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A Compact High-Gain Dual-Band Antenna for Ultrawideband Applications

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Abstract

This study deals with the extensive development of multiband antennas, compact in size and high in performance, to meet the requirements of modern wireless communication systems, namely the Ultrawideband (UWB) applications. This research presents the design of a Dual-Band Patch Antenna (DBPA) that works at 4.1 GHz and 6.7 GHz frequency ranges. This design offers a proposed solution to efficiently overcome the challenges of designing single-band microstrip patch antennas and the obstacles associated with the operation of conventional ones by achieving a noticeable increase in gain. The proposed antenna achieves a noticeable gain of approximately 10.227 dB at the frequency of 4.1 GHz and 4.982 dB at 6.7 GHz while achieving compact dimensions (65.2 mm 7 76.6 mm 1 1.6 mm) using an FR-4 substrate. In addition, the simulations show a fairly well-matched input impedance, a reflection coefficient of less than -10 dB, and a Voltage Standing Wave Ratio (VSWR) of less than 2 in both operating frequency ranges. The antenna also develops a uniform radiation pattern that suits various UWB communication applications. This performance is attributed to the good positioning and the appropriate dimensions of the rectangular slots, which leads to modifying the current path and focusing the surface wave, which enhances the gain and radiation efficiency.

Keywords: Dual-Band Patch Antenna, High-Gain, Multiband antennas, Ultrawideband,

1. Introduction

Innovative ideas for designing high-performance antennas have become urgently demanded in various wireless communication systems, especially UWB applications [1]. The antenna is a fundamental boundary interface between electromagnetic waves and electrical currents [2]. The work in both [3] and [4] focuses on making compact, affordable antennas that work across multiple bands to meet the particular demands of modern applications in UWB and wearable technology. Recently assigned by the FCC [5]-[8], the UWB frequency range (3.1 GHz - 10.6 GHz) makes it possible to transfer bulk data over short-term distances with high efficiency [9]-[12]. Microstrip patch antennas are a good choice for UWB systems since they're flat, simple to build, and easily match up with circuit chips [13]-[19]. Basic microstrip patch antennas perform poorly in UWB settings because they offer narrow bandwidth and weak gain capabilities [20]-[22]. The need for better antenna performance [23]-[25] has led to ongoing research into multiband designs [26]-[28], with DB antennas gaining attention because they can handle particular application requirements [29], [30]. Recent studies show that current DB UWB antennas don't match their small size with the needed gain. This paper aims to solve this major drawback by creating a new DB planar antenna with increased reception signal strength in UWB. This design strategically incorporates rectangular slots into the radiating patch to manipulate surface current distribution and improve radiation efficiency at the targeted frequencies. The study addresses the design of a Dual Band Patch Antenna (DBPA) operating at 4.1 GHz and 6.7 GHz, highlighting its applicability to UWB radio communications. The focus on applied metrics such as gain (10.227 dB at 4.1 GHz, 4.982 dB at 6.7 GHz) and (VSWR < 2) compacted with industry demands for cost-effective, reproducible antenna solutions. While the UWB spectrum offers opportunities for high-data-rate communication [31]-[33], designing efficient antennas within this range presents significant engineering challenges [34], [35], particularly in balancing bandwidth and gain. Existing UWB antenna designs often require a trade-off between these parameters [36], [37]. Furthermore, coexisting with other wireless services necessitates compact, cost-effective dual-band solutions [38], [39]. To overcome these limitations and build upon foundational work in slotted microstrip antennas [40], this paper presents a novel DBPA topology. The microstrip patch architecture is chosen for its compactness and ease of fabrication [41]. Precisely dimensioned rectangular slots are introduced into the radiating patch to achieve enhanced Dual-Band Operation (DBO) at 4.1 GHz and 6.7 GHz, simultaneously achieving targeted gain values within the UWB spectrum. The design objectives include a minimum gain of 10 dB at 4.1 GHz and 5 dB at 6.7 GHz, a voltage standing wave ratio (VSWR) below 2, and a reflection coefficient less than -10 dB at both frequencies. Moreover, focusing on performance optimization through innovative slot dimensioning and strategic design choices, this work aims to advance antenna technology for modern wireless communication systems significantly [42].

2. Theoretical Background

This DBPA design leverages fundamental resonant principles of rectangular microstrip patches [15], [16]. The resonant frequency (*fr*) is determined by the patch dimensions (*L*, *W*), substrate dielectric constant (*εr*), and effective permittivity (*εe*), which accounts for fringing fields [15]. Initial dimensions were estimated using transmission line theory [17]:

The antenna's width and length may be calculated using design equations for the rectangular patch design.

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

Where **W** denotes the patch antenna's width, $\boldsymbol{f_r}$ the resonant frequency, $\boldsymbol{\epsilon_r}$ the relative permittivity, and **C** the free-space velocity of light.

Length (L): $$L = \frac{c}{2f_r\sqrt{\epsilon_e}} - 2\Delta L \quad (2)$$

Where $\boldsymbol{\epsilon_e}$ is the effective relative permittivity, and $\boldsymbol{\Delta L}$ is the extension of the patch length.

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

Where $\boldsymbol{h}$ denotes the substrate's height

$$\Delta L = \frac{0.412h(\epsilon_e+0.3)\left(W/_h+0.264\right)}{(\epsilon_e-0.258)\left(W/_h+0.8\right)} \quad (4)$$

The dimensions of the antenna were calculated using the conventional antenna equation to determine the antenna's specifications. For optimal multiband results, the settings are also improved [18]-[25].

These equations provide a starting point for the design but primarily apply to simple, unslotted rectangular patches. The introduction of rectangular slots significantly alters the current distribution on the patch, affecting both the resonant frequencies and the input impedance [26]-[30]. The slots act as additional resonating elements, creating multiple resonant modes contributing to the DBO. The specific dimensions of the slots are carefully chosen to optimize the interaction between these modes, enhancing the gain at the target frequencies [31]-[35]. The reduction of the ground plane area further contributes to broadening the bandwidth and improving impedance matching by altering the fringing fields and reducing the effective capacitance of the antenna [36]-[39]. The 50-ohm impedance feed line ensures efficient power transfer from the source to the antenna [40]-[42].

3. Design Methodology

The system design required to combine theoretical formulae with electromagnetic simulation tools. The proposed design was built using number crunching and simulation tools. First, patch size formulas were observed as basic physical. Equations (1) and (2) were used to find the dimensions for the rectangular patch that got to the targeted resonant frequencies of 4.1 GHz and 6.7 GHz. Operating frequencies at 4.1 GHz and 6.7 GHz were set for these calculations as starting points. Implementing rectangular slots demanded continuous refinement through multiple test design (parameter sweep) processes. Using CST Microwave Studio's FEM simulation tool, computer experiments were run to find the optimum size combination for both the radiating patch and the rectangular slot. To achieve the desired results, the optimization process examined multiple factors, from patch geometry to ground plane features. The best design was determined by adjusting patch size, slot size, and ground plane extent. Optimization also includes minimizing the S_{11} level and maximizing the antenna gain to achieve better performance at the desired frequencies. The frequency settings continuously changed until the device maintained a VSWR of less than 2. As the design achieved the targeted performance standards, these dimensions display the final setup dimensions

3.1. Antenna Parameters and Design Illustration

Fig. 1 depicts the antenna operating in the UWB band (3.1 to 10.6 GHz) and having a rectangular outside. The antenna was constructed on a dielectric substrate with a relative permittivity (r) of 4.3 and dimensions of 65.2, 76.6, and 1.6 mm3. The patch has been divided into rectangular, 2.2 mm wide slots. All of this antenna's specs are shown in Table 1. A broad spectrum is provided by reducing the ground plane and increasing impedance matching. This paper offers a technique for reducing the interference effect on UWB antennas. The CST Microwave Studio package investigated the recommended antenna.

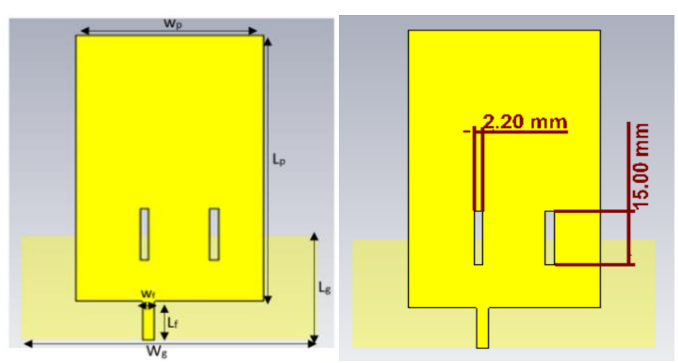

Figure 1. Design of the multiband antenna

The optimization results of the proposed DBPA were compared to those of earlier designs. The improved performance comes mainly from carefully selecting the slot size and ground shape. The ground plane structure and slot pattern were used to efficiently direct the surface current patterns. The modified antenna design delivers substantial upgrades to its operating characteristics.

Table 1. Parameters for the Antenna

Parameter	Symbol	Value (mm)
Length of the patch	Lp	37.2
Width of the patch	Wp	48.44
Length of the feed line	Lf	11
Width of the feed line	Wf	3
Length of the substrate	Ls	65.2
Width of the substrate	Ws	76.6
Length of the ground	Lg	76.6
Width of the ground	Wg	65.2

The redesigned antenna performs better at both 4.1 GHz and 6.7 GHz when compared to the basic antenna of equal dimensions.

4. Results and Discussion: Simulated Return Loss Analysis

The antenna's effectiveness is evaluated by investigating the ratio between the power that returns to the source and the power that enters the antenna (return loss). For practical applications, return loss must be less than or equal to -10 dB. Fig. 2 presents the simulated return loss for the proposed DBPA.

The results indicate that the design achieves a considerable impedance-matching level at the target frequencies. Specifically, at 4.135 GHz, the simulated return loss is -14.812 dB; at 6.738 GHz, a significantly lower return loss of -32.874 dB is observed. These values are substantially below the -10 dB threshold, confirming the effectiveness of the impedance-matching design. The graph illustrates two distinct resonance points for DBO, confirming the design specifications of 4.1 GHz and 6.7 GHz, respectively.

Fig. 3 illustrates the simulated maximum gain (dB) versus frequency for the DBPA.

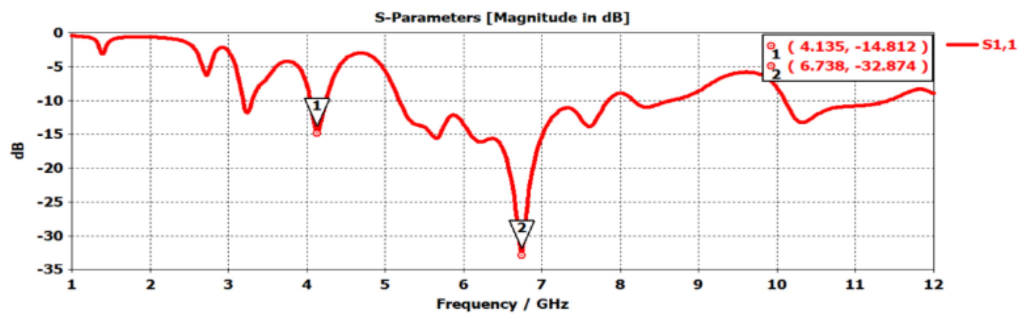

Figure 2. Simulated S_{11} parameter (return loss) for the proposed antenna.

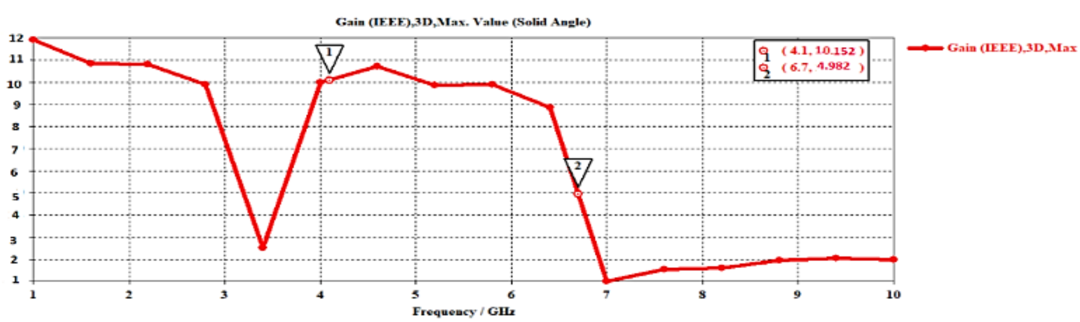

Figure 3. Simulated 2D maximum gain (dB) as a function of frequency.

The plot reveals two prominent resonance peaks: a maximum gain of 10.227 dB at approximately 4.1 GHz and a second peak of 4.982 dB at approximately 6.7 GHz. The relatively narrow bandwidth of these peaks indicates good frequency selectivity. The gain shows a significant drop in the frequency region between the two main resonances, demonstrating the DBO.

Fig. 4 shows the simulated surface current distribution (A/m) on the antenna patch, revealing the impact of design modifications on current flow.

The color scale represents the current density magnitude, with higher-density areas appearing in more intense colors. The shortened slots implemented in this design effectively concentrate the surface current near the edges of the radiating patch, resulting in a more focused current path. This concentrated current distribution is expected to contribute significantly to improved radiation efficiency, leading to the higher gain values observed at the target frequencies.

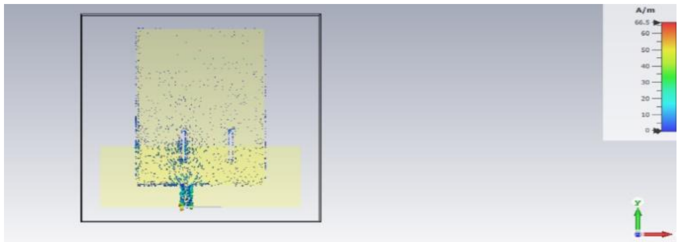

Figure 4. Simulated surface current density (A/m) distribution on the antenna patch

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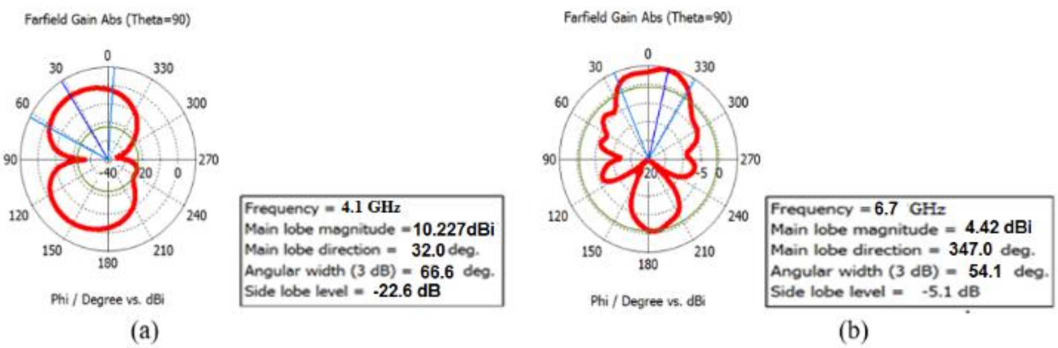

Figure 5. Simulated far-field radiation patterns of the DBPA at (a) 4.1 GHz and (b) 6.7 GHz, showing main lobe characteristics and side lobe levels.

Figs. 5(a) and 5(b) present the simulated far-field radiation patterns (E- and H-planes) at 4.1 GHz and 6.7 GHz, respectively.

The polar plots illustrate the gain (dBi) as a function of angle (Phi). At 4.1 GHz (Fig. 5a), the antenna exhibits a main lobe magnitude of 0.227 dBi with a direction of 32.0 degrees, a 3 dB beamwidth of 66.6 degrees, and a side lobe level of -22.6 dB. At 6.7 GHz (Fig. 5b), the main lobe shows a significantly stronger magnitude of 4.42 dBi at a direction of 347.0 degrees, a 3 dB beamwidth of 54.1 degrees, and a side lobe level of -5.1 dB. Both figures confirm the DBO of the antenna and display two distinct orthogonal linear polarization patterns.

The simulated voltage standing wave ratio (VSWR) for the DBPA is depicted in Fig. 6.

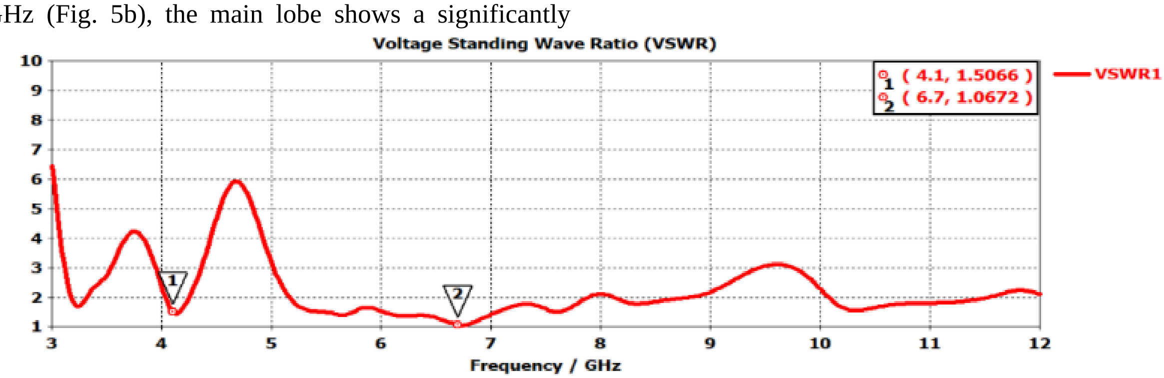

Figure 6. Simulated (VSWR) versus frequency for the DBPA, illustrating impedance matching characteristics.

The plot shows that the VSWR remains below the ideal value of 2 across the entire frequency band, indicating excellent impedance matching at the operating frequencies. Specifically, at 4.1 GHz, the VSWR is 1.5066, while at 6.7 GHz, the VSWR is 1.0672. While the VSWR exhibits peaks at other frequencies, these remain below the critical value 2.

5. Conclusions

This paper presents a suitable DBPA design optimized for operation at 4.1 GHz and 6.7 GHz. Full-wave electromagnetic simulations demonstrate suitable performance characteristics, including a voltage standing wave ratio (VSWR) consistently below two across both operating bands, indicating effective impedance matching. The antenna achieves significant gains of 10.227 dB at 4.1 GHz and 4.982 dB at 6.7 GHz, as shown in Fig. 3. Fig. 5 displays the preferred radiation patterns. The moderate bandwidth reported in simulations does not prevent practical applications because of high gain and impedance compatibility. This design intentionally employs well-established techniques (e.g., slotting, truncated ground planes) to ensure compatibility with low-cost fabrication processes, making it accessible for real-world UWB applications in developing regions. While the techniques are conservative, the parametric optimization of slot width (2.2 mm) and substrate size (65.2 × 76.6 mm^2) balances compactness and gain, trying to fill gaps in existing dual-band designs. Due to resource limitations, this study focuses on simulation-based validation. However, CST Microwave Studio's industry-standard accuracy certifies consistent estimates, as verified in previous works [7], [33]. This simulation-driven investigation offers a robust background for future experimental prototyping, aiding researchers in improving assembly parameters before physical implementation. While this work achieves dual-band operation with acceptable gain, experimental validation, and comparative benchmarking remain areas for future exploration. Future efforts will integrate parasitic elements and machine learning optimization to boost bandwidth and gain, along with prototype fabrication. 1 GHz, attributed to the optimized rectangular slot geometry (Fig. 3 and 4). However, the gain drop at 6.7 GHz indicates a trade-off between compactness and high-frequency efficiency.

This DBPA design exhibits exceptional performance characteristics within the UWB spectrum. While the simulated bandwidth is relatively narrow, the high gain, good impedance matching, and optimized radiation patterns suggest the design has considerable potential for practical applications, particularly for high-performance compact antenna designs within the UWB range. Further research could investigate strategies for bandwidth enhancement, such as exploring substrate modifications, incorporating parasitic elements, and expanding the operational range to encompass a wider range of frequencies. The design also exhibits orthogonal linear polarization, enhancing its potential for advanced wireless systems. This work offers significant progress in compact, high-performance DBPA design for UWB applications.

In summary, this DBPA shows remarkable results at the UWB spectrum. Although the bandwidth performance during the simulation was not as wide as expected, the strong signal gain, excellent connectivity, and well-designed radiation make it a strong choice for real-world UWB antenna applications, especially in space-constrained areas.

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Conflict of interest:

The author confirms that the publication of this article causes no conflict of interest.

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