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Performance Enhancement of 10GHz Patch Antenna using DGS and Perforated Patch Configuration for Advanced Wireless Communication Systems

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Abstract This paper presents the design and performance analysis of a rectangular microstrip patch antenna (rmpa) operating at 10 GHz, which incorporates a Split Ring Defective Ground Structure (DGS) and holes in the patch antenna to achieve high gain. The proposed antenna has a compact size of 30.7 × 27.9 mm^2, which makes it suitable for various applications where space is a constraint. The DGS is created by introducing a series of slots in the ground plane, which acts as a resonant structure and helps to suppress unwanted frequencies. The holes in the patch antenna help to further improve the performance by reducing surface wave losses and enhancing radiation efficiency. The proposed antenna exhibits a gain of 8.8 dBi, favorable return loss, and effective impedance matching with a bandwidth extending to 397.5 MHz. The proposed antenna design offers a cost-effective solution for achieving high gain and improved performance in microstrip patch antennas operating at 10 GHz making it suitable for applications requiring a wide coverage area.

Keywords:. DGS; High Gain; Inset feeding; Perforated Patch; Rectangular Microstrip Antenna; Rogers RT 5880.

1 Introduction

Wireless communication has become an integral part of modern life, spanning applications such as satellite communication, point-to-point links, radar systems, and wireless networks. At the heart of these systems lie antennas, which are crucial components responsible for transmitting and receiving electromagnetic signals [1]. Among various antenna types, microstrip patch antennas have gained significant attention due to their compact size, ease of integration, and compatibility with modern communication systems. They operate based on the microstrip transmission line principle, consisting of a thin metallic patch placed on a dielectric substrate, supported by a ground plane [2]. The dimensions and properties of the patch and substrate play a critical role in determining the antenna's resonant frequency, radiation pattern, polarization, bandwidth, and other performance parameters.

In recent years, the need for higher frequencies and improved performance has driven extensive research into optimizing microstrip patch antennas operating at 10 GHz. The 10 GHz frequency range offers advantages such as wider bandwidth, reduced atmospheric attenuation, and increased data transmission rates [3]. However, realizing efficient and reliable communication systems at this frequency range requires careful consideration of various design aspects [4]. This research paper aims to explore the performance optimization of microstrip patch antennas at 10 GHz, focusing on improving key parameters such as gain, efficiency, and bandwidth. To achieve these objectives, this study employs a comprehensive approach that combines theoretical analysis and numerical simulations. Y. Tawk et al. propose a specific design for the stacked antenna and analyze its radiation characteristics, impedance bandwidth, gain, and polarization [5]. Wahbh et al. present a novel approach to microstrip patch antenna design using a perforated substrate. The proposed antenna structure incorporates carefully arranged perforations on the substrate, aiming to enhance the overall performance of the antenna in terms of radiation characteristics, bandwidth, and polarization [6]. In this research work, the authors investigate the bandwidth and polarization properties of perforated patch antennas. The study explores the impact of different perforation geometries and

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configurations on the antenna's bandwidth and polarization performance. Extensive experimental measurements and simulations are conducted to analyze the influence of various parameters on the antenna's characteristics [7]. X. -H. Ding et al. present a novel dual-band shared-aperture antenna design tailored for 5G wireless communication systems operating in the microwave and millimeter-wave frequency bands. The antenna structure is carefully optimized to achieve dual-band operation while maintaining compactness and efficiency [8].

The remainder of this paper is organized as follows: Section 2 presents the proposed methodologies of microstrip patch antenna design at 10 GHz. Section 3 details the design equations based on the governing electromagnetic principles. Section 4 discusses the results and analyses obtained from the conducted experiments. Finally, Section 5 concludes the paper, by highlighting the key findings, their implications, and potential avenues for future research.

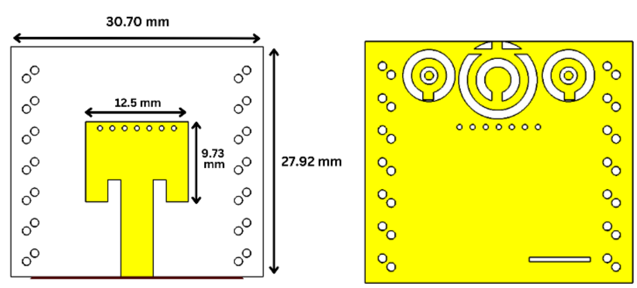
2 Methodology

A microstrip patch antenna is a compact and versatile radiating element used in various wireless communication applications. It consists of a thin metallic patch placed on a dielectric substrate, which is supported by a ground plane. The patch is designed to resonate at a specific frequency and radiate electromagnetic waves efficiently. Microstrip patch antennas offer several advantages, including low profile, lightweight structure, ease of integration with printed circuit boards, and the ability to produce directional radiation patterns. They are widely utilized in mobile phones, Wi-Fi routers, satellite communication systems, and radar systems, playing a crucial role in modern wireless communication technology.

A DGS is a unique concept used in microstrip patch antenna design to mitigate various electromagnetic issues. By introducing specific patterns or slots in the ground plane adjacent to the patch, undesired radiation modes can be suppressed and overall antenna performance can be improved. This technique effectively enhances the antenna's radiation efficiency, impedance matching, and radiation pattern control. In a similar vein, Perforated Microstrip Patch Antennas utilize a patch with strategically placed perforations or slots, allowing for better control over the antenna's resonance frequency and radiation characteristics. These perforations enable engineers to fine-tune the antenna's performance parameters, such as bandwidth, gain, and radiation pattern, offering a higher degree of design flexibility. Both DGS and Perforated Microstrip Patch Antennas showcase innovative approaches that play a significant role in optimizing the functionality of microstrip patch antennas across various communication systems and wireless applications.

Whereas perforated microstrip patch antenna is an innovative variation of the traditional microstrip patch antenna design. It incorporates strategically placed perforations or slots on the patch, which effectively alter the electromagnetic characteristics of the antenna. By introducing these perforations, engineers gain enhanced control over the antenna's resonance frequency, impedance matching, bandwidth, and radiation pattern. This design flexibility allows for tailored optimization of the antenna's performance parameters to meet specific communication requirements. The perforations influence the distribution of electromagnetic fields on the patch and modify the surface current flow, resulting in improved radiation efficiency and reduced superfluous radiation modes. Perforated microstrip patch antennas find applications in a wide range of wireless communication systems, including satellite communication, Wi-Fi networks, RFID systems, and more, due to their ability to achieve desired performance outcomes with increased efficiency and accuracy

The methodology for designing a patch antenna using DGS involves several steps. The DGS is a patterned structure etched on the ground plane of the patch antenna to create a bandstop or bandpass filter. The DGS can improve the bandwidth and reduce the cross-polarization of the antenna. The initial phase involves designing the microstrip patch antenna with the incorporation of DGS and perforations. In Fig. 1 the parameters of the substrate, patch dimensions, and the arrangement of the perforations are carefully considered during the design process. To design the DGS-based patch antenna, the first step is to



(a) (b)

Fig. 1 (a) Front View; (b) Back View of RMPA

determine the substrate material and dimensions of the patch antenna. Then, the DGS pattern is chosen and designed to be etched onto the ground plane. Depending on the desired frequency response, the DGS pattern can be selected from various configurations, such as circular, rectangular, or elliptical slots, or meander line structures. Additionally, the use of holes in the patch antenna can further enhance the antenna's performance. The holes can be drilled on the patch to create a more complex current distribution improving the antenna's gain and radiation efficiency.

Table 1. Dimensions of RMPA

Dimension	*Value (mm)*	*Description*
Lp	9.73	Patch Length
Wp	12.5	Patch Width
Ls	27.92	Substrate Length
Ws	30.70	Substrate Width
Lms	11.77	Microstrip Length
Wms	3.92	Microstrip Width
Linset	2.68	Inset Length
Winset	1.60	Inset Width
R1	0.3	The radius of a Small hole
R2	0.5	The radius of the Bigger hole

The patch has a length of 9.73 mm and a width of 12.5 mm. The substrate measures 27.92 mm in length and 30.70 mm in width. The microstrip has dimensions of 11.77 mm in length and 3.92 mm in width, and there is an inset with measurements of 2.68 mm in length and 1.60 mm in width. Additionally, the design incorporates two holes, one with a small hole radius of 0.3 mm and the other with a bigger hole radius of 0.5 mm. The size, shape, and position of the holes can be optimized based on the desired frequency response and performance showed in Table 1. The antenna's resonant frequency is 10 GHz, specifying its efficient operation for electromagnetic waves at this frequency. It employs a substrate with a dielectric constant of 2.2, affecting its electrical characteristics. Both the patch and ground have a thickness of 0.0175 mm, shaping the antenna's structure. The overall substrate height is 1.57 mm, a critical factor influencing the antenna's performance shown in Table 2. To simulate the DGS-based patch antenna, using CST. The designed antenna structure is modeled, and the simulation

Table 2. Selected parameters for RMPA

Parameters	*Value*	*Description*
f	10 GHz	Resonant frequency
ε_r	2.2	RT5880 Dielectric Constant
t	0.0175 mm	Patch/Ground thickness
h	1.57 mm	Substrate Height

is run to obtain the antenna's performance characteristics, such as return loss, impedance bandwidth, radiation pattern, and gain. After simulation, the performance of the DGS-based patch antenna with holes is analyzed and discussed.

3 Design Equation

These are the essential equations needed for designing the MPA:

$$W = \frac{1}{2f_r\sqrt{\mu_0\epsilon_0}}\sqrt{\frac{2}{\epsilon_r+1}} = \frac{\upsilon_0}{2f_r}\sqrt{\frac{2}{\epsilon_r+1}} \quad (1)$$

Equation (1) defines the practical width, with υ_0 representing the speed of light in free space, μ_0 denoting the permeability of free space, and ε_0 representing the permittivity of free space [9].

$$L = \frac{1}{2f_r\sqrt{\epsilon_{\text{reff}}}\sqrt{\mu_0\epsilon_0}} - 2\Delta L \quad (2)$$

$$\epsilon_{\text{reff}} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}\left[1 + 12\frac{h}{W}\right]^{-\frac{1}{2}} \quad (3)$$

$$\frac{\Delta L}{h} = 0.412\frac{(\epsilon_{\text{reff}}+0.3)\left(\frac{W}{h}+0.264\right)}{(\epsilon_{\text{reff}}-0.258)\left(\frac{W}{h}+0.8\right)} \quad (4)$$

$$L_{\text{eff}} = L + 2\Delta L \quad (5)$$

$$Z_c = \begin{cases} \frac{60}{\sqrt{\epsilon_{\text{reff}}}}\ln\left[\frac{8h}{W_0}+\frac{W_0}{4h}\right], & \frac{W_0}{h} \le 1 \\ \frac{120\pi}{\sqrt{\epsilon_{\text{reff}}}\left[\frac{W_0}{h}+1.393+0.667\ln\left(\frac{W_0}{h}+1.444\right)\right]}, & \frac{W_0}{h} > 1 \end{cases} \quad (6)$$

$$Ls=2Lp;\ Ws=2Wp \quad (7)$$

In this context, Equation (2) provides the actual length, while (3) calculates the effective dielectric. Furthermore, (5) determines the effective length, and (6) establishes the relationship between the characteristic impedance and the width of the microstrip [10,11,12]. Whereas, Ls refers to the length of the substrate, and Ws represents the width of the substrate in Equation (7).

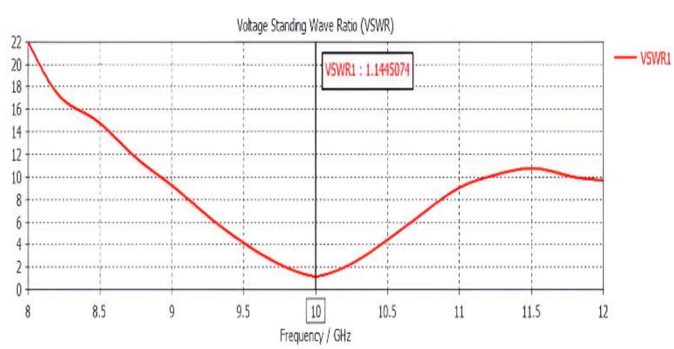


Fig. 2 VSWR vs Frequency (GHz) Plot

4 Result and Discussion

This section of the research paper provides a comprehensive account of the study's findings and presents an impartial and systematic evaluation of the results obtained. The research was centered around the design and performance analysis of a Microstrip Patch Antenna (MPA) operating at the frequency of 10 GHz. The assessment of the antenna's performance is based on a set of crucial parameters, encompassing S11, VSWR, side lobe level (SLL), gain, and directivity. In Fig. 2, the VSWR value of 1.14 is another significant parameter, indicating the efficiency of power transfer between the feed line and the antenna. A VSWR value approaching unity suggests excellent power transfer with minimal reflection. In Fig. 3, the S11 measurement of -23.4 dB for a single antenna signifies a notably high level of efficiency in signal transmission, indicating minimal signal reflection.

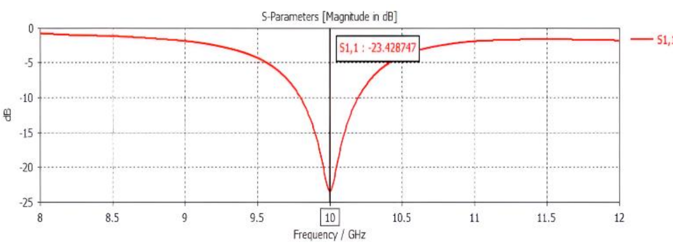
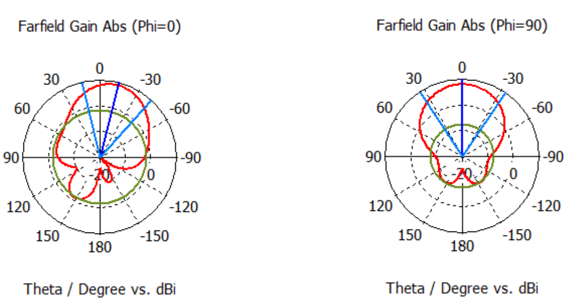


Fig. 3 S_{11} (dB) vs Frequency (GHz) Plot

The SLL, depicted as -15.8 dB in the H-plane and -10.7 dB in the E-plane in Fig. 4, reflects the antenna's effective radiation directionality. The antenna predominantly focuses its radiation in the desired direction while reducing radiation in undesired directions.

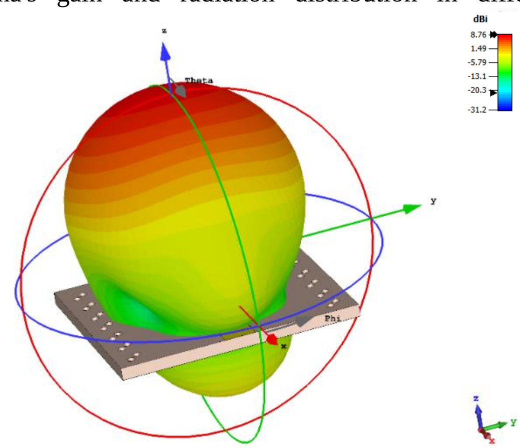
The gain and directivity are vital metrics that reflect the antenna's capacity to amplify and concentrate radiation, respectively[13]. With a gain of 8.76 dBi, the antenna efficiently enhances both received and transmitted signals. Additionally, boasting a directivity of 9.280 dBi, the antenna demonstrates its capability to precisely concentrate radiation in a specific direction, a crucial attribute for directional antennas utilized in communication systems. The findings presented in this section indicate that the designed MPA operating at 10 GHz exhibits exceptional performance characteristics. It demonstrates a good match between the antenna and the feed line, resulting in low reflection and efficient power transfer. Moreover, the antenna's ability to concentrate radiation in the desired direction, amplify signals, and focus radiation further emphasizes its high-performance capabilities. These results confirm that the designed MPA is a top-performing antenna suitable for a wide range of applications in radio communication systems.

The 3D pattern of the MPA, as shown in Fig. 5, represents its radiation pattern in three dimensions[14]. This crucial parameter determines the antenna's directionality and radiation strength in various directions. Several factors, such as the patch's size, shape, height above the ground plane, and feed position, influence the radiation pattern. CST-MWS software is employed to visualize the 3D pattern, providing a graphical representation of the antenna's radiation pattern. Typically presented as a 3D polar plot, the pattern displays the antenna's gain and radiation distribution in different

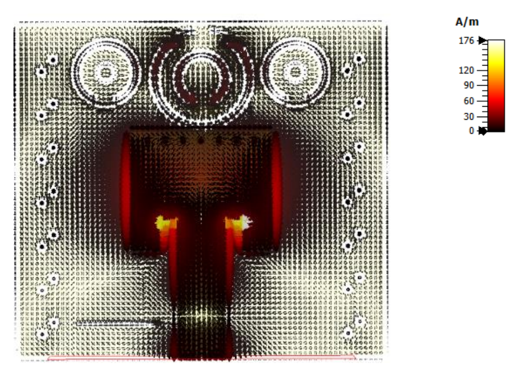


(a) (b)

Fig. 4 (a) E-field (b) H-Field



(a)



(b)

Fig. 5 (a) 3-D Radiation Pattern of 10GHz MPA (b) Surface Current Distribution directions[15]. The 3D pattern at 10 GHz for the designed MPA serves as a vital parameter for evaluating its performance and suitability for diverse applications. The current distribution of the MPA, as depicted in Fig. 5, refers to the pattern of current flow on the patch and its interaction with the ground plane. This parameter plays a critical role in shaping the antenna's radiation pattern, gain, and impedance bandwidth. Various factors, such as the patch geometry, substrate thickness, dielectric constant, and feed position, influence the current distribution on the patch. The interaction between the patch and the ground plane results in a current distribution typically concentrated near the patch's edges and gradually decays towards the center[16]. CST-MWS software is utilized to visualize and graphically represent this current distribution on the patch. Understanding the current distribution is essential for optimizing the antenna's performance and achieving a good impedance match with the feed line. In the case of the designed MPA operating at 10 GHz, careful optimization of the current distribution was performed to achieve outstanding performance characteristics, including a good impedance match, low reflection, high power transfer, and the ability to direct radiation in the desired direction. This optimization process ensures that the antenna is well-suited for various communication applications and exhibits excellent performance in its operating frequency range.

Table 3. Comparison Table

Reference	Operating Frequency	Gain (dBi)	Substrate	Size (Substrate, Patch)
[17]	10.1 GHz	5.51 (CST S/W)	Rogers RT5880	19x19 mm^2 9x9mm^2
[18]	10 GHz	6.5	Rogers RO4350	40x40 mm^2 10x7.5 mm^2
[19]	10 GHz	7.1	Rogers RT5880	28.1x32 mm^2 12.45x16 mm^2
[20]	10GHz	7.5	Rogers RT 5880	21x16 mm^2 9.8x9.5 mm^2
Proposed Work	10 GHz	~ 8.8	Rogers RT5880	30.7x27.9mm^2 12.5x9.7mm^2

5 Conclusion

The designed and simulated 10GHz RMPA using DGS and holes has shown promising results. The obtained S11 value of -23.4dB indicates a good impedance matching, and the VSWR of 1.14 confirms that the antenna can efficiently transmit and receive signals at 10GHz. The gain of 8.76dBi and directivity of 9.280 indicate that the antenna has a high radiation efficiency, and the bandwidth of 397.5 MHz confirms that the antenna has a wide operating frequency range. In conclusion, the DGS and holes designed on the patch antenna have significantly improved their performance. The use of DGS has reduced the cross-polarization and improved the bandwidth, while the use of holes has created a more complex current distribution on the patch, resulting in higher gain and radiation efficiency.

The work contributes by presenting a compact RMPA, featuring a Split Ring DGS and strategically placed holes in the patch. This design achieves a notable gain, favorable return loss, effective impedance matching, and wide bandwidth. This antenna offers a cost-effective solution for high-gain microstrip patch antennas in space-constrained applications, encompassing mobile devices, wearable technology, IoT sensors, unmanned aerial vehicles (UAVs), medical devices, embedded systems, and vehicular communication setups are catering to the demand for improved performance and wide coverage areas at 10 GHz.

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