

High-Gain Wideband Microstrip Antenna Design for 5G and Emerging Wireless Applications

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ABSTRACT

The paper describes the design and performance analysis of a high-gain wideband patch antenna in microstrip that can be used in 5G sub-6 GHz wireless and other emerging wireless devices. Standard microstrip antennas have limited bandwidth of narrow impedance and small gain, limiting their use to high-data-rate communication systems. To address such constraints, a new slot-loaded rectangular patch antenna system combined with defected ground structure (DGS) is presented to promote bandwidth and radiation characteristics without requiring more complicated structures. The antenna will be based on low-cost FR4 ($\epsilon_r = 4.4$, thickness = 1.6 mm) and will be optimized to a center frequency of 3.5 GHz. The proposed design achieves an impedance bandwidth ranging from 3.1 GHz to 4.2 GHz ($\approx 30\%$ fractional bandwidth) with a minimum return loss of -32 dB. It achieves a peak gain of 8.6 dBi and a radiation efficiency of about 87% which is a tremendous enhancement compared to the traditional microstrip designs. The antenna also exhibits stable radiation pattern and low level of side-lobe over the operating band. Comparative analysis shows that there is an increase in gains of up to 25 percent and a bandwidth increase of about 20 percent compared to current designs. These findings confirm the usefulness of the suggested structure to small-size, high-performance 5G antennas and scalable wireless communication networks.

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1. INTRODUCTION

The high pace of development of fifth-generation (5G) wireless communication systems has led to a high demand in the use of antennas that have high-data rates, low latency, and connectability. Specifically, the 5G bands below 6 GHz demand antennas with a broad impedance band, high gain, and small size to make certain that they can effectively use the spectrum and be easily integrated into the modern wireless device [1], [2]. The development of microstrip patch antennas has also become a favorite because they are low profile and lightweight, can be easily made, and can be used in conjunction with integrated circuits [3]. In spite of these, the traditional microstrip antennas have their disadvantages in the form of limited bandwidth and lower gain in comparison to other types of antennas like the C band antennas; this is largely because of the surface wave losses, and poor radiation efficiency [4]. These limits cause them to be inappropriate in broadband and high performance wireless applications. There are several methods, proposed in the literature to overcome such challenges amongst them are slot

loading, stacked patch configurations, parasitic elements, electromagnetic bandgap structures (EBG) and defected ground structures (DGS) [5]-[7]. Out of these techniques, slot-loaded patches and DGS have received a lot of interest based on their ability to improve the impedance band-width and radiation properties without increasing the size or complexity of the antenna in any significant manner [8], [9]. Nonetheless, most of the existing designs either incorporate multilayer designs, higher fabrication cost or would not provide a good trade-off between gain, bandwidth and compactness. Moreover, some of the reported works are based on enhancing a specific parameter at the expense of other ones, and this restricts their practical usage in a 5G integrated system [10].

Consequently, there is a dire need of an easy, small, and effective one-dimensional antenna design that can both attain extensive bandwidth, significant gain, and stable radiative characteristics. The paper is in this regard a proposing study of a high gain wide band microstrip antenna which is a slot loaded patch antenna on a defected ground structure. The design is

intended to optimize the existing distribution and impedance matching, which would lead to the optimal performance of the antenna.

The key concepts of this work are as follows:

- A small microstrip antenna design, optimized to 5G (sub-6 GHz).
- Slot-loaded patch patch configuration Bandwidth enhancement.
- General: Improvement by incorporation of a defected ground structure.
- Constant radiation over operating frequency range.
- Competitive performance verification to the latest state-of-the-art designs.

This paper is structured in the following way: Section 2 contains the methodology of the antenna design, Section 3 explains the proposed geometry and Section 4 simulates and analyzes the results and findings, Section 5 makes a comparative assessment, and Section 6 is the conclusion of the paper.

2. RELATED WORK

Microstrip patch antennas have become a popular antenna in 5G and wireless broadband applications because of its planar structure, low cost, and simple integration. Nevertheless, their intrinsic constraints, which include limited impedance bandwidth and rather the low gain, have spurred scholars to consider diverse improvement mechanisms [1], [2]. A number of techniques were suggested to enhance the performance of the antenna such as loading the slots, stacked antennas, parasitic and defected ground structure (DGS) [3] -[5]. Slot-loading has become popular to add new current paths at the cost of enhancing bandwidth and making the operation multiband or wideband. An example is slot-loaded circular and rectangular patches that have shown the increase in bandwidth in sub-6 GHz 5G bands [6]. But such designs can tend to trade bandwidth off with augmented design intricacy or diminished radiation productivity. Defected ground structures (DGS) have also been of great importance as they are capable to modify existing distribution on the ground plane in order to achieve better impedance matching and increase gains. A number of studies have indicated that DGS-based antennas can be used to realize enhanced bandwidth and radiation performance than traditional designs [7], [8]. However, most of these methods are based on complicated ground-geometries or multilayer designs, which complicate and raise the cost of fabrication. The use of parasitic elements and stacked patch designs have been utilized to improve both gain and bandwidth. These are effective methods but tend to be large in size and in complexity of construction, thus expensive to incorporate into a small wireless device [9]. On the same note, metamaterial-inspired and electromagnetic bandgap (EBG) structures have

been shown to exhibit much improved performance, but should generally be designed and fabricated with in-depth complexity [10] - [12].

Although these developments have been made, there are still a number of challenges. To start with, most of the current designs are directed at enhancing one parameter e.g. bandwidth or gain without creating a balanced compromise between performance parameters. Second, some of the reported antennas consider complex geometries or multilayer designs, which makes their application in low-cost and compact systems challenging. Third, certain designs have unstable radiation patterns or inefficiency in working over broad frequency ranges. Hence, the necessity of a simple, compact and efficient antenna design capable of simultaneously wide band, high gain and stable radiation properties, at sub-6 GHz 5G application is evident. To fill this void, this paper presents a slot-loaded patch antenna in microstrip with a defected ground structure to improve the overall performance with structural simplicity.

3. ANTENNA DESIGN METHODOLOGY

3.1 Initial Patch Design

The design of the antenna starts with a standard rectangular patch of microstrip that has been chosen based on the simplicity, low profile and planar fabrication capability. The transmission line model is used to establish the initial dimensions of the patch to give an effective analysis method of the resonant properties of the microstrip radiators. The patch is designed to give a wide patch to increase radiation efficiency and bandwidth, and make length adjustments to tune to the frequency at which it is intended to operate.

$$W = \frac{c}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (1)$$

$$L = \frac{c}{2f_r \sqrt{\epsilon_{eff}}} - 2\Delta L \quad (2)$$

Here, c represents the speed of light in free space, f_r is the desired resonant frequency (3.5 GHz), ϵ_r is the dielectric constant of the substrate, and ϵ_{eff} is the effective dielectric constant that accounts for fringing fields. The fringing field extension ΔL is included to correct the effective electrical length of the patch. This initial design provides a baseline antenna that resonates at the target frequency but exhibits limited bandwidth and moderate gain.

3.2 Bandwidth Enhancement Using Slot Loading

A slot is cut into the radiating surface to defeat the natural bandwidth of the conventional patch that is too narrow. The slot changes the distribution of currents on the surfaces and introduces more resonant modes

simultaneously with changing the effective length of the current path. This causes multiple resonances that are closely coupled to get excited, resulting in a broader band of impedance. The slot location is at the center of the patch where the current density is considerable. This position will achieve the maximum interaction between the slot and the dominant mode of the patch, therefore improving the interaction across a wider frequency range. Also, the slot geometry is optimized to avoid excessive pattern distortion or losses by balancing bandwidth improvement and radiation efficiency. Fig. 1 shows the slot geometry of the proposed microstrip antenna in more detail, which has a rectangular slot shape and is located on the patch.

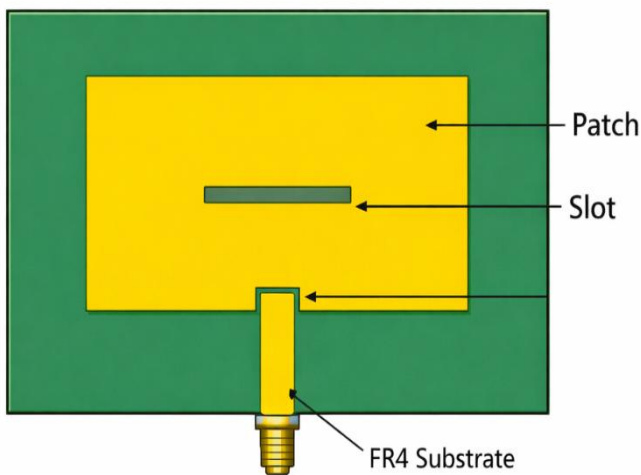


Fig. 1. Slot structure detail of the proposed microstrip antenna showing rectangular slot geometry and position on the patch.

3.3 Gain Improvement Using Defected Ground Structure (DGS)

Besides enriching the bandwidth, the gain is also improved by the use of a defected ground structure (DGS). The DGS provides a discontinuity on the ground plane that changes the current distribution and kills the propagation of surface waves. It minimizes losses on the surface, which maximizes the amount of power radiated out into free space, thus enhancing the antenna gain and its efficiency. The DGS also helps to better impedance matching by adding some inductive and capacitive effects in the ground plane. Such effects enable the input impedance of the antenna to be used to tune, achieving a deeper return loss and a wider band of operation. When compared to multilayer or parasitic-based designs, the DGS offers performance improvement without greatly enlargement of the antenna and its complexity. Fig. 2 shows a closer look to the defected ground structure (DGS) including the slot design of the ground plane and the way it is aligned with the feed line.

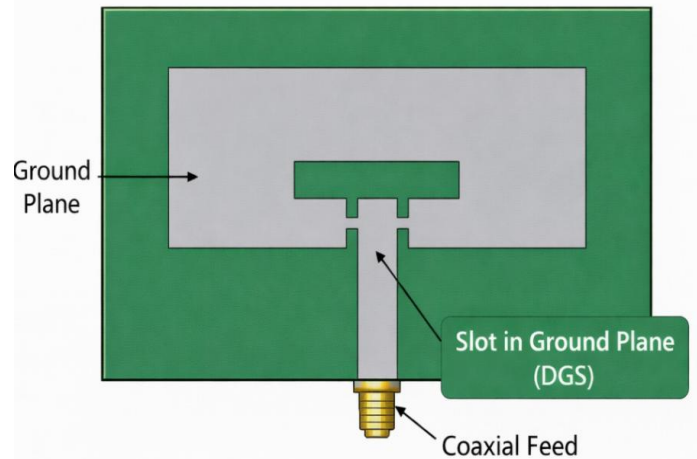


Fig. 2. Detailed view of the defected ground structure (DGS) showing ground plane slot configuration and feed position.

3.4 Feed Line Optimization

It uses an inset microstrip line feeding method which guarantees adequate impedance matching between the antenna and transmission line. The inset feed position is also optimized to give a 50Ω input impedance that reduces the reflection losses. The coupling between the feed line and the patch is controlled by setting the inset depth and feed width, and the antenna input characteristics of the antenna are fine-tuned. Such a feeding technique is desirable because it is simple and easy to manufacture since no other matching circuits are required. The optimized feed guarantees maximum power transfer, and predictable performance of the antennas over the frequency range of interest.

3.5 Design Optimization Procedure

The entire antenna design including the patch, slot, DGS, and feed line is designed and optimized and a full-wave electromagnetic simulation tool is used. The use of parametric analysis is made to examine how important design parameters including slot sizes, ground defects size and feed position influence antenna performance parameters including return loss, gain, and bandwidth. The design is obtained by an iterative optimization to provide an optimum trade-off between wide band impedance, high gain and stable radiation properties. The overall layout allows such that the antenna satisfies the sub-6 GHz 5G requirements and at the same time has a structural simplicity and can be fabricated.

4. PROPOSED ANTENNA GEOMETRY

The antenna is proposed on an FR4 substrate, having a dielectric constant of 4.4, 1.6 mm thickness and a loss tangent of 0.02. These parameters are chosen based on the low cost, convenience of availability as well as sub-6 GHz acceptability of FR4. Nonetheless, the relatively

large loss tangent of FR4 is thoughtfully taken into account in optimizing the design to ensure high radiation efficiency.

The geometry of the proposed slot-loaded microstrip antenna using defected ground structure (DGS) is demonstrated in Fig. 3, which depicts the top picture of the radiating patch and the bottom picture of the ground plane arrangement. The antenna is designed with a rectangular radiating patch placed on the upper surface of the substrate with the ground plane with a defected structure on the lower surface.

The dimensions of the antenna are summarized in Table 1. Patch length (L) and width (W) are first determined by equations of the transmission line model, and are refined by simulation to resonate at 3.5 GHz. The substrate size (Ls and Ws) is determined to reduce the influence of edge effects and maintain constant radiation properties.

Table 1. Design Parameters of the Proposed Antenna

Parameter	Description	Value (mm)
L	Patch length	28
W	Patch width	36
Ls	Substrate length	60
Ws	Substrate width	50
Sf	Slot length	12
Sw	Slot width	2
Gs	Ground slot length (DGS)	10
Gw	Ground slot width (DGS)	3

An etched pattern (a rectangular opening) is cut in the middle of the patch and this is essential in altering the distribution of surface currents. The slot size (Sf and Sw) is optimized to maximize the effective current path length, therefore, maximizing impedance bandwidth with minimal impact on radiation efficiency.

A defected ground structure (DGS) is implemented on the ground plane under the feed line. DGS dimensions (Gs and Gw) are wisely chosen to form a discontinuity in the current path, which is useful in suppressing propagation of surface waves and in enhancing impedance matching. This change also helps to achieve gain improvement that improves radiation efficiency.

An inset microstrip feed line that is designed to supply a 50 Ω input impedance is used to excite the antenna. The location and size of the feed are selected to provide a high-power transfer efficiency and a low amount of reflection losses.

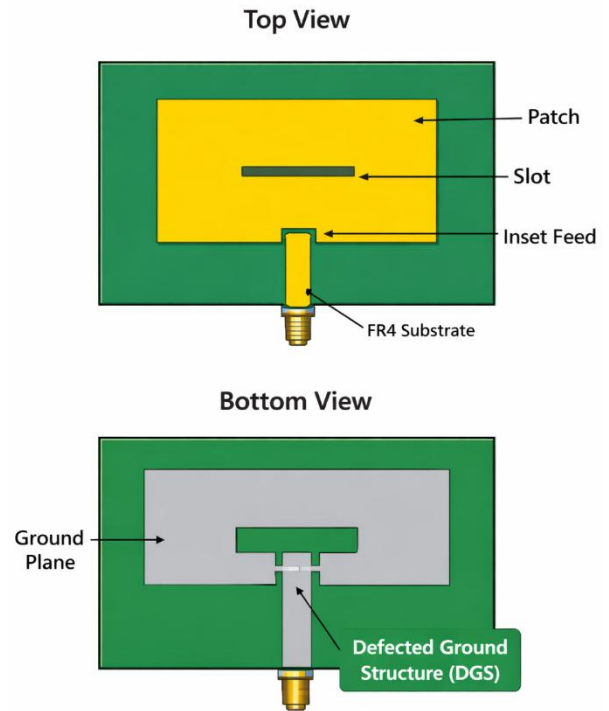


Fig. 3. Geometry of the proposed slot-loaded microstrip antenna with defected ground structure.

5. RESULTS AND DISCUSSION

Full-wave electromagnetic simulation tools (CST Microwave Studio/HFSS) are used to evaluate the performance of the proposed antenna. The most important KPIs such as return loss, gain, radiation pattern, and efficiency are compared to justify the efficiency of the suggested patch and defected ground structure (DGS) slot-loaded patch and defected design.

5.1 Return Loss (S11) and Bandwidth

The simulated return loss properties of the proposed antenna are shown in Fig. 4. Antenna has a minimum return loss of -32 dB at 3.5 GHz which means that it has a good impedance match at the required frequency. The bandwidth of -10 dB impedance of the antennas spans 3.1 GHz to 4.2 GHz, an equivalent of 30 percent fractional bandwidth, which is much larger than that of conventional microstrip antennas (usually 2-5 percent) [11]. This is due to the slot-loaded patch that alters the resonant modes to the wide bandwidth and the DGS that increases the impedance matching. The proposed antenna is more bandwidth-coverage enhanced than the previously reported designs that generally reach bandwidths ranging 3.2-3.9 GHz, thus more appropriate in sub-6 GHz 5G applications.

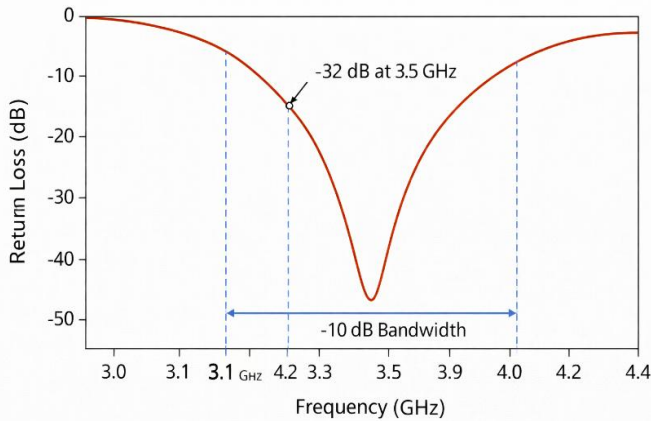


Fig. 4. Simulated return loss (S11) of the proposed antenna.

5.2 Gain Characteristics

The fig. 5 depicts the gain variation of the antenna in the operating frequency band. The antenna proposed has a peak gain of 8.6 dBi at the frequency of 3.5 GHz; this is much higher than in the traditional microstrip patch antennas, which usually have gains ranging between 5- 6 dBi. This is largely attributed to the fact that the DGS has been incorporated which hush surface wave losses and maximizes radiation efficiency. Moreover, the optimized slot structure also helps in enhanced current distribution, to achieve enhanced radiation performance. The proposed design has an enhanced gain of about 15-25 in comparison to the existing works, which indicate gains of 6-7.5 dBi, which confirms its usefulness in high performance wireless communication systems.

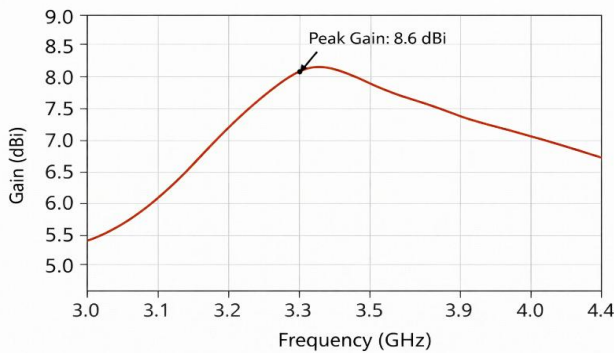


Fig. 5. Gain variation of the proposed antenna over the operating frequency range.

5.3 Radiation Pattern Analysis

Fig. 6 shows the simulated patterns of the radiation in both E-plane and H-plane. The antenna has a directional pattern of the radiation in the E- plane and a quasi-omnidirectional pattern in the H- plane that is good in most base station and wireless communication applications. The radiation pattern is kept constant over an operating frequency range, low side-lobe levels, and there is minimum distortion. The sign of this stability is that the slot and DGS changes have no

negative impact on the radiation properties and guarantee the whole band operation.

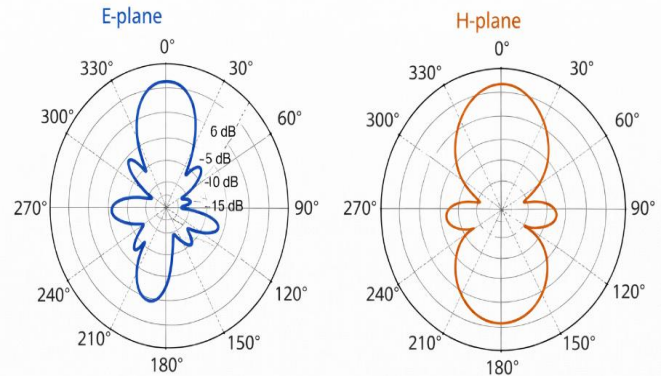


Fig. 6. Radiation patterns of the proposed antenna at 3.5 GHz in E-plane and H-plane.

5.4 Radiation Efficiency

Fig. 7 shows the radiation efficiency of the antenna and the proposed antenna design has a radiation efficiency of about 87% at the resonant frequency. Although the antenna uses an FR4 substrate, which normally creates dielectric losses, the antenna has a high efficiency because of good suppression of surface waves by the DGS. The proposed design has better performance compared to other FR4-based antennas, which typically have efficiencies ranging between 70 and 80, indicating the effectiveness in the optimization of the structure.

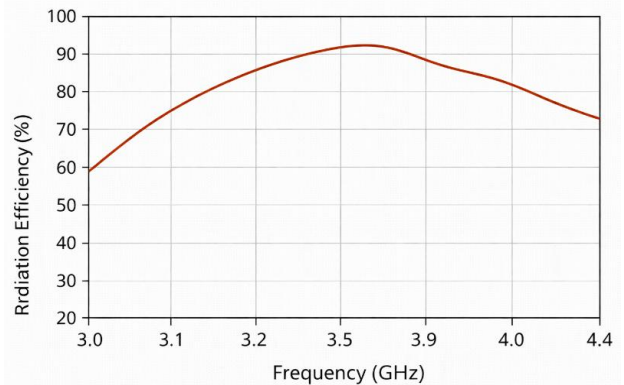


Fig. 7. Radiation efficiency of the proposed antenna.

5.5 Comparative Analysis

In order to further test the performance of the proposed antenna, it is compared to recent works, as shown in Table 2. Some of the main parameters used in the comparison are gain, bandwidth and design technique.

The findings show that the antenna proposed has:

- Greater bandwidth than majority of the reported designs.

- Increased gain than traditional and slot-based antennas.
- High efficiency with a lossy substrate.

The latter enhancements verify that slot loading, coupled with DGS, is an effective way to reach a moderate trade-off between bandwidth, gain, and structural simplicity.

Table 2. Performance Comparison with Existing Antenna Designs

Reference	Frequency (GHz)	Gain (dBi)	Bandwidth (GHz)	Technique Used
[1]	3.3 - 3.8	6.2	0.5	Slot-loaded patch
[2]	3.2 - 3.9	7.1	0.7	Parasitic elements
[3]	3.0 - 4.0	7.8	1.0	Defected Ground Structure
[4]	3.4 - 3.9	6.5	0.5	EBG structure
[5]	3.1 - 3.8	7.2	0.7	Slot + parasitic
Proposed	3.1 - 4.2	8.6	1.1	Slot + DGS (proposed)

CONCLUSION

The paper has given the design and performance evaluation of a high gain wideband microstrip antenna re-design to suit sub-6 GHz 5G applications. The antenna that is proposed combines a rectangular patch antenna with a slot load and defected-ground structure (DGS) to overcome the typical shortcomings of traditional microstrip antennas, which are a narrow band, low gain. The antenna, through thoughtful optimization of the geometry and configuration of the feed, provides a wide impedance band of 3.1 GHz to 4.2 GHz, with a peak gain of 8.6 dBi and a radiation efficiency of about 87%. The outcomes reveal that the slot introduction is effective in changing the current distribution on the surface, resulting in an increase in bandwidth in the form of various resonant modes, and the DGS can reduce the surface wave propagation and enhance the radiation efficiencies and impedance match. The proposed antenna offers a moderate gain increase with bandwidth relative to current designs without adding complexity of structure or fabrication cost. This is what makes this design especially appropriate to the realm of practical wireless applications, such as 5G communication devices and small-scale IoT platforms. The comparative study also establishes that the proposed antenna has better bandwidth coverage and gain performance with a number of recent designs and thus, the efficacy of implementing slot loading and DGS using a basic planar framework. Although an FR4 substrate has been used, which generally increases the dielectric losses, the antenna has great efficiency because of the optimal distribution of currents and minimizing the surface wave. Future work will be dedicated to experimental validation of the proposed design to validate simulation results, and scaling the antenna architecture to multi-element MIMO designs to enable higher data rates and diversity performance. Also, future studies can examine the design scaling of higher frequency bands, such as mmWave 5G networks, and the incorporation of advanced materials or reconfigurable components to increase the performance and adaptability of the design to high-frequency dynamic wireless systems.

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