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Design of an enhanced dual-band microstrip patch antenna with defected ground structures for WLAN and WiMax

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ABSTRACT

This research presents an innovative dual-band microstrip patch antenna design enhanced with defected ground structures (DGS) and barium strontium titanate (BST) thin film, tailored for wireless local area network (WLAN) and WiMax applications. The first design phase involved the development of an microstrip patch antenna (MPA) using an flame retardant (FR4) substrate with a permittivity (εr1) of 4.3 and a thickness of 1.524 mm, enhanced with DGS. This configuration achieved a single-band resonance at 4.1 GHz, with a bandwidth of 0.82 GHz and a return loss (S11) of -32 dB. The second phase involved the integration of a BST thin film, with a high permittivity(εr2) of 250 and a thickness of 0.1 mm, into the DGS-enhanced microstrip patch antenna (MPA). This modification led to a transformation in the antenna's performance, enabling dual-band operation at resonance frequencies of 2.8 GHz and 5.8 GHz. Further, there was a corresponding substantial increase in bandwidth to 1.34 GHz and 1.25 GHz, respectively, an improvement in S11 values to -16.3 dB and -21.4 dB. Moreover, and antenna's size of $14 \times 10 \times 1.524$ mm^3. The study underscores the critical role of innovative material use and design optimization in advancing antenna technology, offering significant enhancements in bandwidth, and miniaturization, for wireless communication systems.

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1. INTRODUCTION

The evolution of wireless communication technology over recent decades has necessitated innovative antenna designs to meet the sophisticated demands of modern wireless systems. Amidst this rapid advancement, the development of compact, multiband antennas has become crucial, driven by the need for efficient data transmission and versatile application across various domains [1], [2]. At the forefront of these developments is the microstrip patch antenna (MPA), an entity renowned for its versatility and adaptability across a spectrum of industries including automotive, radar, medical, and communication sectors [3]. The inception of microstrip radiators, tracing back to 1953, marked a pivotal moment in antenna technology, subsequently instigating a plethora of research focused on exploring and enhancing their properties [4].

MPAs, comprising a patch, substrate, feed line, and ground plane, have emerged as a paradigm of choice owing to their lightweight, low-profile design, cost-effectiveness, and ease of fabrication [5].

Despite their many advantages, MPAs suffer from several disadvantages such as narrow bandwidth, low efficiency, have low power [6]–[8]. Addressing this constraint has been a focal point of research over the past two decades, with various innovative geometries and design methodologies being introduced to achieve multiband frequency capabilities for wireless communication.

The last decade has seen remarkable advancements in dual-band microstrip patch antennas some of which have already been proposed in [9]–[12], a compact, highly efficient MPA for WiMAX and 5G, fabricated on Rogers RT 5880, features seven small square-shaped elements achieving significant bandwidth and efficiency [13]. Studies have introduced various innovative designs, such as circularly polarized antennas for wireless local area network (WLAN), Wi-Fi, and Wi-MAX applications [14], an antenna employing a partial ground architecture has been developed, measuring 40×30×1.6 mm and constructed on an flame retardant (FR-4) substrate, demonstrating a return loss below -10 dB across 3 to 5.64 GHz, with gains ranging from 1.73 to 3.22 dB and a maximum radiation efficiency of 90%. This design exhibits end-fire characteristics [15] and E-shaped dual-band antennas with defective ground structures for enhanced performance [16]. Other research has focused on optimizing antennas for the widely used Wi-Fi frequency bands of 2.4 GHz and 5 GHz, utilizing microstrip lines and low-cost materials for cost-effective production [17]. Additionally, the integration of complementary split ring resonators (CSRR) has enabled compact antennas to achieve dual-band operate at 5.8 GHz and 7.1 GHz, suitable for Wi-Fi and C-band applications [18]. Moreover, compact antennas featuring modified monopoles and C-shaped strips have demonstrated exceptional dual-band operation with significant implications for geometric parameter optimization [19]. Finally, the utilization of HFSS software has facilitated the design of small dual-band antennas operating at 4.9 GHz and 6.7 GHz, highlighting the potential for compact, efficient designs in WLAN applications [20].

In recent years, the pursuit of enhancing the performance of miniaturized MPAs has gained momentum. A notable study proposed the use of a thin film composed of a high relative permittivity material, optimizing the dimensions of the antenna's patch via genetic algorithms. This approach yielded a reduction in the resonance frequency from 5.8 GHz to 4.0 GHz, alongside a 60% decrease in the antenna's area, while simultaneously improving key performance metrics such as return loss, bandwidth, and voltage standing wave ratio (VSWR) [21]. Similarly, the introduction of a heart-shaped antenna employing countersink and partial ground plane methodologies demonstrates the ability to achieve high electromagnetic performance and operate as a multiband device [22]. This design effectively caters to multiple modern wireless applications, operating as both narrowband and wideband in its designated frequency bands.

This manscript introduces a novel design methodology that leverages the synergistic benefits of DGS and barium strontium titanate (BST) thin films, aiming to surpass the current limitations of MPAs by offering enhanced dual-band capability operate at 2.8 GHz/5.8 GHz and miniaturization suitable for WLAN and WiMax applications. Unlike existing solutions, our approach not only broadens the bandwidth but also significantly reduces the antenna's size, marking a notable advancement in the antenna design field. Through a meticulous design process and empirical analysis, this paper delineates the technical nuances of our innovative antenna design, its comparative advantages over prior art, and its potential implications for future wireless communication systems.

The rest of the manuscript is organized as follows: section 2 delves into the design methodology and the steps involved in the approach. Section 3 elaborates on the study's results and the analytical observations made. The paper is wrapped up in section 4, which summarizes the key findings and concepts, leading to the references section.

2. METHOD

In this research, we employed a two-phased methodology to design and optimize a MPA, with a focus on achieving miniaturization and enhanced performance for wireless communication systems. CST Microwave Studio (Computer Simulation Technology) 2022 software used for simulation and analysis. CST is a widely acclaimed electromagnetic simulation tool, known for its robust capabilities in modeling and simulating complex antenna structures with high accuracy. The first designed of MPA utilizing an FR4 substrate, characterized by a permittivity of 4.3 and a thickness of 1.524 mm. The design incorporated defected ground structures (DGS) to attain a single resonant frequency, with the initial phase parameters being guided by a previously published study in [23].

In the second phase, the design was advanced through the integration of a high-permittivity ferroelectric thin film (B0.8S0.2TiO3), have a dielectric constant of 250 and a low loss tangent (tan δ=0.02), similar to the material used in reference [21]. The integration aimed to facilitate dual-band functionality, enabling the antenna to operate efficiently at these frequencies. A comprehensive parametric analysis followed, focusing on refining the antenna's dimensions to improve essential performance metrics such as return loss, bandwidth, and VSWR.

The flowchart presented in Figure 1 delineates the processing steps involved in integrating the thin-film material into the antenna. This illustration is instrumental in demonstrating the sequential approach undertaken to optimize the MPA design, culminating in the realization of a dual-band antenna that meets the requisites of modern wireless communication standards. The incorporation of the thin-film material BST, was a critical factor in achieving the objectives of miniaturization and dual-band functionality, marking a significant contribution to the development of compact and efficient antenna solutions in the wireless communications domain.

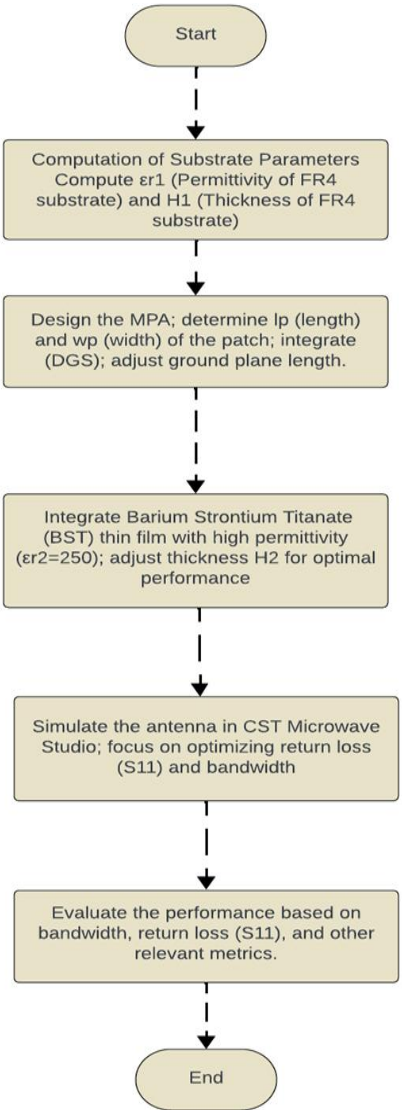


Figure 1. Flowchart of the antenna design method

2.1. Mathematical model

The equations used for designing a microstrip patch antenna are mentioned as (1) to (6). The width and length of the patch can be calculated using the following equations where fr is the resonant frequency, εr is the relative permittivity of the substrate, µo is the permeability of free space, and hs is the thickness of the substrate [24].

– Width of the patch:

$$W = \frac{c}{2f_0\sqrt{\frac{\varepsilon_r+1}{2}}} \quad (1)$$

– Length of the patch (L):

$$L = L_{eff} - 2\Delta l \quad (2)$$

– The effective (relative) permittivity:

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+\frac{12h}{W}\right)^{\frac{-1}{2}} \quad (3)$$

– Length extension ΔL:

$$\Delta l = 0.412h\ \frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)} \quad (4)$$

– The ground plane dimensions:

$$L_g = 6h + L \quad (5)$$

$$W_g = 6h + W \quad (6)$$

Where Lg represents the ground plane's length and Wg denotes the ground plane's width [25].

2.2. Antenna design

In this study, we examine two advanced antenna design methodologies to address the demands of contemporary wireless communication systems. The first method involves a MPA with a DGS, which utilizes strategic modifications to the ground plane to achieve desired resonant frequencies and performance enhancements. The second approach advances this concept by integrating a high permittivity BST thin film into the MPA design. This innovation enables dual-band operation and significantly improves the antenna's performance, illustrating the potential of material science in enhancing wireless communication technologies.

2.2.1. MPA with DGS design

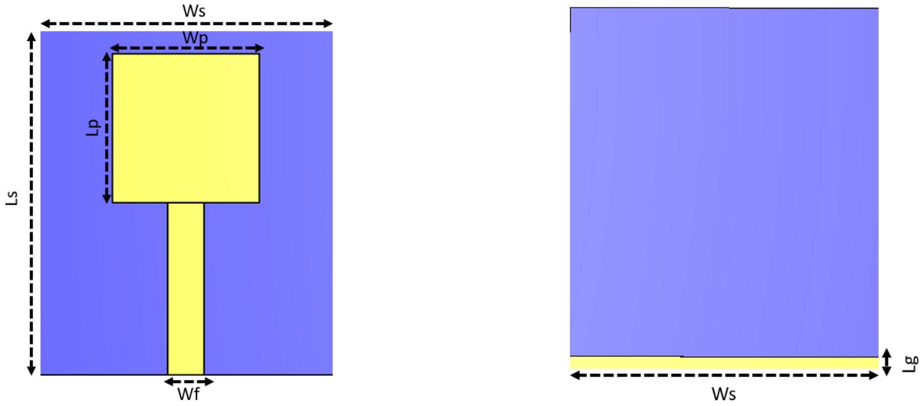
In the initial phase of the MPA design, an FR4 substrate characterized by a permittivity of 4.3 and a thickness of 1.524 mm was employed. This phase focused on utilizing ground reduction techniques to refine the antenna's structure for a single resonant frequency. The antenna's dimensions were meticulously designed to be 14×12×1.524 mm^3, as detailed in Table 1. Figure 2 provides a visual representation of the MPA's geometry, where Figure 2(a) illustrates the top view of the antenna. It shows the placement and dimensions of the patch and feedline. Conversely, Figure 2(b) depicts the bottom view, emphasizing the ground plane reduction and its contribution to achieving the antenna's resonant frequency. These figures collectively illustrate the strategic design choices made to achieve the desired operational characteristics.

Table 1. Dimensions of MPA with DGS

Parameter	Value(mm)	Description
lg	0.600	Length of ground plan
wg	12	Width of ground plan
ls	14	Length of substrate
ws	12	Width of substrate
lp	6	Length of the patch
wp	6	Width of the patch
wf	1	Width of feedline
H1	1.524	High of substrate

2.2.2. Enhanced microstrip patch antenna with thin film BST integration

The second design we enhanced the MPA by incorporating a high permittivity BST thin film. This modification tailored the antenna's physical dimensions to 14×10×1.524 mm^3 and optimized its operational capabilities for dual-band functionality. Integrating the BST thin film into the antenna's structure leverages its high permittivity properties to enhance performance. This phase of the design, detailed in Table 2, is depicted in Figure 3, where Figure 3(a) shows the top view of the MPA, illustrating the placement of the BST layer in relation to the patch and feedline. Concurrently, Figure 3(b) provides the side view, demonstrating the layering order of BST, patch, substrate, and DGS, each contributing to the antenna's enhanced capabilities. These visual aids substantiate the strategic optimization of the MPA's parameters to fully harness the advantages of BST, emphasizing the vital role of materials science in expanding the functionality of conventional antenna designs to fulfill the intricate demands of current wireless communication systems.

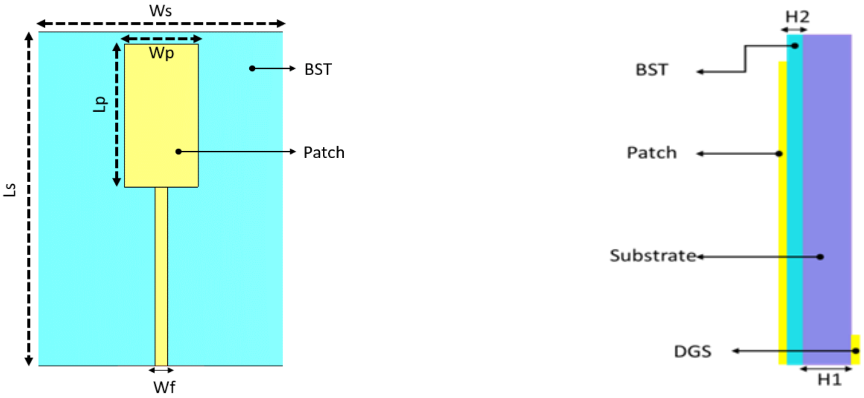


(a) (b)

Figure 2. The structure of MPA with DGS design (a) top view and (b) bottom view

Table 2. Dimensions of the MPA with DGS and BST

Parameter	Value (mm)	Description
lg	0.600	Length of ground plan
wg	10	Width of ground plan
ls	14	Length of substrate
ws	10	Width of substrate
lp	6	Length of the patch
wp	3	Width of the patch
wf	1	Width of feedline
H1	1.524	High of substrate
H2	0.120	High of BST
hg	0.035	High of ground plan



(a) (b)

Figure 3. The structure of the MPA with DGS and BST design (a) top view and (b) side view

3. RESULTS AND DISCUSSION

In this section, the results from simulating MPA designs with DGS and BST integration are discussed. The first MPA design with DGS showed substantial bandwidth in single-band operation. The addition of BST in the second design enhanced its capabilities, enabling dual-band functionality important for WLAN and WiMax applications, while optimizing the antenna's size and bandwidth.

3.1. MPA with DGS design

The initial design of the MPA with DGS has demonstrated promising results. The S11 graph, as shown in Figure 4, indicates a strong resonance at 4.1 GHz with an excellent bandwidth of 0.82 GHz and an optimal return loss of -32 dB. Complementing this, the VSWR value of 1.04, depicted in Figure 5, suggests minimal signal reflection and maximized power delivery to the antenna. The DGS's role in minimizing ground plane size is crucial, as it directly correlates with the antenna's enhanced performance, affirming the design's suitability for targeted single-band applications.

The performance of the antenna without BST integration is characterized by the return loss and VSWR measurements as shown in Figures 4 and 5, respectively. Figure 4 indicates a significant return loss with a pronounced minimum, demonstrating good impedance matching at the resonant frequency. Correspondingly, Figure 5 shows the VSWR reaching an optimal minimum at the same frequency, further confirming the efficient power radiation at resonance.

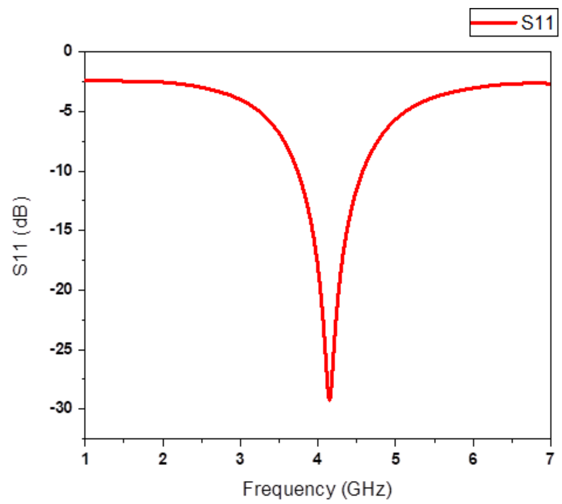


Figure 4. The return loss of the antenna without BST

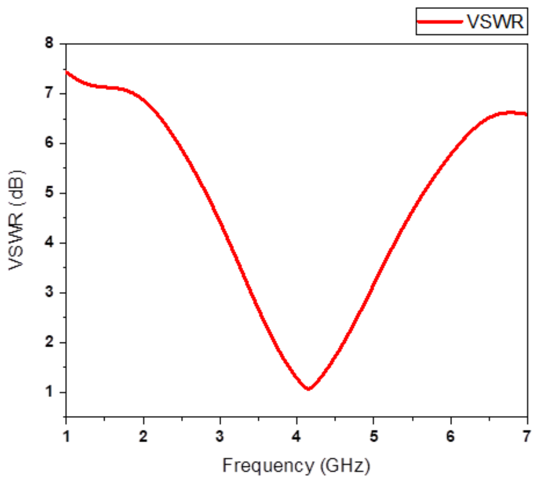


Figure 5. Voltage standing wave ratio of the antenna without BST

3.2. Enhanced microstrip patch antenna with thin film BST integration design

The integration of BST into the initial MPA design with DGS represents a notable advancement in antenna technology. It has achieved dual-band functionality vital for WLAN and WiMax applications, as depicted in the S11 parameter graph as shown in Figure 6 this integration resulted in resonant frequencies at 2.8 GHz and 5.8 GHz with significant return losses of -16.3 dB and -21.4 dB respectively, indicating effective signal retention. The bandwidths were considerably expanded to 1.34 GHz and 1.25 GHz for each frequency band. Furthermore, the VSWR graph as shown in Figure 7 shows excellent impedance matching, with VSWR of 1.35 at 2.8 GHz and 1.18 at 5.8 GHz, demonstrating the antenna's optimized performance. The BST and DGS combination has not only facilitated dual-band capabilities but also reduced the antenna's size, confirming the effectiveness of this approach.

The presented graphs showcase the performance of a dual-band rectangular MPA integrated with BST and DGS. Figure 6 illustrates the return loss (S11), indicating dual resonant frequencies with deep notches, implying efficient impedance matching at these points. Figure 7 displays the VSWR, where lower values near unity at resonant frequencies suggest minimal signal reflection, indicative of effective power transfer to the antenna. These results collectively validate the enhanced dual-band functionality and improved bandwidth of the antenna design.

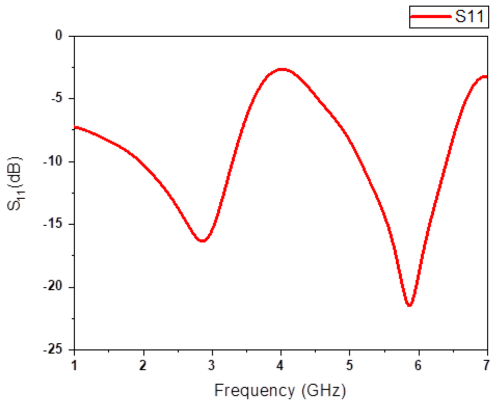


Figure 6. Return loss (*S*11) of for the proposed rectangular MPA with BST and DGS

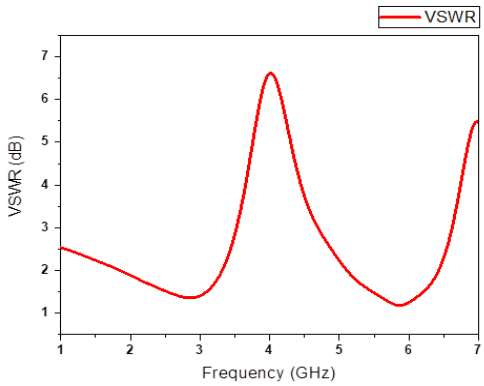


Figure 7. Voltage standing wave ratio for the proposed rectangular MPA with BST and DGS

3.3. Comparaison of the two designs

In our study, we have evaluated two distinct designs of MPA to ascertain their suitability for WLAN and WiMax applications. The initial design, featuring DGS, was optimized to resonate at 4.1 GHz. Upon the integration of BST, the antenna not only improved its performance but also exhibited dual-band characteristics, resonating at both 2.8 GHz and 5.8 GHz as shown in Table 3. The incorporation of BST was pivotal, enhancing bandwidth significantly while maintaining robust return loss metrics. This comparison, captured in Table 3, underscores the enhancements in bandwidth and frequency range post-BST integration, which are critical factors in the antenna's performance for the intended wireless applications.

Table 3. Comparison of the two-antennas design

S/N	Antenna design	Resonate frequency (GHz)	S11(dB)	BW (GHz)
1	MPA with DGS	4.1	-32	0.82
2	MPA with DGS and BST	2.8	-16.3	1.34
		5.8	-21.4	1.25

3.4. Comparative study

In the sphere of MPA innovation, our design distinguishes itself not only in the realms of bandwidth and compactness but also in the diminutive physicality of the antenna structure. The comparative analysis in Table 4 elucidates our design's supremacy, particularly highlighting its streamlined dimensions of 14×10 mm, which reflects a significant reduction when juxtaposed with the larger sizes reported in existing literature. For instance, Sura and Sekhar [14] present an antenna with dimensions of 40×29 mm, and Jha *et al.* [15] with 40×30 mm, underscoring the remarkable miniaturization our design achieves. This strategic integration of a DGS with the BST within the antenna's ground plane manifests not only in superior bandwidth but also in the substantial miniaturization of the antenna's footprint. The consistent and enhanced performance metrics, accentuated by our rigorous comparative study, validate the efficacy of our design approach. It masterfully balances the dual imperatives of miniaturization and bandwidth augmentation, thereby marking our contribution as a pioneering stride in the research landscape of antenna design.

Table 4. An evaluative comparison of the proposed design against existing literature

Reference	Size(mm)	Frequency (GHz)	Bandwidth (GHz)	Return loss(dB)
Sura and Sekhar [14]	40×29	3.5, 5.2	3.35-3.9, 4.8-6	<-11
Jha *et al.* [15]	40×30	4	3-5.64	−26.5
Goyal *et al.* [16]	46.83×38.41	1.9, 2.89	1.9546 -2.0113, 2.5 - 3.0632	-18, -13.7
Kaplan and Gocen [17]	10×50	2.4, 5	2.19-2.75, 4.74-6	-31.17, -42
Ambika *et al.* [18]	12×12	5.8, 7.1	5.66-5.97, 6.45-7.50	-27
Sharma *et al.* [19]	12×15	2.4, 6.7	2.1-2.5, 3.4-10.1	<-10
Hussain *et al.* [20]	17.95×16.89	4.9, 6.7	2.98-5.34, 6.6-7.2	-27.5, -27.6
Boudjerda *et al.* [21]	13.76×11.32	4.0	3.9-4.07	-29.81
This work	14×10	2.8, 5.8	5.15-6.40, 1.95-3.29	-16.3, -21.4

4. CONCLUSION

In This research introduces a groundbreaking dual-band MPA, leveraging DGS and BST integration, to surpass existing performance benchmarks in antenna design. Achieving dual-band operation at 2.8 GHz and 5.8 GHz, with substantial bandwidths of 1.34 GHz and 1.25 GHz and return losses of -16.3 dB and -21.4 dB, the study meets the demanding requirements for WLAN and WiMax applications. The strategic integration of BST with DGS highlights the critical role of advanced material science and innovative design techniques in enhancing antenna performance. This contribution is significant, showcasing a notable leap towards compact, efficient wireless communication systems. Future directions of this research include exploring additional slot integrations in the ground plane for further performance optimization and the practical implementation of the dual-band MPA design in real-world applications. These efforts aim to refine antenna efficiency and utility, underscoring the potential of our design in advancing wireless communication technologies and their applications across various sectors. This study's interdisciplinary approach emphasizes the importance of collaborative research in addressing the evolving challenges of global connectivity and network performance.

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