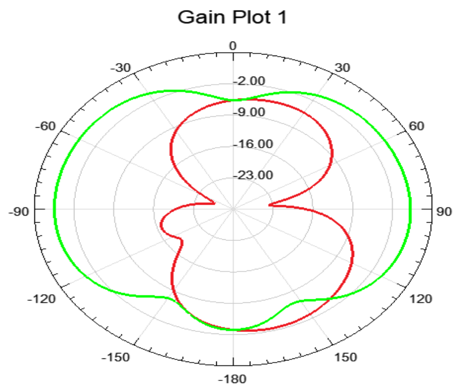

Figure.12 E Plane(red) and H plane(green) pattern proposed antenna

Table. 1 Performance Comparison of Antenna at Different Phases

Phase	Frequency (GHz)	Return Loss (dB)	Bandwidth	Gain (dBi)
Phase 1	8.37, 12.06	−23.21, −21.22	240, 460 MHz	4.2
Phase 2	5.01, 7.2, 10.44	−15.91, −11.07, −19.51	200, 150, 660 MHz	3.3
Phase 3	4.71, 5.7, 8.49, 10.26, 12.15	−26.61 to −10.42	100–280 MHz	3
Phase 4	4.59, 4.7, 8.49, 11.31, 12.21	−27.95 to −13.27	100–270 MHz	4
Phase 5	5.22, 8.49	−36.57, −14.95	560 MHz, 1.49 GHz	6.6
Phase 6	7.56, 11.79	−25.57, −45.93	3.44 GHz, 2.71 GHz	3.9–5.2
Phase 7	6.93	−37.45	6.33 GHz	4.9

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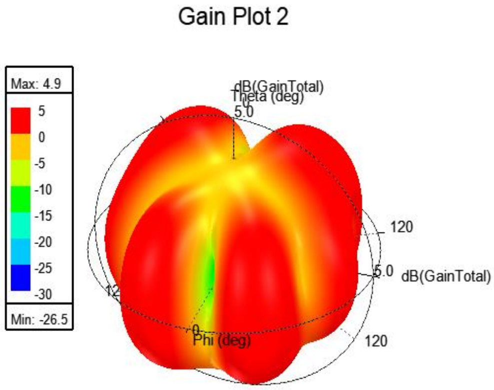

Figure.13 Gain plot of proposed antenna

5. Conclusion and Perspectives: A Visionary Synthesis

The design and analysis of the proposed small broadband elliptical slot antenna with a defected ground structure have been successfully completed. Antenna characteristics can be greatly enhanced with specific design changes, such as slot loading and a defected ground plane. The designed antenna achieves a super-wide bandwidth of 6.33 GHz, along with excellent gain and return loss values. It has the potential to be used in broadband wireless communication systems.

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Declaration

Conflicts of Interest: The authors declare no conflict of interest.

Author Contribution: All authors wrote the main manuscript text and also consent to the submission.

Ethical approval: Not applicable.

Consent to Participate: All authors consent to participate.

Funding: Not applicable, and No funding was received

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Personal Statement: We declare with our best of knowledge that this research work is purely Original Work and No third party material used in this article drafting. If any such kind material found in further online publication, we are responsible only for any judicial and copyright issues.

Acknowledgements

We thank everyone who inspired our work.