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Microstrip Patch Antenna Design for Enhanced Bandwidth and Harmonic Suppression

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Abstract
Antennas are essential components in wireless communication systems, often requiring a delicate balance between achieving wide bandwidth and suppressing harmonics effectively. This study focuses on the integration of defected ground structures (DGS) to enhance antenna performance. Through rigorous experimentation and analysis, the research aimed to optimize microstrip patch antenna designs for improved bandwidth while maintaining efficient harmonic suppression. The investigation involved parametric studies to determine the optimal dimensions and configurations of DGS for wideband-stop characteristics. Simulation tools were utilized to analyse the impact of DGS on the antenna's behaviour, leading to the development of an accurate equivalent circuit model. Current distribution analysis provided insights into the radiation pattern and impedance matching of the antennas with and without DGS. Experimental results demonstrated significant improvements in antenna performance. The measured reflection coefficient values indicated successful harmonic suppression, with reductions around 22 dB at the third harmonic frequency. The input impedance values were optimized to utilize a modified ground plane featuring diagonal edges and a rectangular slot cut to design compact antennas, contributing to enhanced bandwidth and improved overall performance. Radiation pattern measurements validated the effectiveness of the optimized designs. This study demonstrates successful integration of DGS into slot antennas, achieving wider bandwidth with robust harmonic suppression. Experimental results validate design strategies, offering insights for high-performance slot antennas in modern communication systems.

Keywords: *Patch Antenna, Defected Ground Structure (DGS), Harmonics.*

1. Introduction
Microstrip patch antennas are widely used in modern communication systems due to their low profile, lightweight, and ease of integration with electronic circuits. However, one of the key challenges in designing microstrip patch antennas lies in managing harmonics, which can degrade performance and limit the antenna's bandwidth. Harmonics in microstrip patch antennas occur due to nonlinearities in the antenna's operation, leading to the generation of unwanted frequencies that are multiples of the fundamental operating frequency. These harmonics can interfere with the desired signal, causing distortion and reducing overall system performance. Efficient suppression of harmonics is crucial for achieving high-performance microstrip patch antennas with wide bandwidth and low distortion [1-3]. Traditional methods of harmonic suppression, such as using

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filters or additional circuitry, can be cumbersome, expensive, and may introduce additional losses. In recent years, the integration of defected ground structures (DGS) has emerged as a promising technique for enhancing the performance of microstrip patch antennas while effectively suppressing harmonics. By strategically introducing defects in the ground plane beneath the patch antenna, DGS can alter the electromagnetic properties of the antenna structure, resulting in improved performance characteristics. This study focuses on the integration of DGS into microstrip patch antennas to achieve wider bandwidth and robust harmonic suppression. Through rigorous experimentation and analysis, we aim to optimize the design of microstrip patch antennas with DGS to mitigate harmonic effects while maintaining high efficiency and performance. By investigating the impact of various DGS configurations and dimensions on antenna behavior, the aim is to develop a comprehensive understanding of the underlying principles governing harmonic suppression in microstrip patch antennas. The insights from this research will advance microstrip patch antenna technology and benefit the design of high-performance communication systems across various applications.

2. Experimental Methods or Methodology

Harmonics in microstrip antennas occur as unintended electromagnetic waves produced at integer multiples of the antenna's fundamental frequency. These additional frequencies, like double or triple the fundamental frequency, often stem from nonlinearities within the antenna's components or its immediate environment. To eliminate the effects of harmonics in microstrip antennas requires a multifaceted approach involving various techniques. Filtering mechanisms play a crucial role in suppressing harmonic frequencies, thereby enhancing system performance by minimizing interference. Careful design optimization of both the antenna and its associated components helps mitigate nonlinearities, ultimately reducing harmonic generation. Ground plane modifications, such as employing defected ground structures (DGS) or adding slots, prove effective in suppressing harmonics and improving overall antenna performance.Conventional methods for harmonic suppression in antennas typically involve various techniques such as Photonic Band Gap (PBG), Defected Ground Structure (DGS) (Ilyana nor Rahim, Sapuan, and Jenu 2016; Damaj, Lepage, and Begaud 2015), and incorporating stubs/slots in the ground plane. However, these approaches often necessitate intricate construction of the ground plane, resulting in larger antenna sizes that may not be suitable for many applications. In comparison to other methods documented in the literature, employing a defected ground structure enables wideband harmonic suppression while enhancing the bandwidth characteristics of a simple microstrip patch antenna. Many existing harmonic suppression antennas are characterized by larger dimensions, yet compactness holds significant importance in the antenna domain. Ilyana nor Rahim, Sapuan, and Jenu (2016) proposed the use of defected ground structures (DGS) to reduce harmonics in microstrip patch antennas. They employed two rectangular DGS etched on the ground plane at separate positions and with varying sizes to decrease harmonic radiation effectively [4]. This technique has shown promising results in mitigating harmonics while maintaining antenna performance. Elkhazmi, McEwan, and Ali (2022) introduced an active antenna with an insect-shaped rectangular patch design aimed at minimizing harmonic radiation and improving conversion efficiency. Experimental results demonstrated the effectiveness of active antennas in reducing harmonics and enhancing overall antenna performance. Haiwen Liu et al. (2005) investigated the use of defected ground structure (DGS) cells to suppress undesired frequencies in microwave integrated circuit (MIC) environments. By providing bandgap and slow wave effects, DGS cells offer an efficient means of harmonic reduction in MIC-based communication systems. Prajapati (2015) suggested incorporating a defected ground structure (DGS) under the feed line of the antenna to control harmonics effectively. Additionally, Acharjee et al. (2016) proposed the

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use of U-shaped slots on the patch to further enhance harmonic reduction in microstrip patch antennas. Biswas, Guha, and Kumar (2013) and Ghaffarian, Moradi, and Zaker (2012) successfully demonstrated the control of higher-order modes, including up to the third harmonic of the fundamental operating frequency, in microstrip line-fed patch antennas. Their research contributes to the understanding of harmonic behavior in microstrip patch antennas and provides insights into effective harmonic reduction techniques.Sung, Kim, and Kim (2003) conducted comparative studies between H-shaped DGS and traditional microstrip patch antennas to evaluate their harmonic reduction capabilities. Such comparative analyses help researchers identify the most effective techniques for harmonic reduction in microstrip patch antennas.The incorporation of a defected ground structure (DGS) offers a technically sound solution to mitigate harmonic issues in microstrip patch antennas. By strategically introducing defects in the ground plane, such as slots or discontinuities, DGS effectively suppresses harmonic frequencies while maintaining the desired operational characteristics of the antenna. Unlike traditional methods relying on filters for harmonic suppression, DGS implementation does not incur the drawbacks associated with filters, such as insertion losses, increased complexity, and additional size requirements in the antenna design. Additionally, DGS provides a more integrated and compact solution, optimizing the overall performance of the microstrip patch antenna without compromising its efficiency or bandwidth [5-9]. Consequently, the use of DGS presents a favorable alternative for addressing harmonic challenges in microstrip antenna design, offering improved performance and enhanced functionality while circumventing the limitations posed by conventional filtering techniques.

3. DGS equivalent circuit model

Microstrip antennas consist of distributed resistance, capacitance, and inductance within their metallic components, allowing them to be represented by equivalent circuit models. Analyzing DGS antennas and establishing their equivalent circuit models involves conducting full-wave analysis. However, unlike other methods, full-wave analysis cannot precisely determine the actual dimensions and positioning of the DGS. Typical approaches for analyzing DGS antennas often rely on trial and error, a time-consuming process that may yield suboptimal results (Khandelwal, Kanaujia, and Kumar, 2017).Equivalent Circuit in terms of LC and RLC.

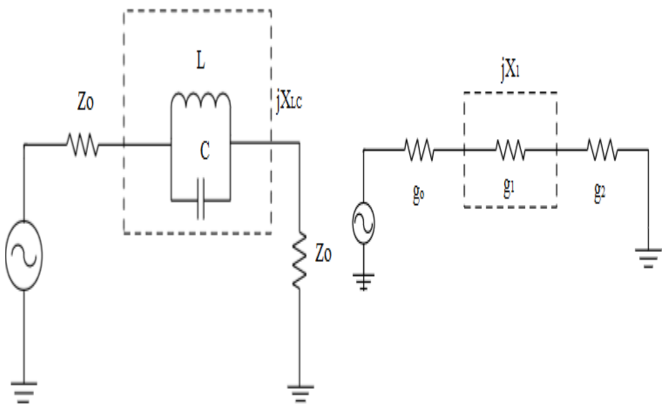

Figure 1 Dgs Equivalent Circuit, And Low Pass Filter Circuit (Butterworth)

Figure 1 illustrates the DGS LC equivalent circuit model alongside the equivalent Butterworth low-pass filter circuit model. The capacitive impact is introduced by the incorporation of two rectangular slots, while the inductance is introduced to the overall impedance through a narrow rectangular defective slot that connects both rectangular-shaped defects. This LC circuit induces resonance at a specific frequency. Notably, the effective capacitance is inversely proportional to the slotted area of the DGS, whereas the effective inductance is directly proportional to the slotted area. Consequently, an increase in the DGS slotted area results in an increase in effective inductance, leading to a reduction in the cutoff frequency. Conversely, reducing the DGS area diminishes the effective capacitance, thereby elevating the resonant frequency.The reactance of the Butterworth low-pass filter is expressed as:

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$$X_{LC} = \frac{1}{\omega_0 C}\left(\frac{\omega_0}{\omega} - \frac{\omega}{\omega_0}\right) \dots\dots\dots\dots\dots\dots (1)$$

Here, ω_0 denotes the angular resonance frequency, and LC can be computed by:

$$C = \frac{\omega_0}{Z_0 g_1} \times \frac{1}{\omega_0^2 - \omega_c^2} \dots\dots\dots\dots\dots\dots (2a)$$

$$L = \frac{1}{4\pi^2 f_o^2 C} \dots\dots\dots\dots\dots\dots (2b)$$

In these equations, f_0 and f_c represents the resonant frequency and cut-off frequency, respectively. Additionally, the DGS is more effectively analysed through a parallel resonant circuit comprising resistance R, inductance L, and capacitance C, as depicted in Figure 2. The conductor, radiation, and dielectric losses are modelled by the resistance R. The values of R, L, and C in Figure 2 can be computed as follows:

$$C = \frac{\omega_c}{2Z_0\omega_0^2 - \omega_c^2} \dots\dots\dots\dots\dots\dots (3a)$$

$$L = \frac{1}{4\pi^2 f_o^2 C} \dots\dots\dots\dots\dots\dots (3b)$$

$$R = \frac{2Z_0}{\sqrt{1/|S_{11}(\omega)|^2 - \left(2Z_0(\omega C - 1/\omega L)\right)^2 - 1}} \dots\dots (3c)$$

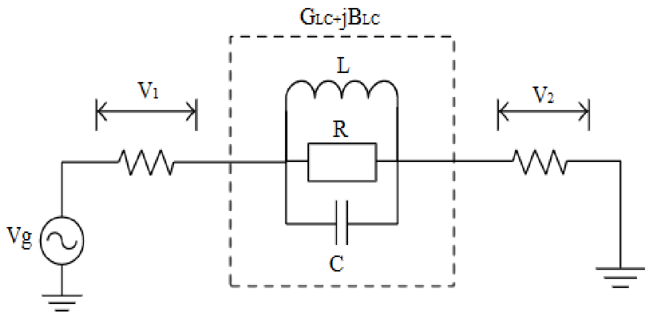
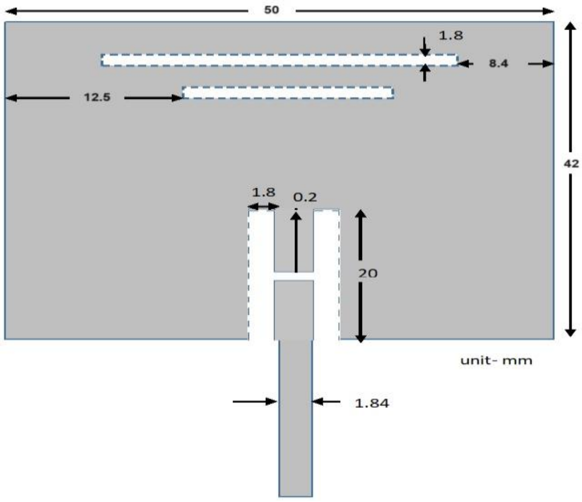


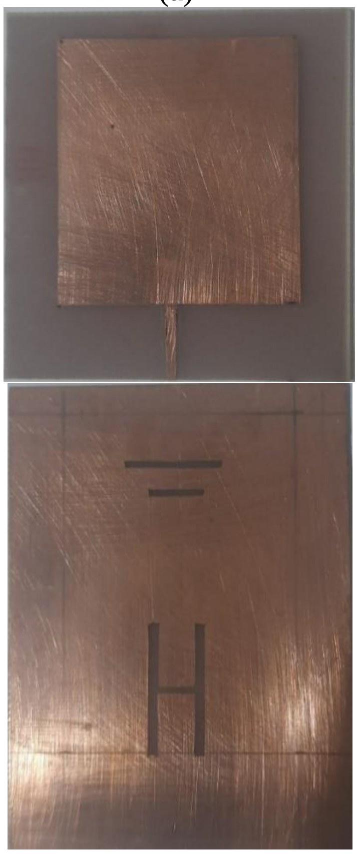
Figure 2 Equivalent Circuit of DGS in Terms of RLC

4. Antenna Design

In the design process of the proposed microstrip square patch antenna, a substrate with a relative permittivity of εr = 4.4 and a thickness of h = 1.6 mm was selected. The square patch antenna is characterized by dimensions L = 30mm, W = 38mm and operates at a resonant frequency of 2.4 GHz. The geometry of the antenna, as depicted in Figure 3, incorporates two wide rectangular slots of unequal length.



(a)



(b)

Figure 3 (A) Geometry of Proposed Antenna, (B) Fabricated Antenna - Patch Side, Ground Side

These slots are strategically positioned to optimize the antenna's performance. Figure 3 provides the comprehensive summary of the optimal physical

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parameters of the proposed antenna, offering valuable insights into its design and configuration. The dimensions of the inset cut, set at 20mm in length and 1.8mm in width, contribute to achieving satisfactory matching with the 50Ω microstrip feed line. Illustrated in Figure 4, the configuration of the Defected Ground Structure (DGS) microstrip patch antenna comprises a square patch positioned on the upper plane and an etched H-shaped structure, alongside two wide slots on the ground plane.

5. Results and Discussion

To attain the desired performance characteristics, all dimensions of the defected ground structure were optimized based on simulation results. This optimization ensures that during the occurrence of second and third-order harmonic frequencies, the insertion loss remains below -20dB, meeting the required specifications for effective antenna operation.

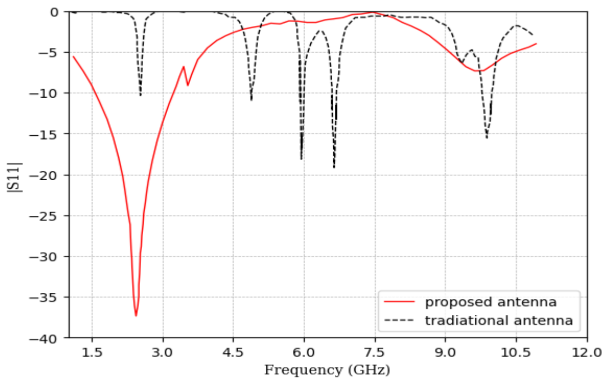

Figure 4 Simulated Reflection Coefficient of Antenna with DGS and Without DGS

Figure 4 depicts the computed reflection coefficients of both a conventional patch antenna and a patch antenna featuring a DGS unit cell. The simulations of the designed antenna were conducted using HFSS (High Frequency Structure Simulator) Version 15. The reflection coefficient of the DGS patch antenna is observed to vary depending on the placement of the DGS unit cell, as indicated by the results. The suggested uneven wide rectangular defected ground structure (RDGS) can be conceptualized as a series of consecutive shunt L-C resonators that function effectively across a wide bandwidth, extending up to the third harmonic frequency. The study underscores the significance of the placements and dimensions of the DGS slots in suppressing the third harmonic frequency and fine-tuning the matching at both the primary resonance and the notched band. In certain instances, the DGS section can serve as a cutoff frequency, attributed to the increase in effective permittivity and subsequent increase in effective inductance of the microstrip line due to the presence of the DGS sections. Evaluating the depth of suppression necessitates careful consideration of the microstrip antenna's etched square area in the ground plane [10]. Multiple modes are stimulated within the microstrip patch antenna, commonly denoted as TM100, TM200, and TM300 for the first three modes, corresponding to the initial three harmonic frequencies. These modes exhibit voids at the radiation edges, aligning with the longitudinal current distribution of the patch. The inclusion of inset incisions introduces supplementary resonances at higher frequencies. With the exception of the fundamental frequency, these elevated resonances are effectively attenuated in the DGS patch antenna. The minor dips observed post 4.3GHz and 5.9GHz frequencies are undesirable but do not constitute harmonic frequencies.

Conclusion

This study introduces a microstrip patch antenna featuring harmonic suppression through the utilization of a defected ground structure. The stop band attribute of the defected ground structure cell serves as the primary foundation for enabling harmonic suppression in the investigated antenna. [11] The antenna demonstrates notable harmonic suppression capabilities (22 dB) along with excellent performance at the designated frequency with bandwidth of 1755MHz. Experimental results confirm the effectiveness of this antenna with a straightforward harmonic suppression structure in efficiently suppressing harmonics. Consequently, the proposed antenna holds promise for seamless integration with active integrated antennas.

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