Design of a Miniaturized Dual-Band Antenna using Slotted Techniques for 2.45/5.8 GHz Microwave Band RFID Utilizations

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ABSTRACT

In this study, a compact dual-band antenna for Radio Frequency Identification (RFID) readers operating at 2.45 GHz and 5.8 GHz is proposed. It is mounted on a FR4 substrate with a dielectric permittivity of 4.3. The proposed structure occupies a total area of 728 mm², with dimensions of 28×26 mm². The antenna features a rectangular radiating patch with integrated slots to enhance performance. A precisely tuned rectangular transmission line feeds the antenna, ensuring efficient signal coupling. The ground plane design incorporates a geometry derived from the slot technique, consisting of a rectangular loop, a square loop, and an attached rectangular element. This slot-based approach facilitates antenna miniaturization and enables the generation of two distinct resonant frequencies, significantly improving overall performance. The antenna was designed, simulated, and analyzed using the CST Microwave Studio (CST MWS) tool. The resulting structure is compact and straightforward, exhibiting suitable gain, coherent

radiation patterns, and efficient impedance matching. Its design allows easy integration into handheld RFID readers operating in the microwave band.

Keywords-compact; dual-band; RFID; slots technique; reader

I. INTRODUCTION

RFID technology is emerging as a pivotal development in the era of digitization and automation, transforming the interactions with physical objects. RFID uses electromagnetic fields to facilitate the automatic identification and tracking of objects, as opposed to traditional methods, such as barcodes and optical recognition. This technology operates over varying distances without requiring a direct line of sight, enabling simultaneous tracking of multiple objects [1-2]. RFID's versatility has led to its adoption in diverse sectors, such as healthcare, military, electronic payments, access control, and tracking [3-6]. An RFID system consists of tags, readers, and data processing units [7]. The reader activates the tags through electromagnetic waves to transmit stored data [6]. RFID encompasses several standardized frequencies, with UHF (840-960 MHz) and microwave (2.45/5.8 GHz) frequencies being particularly beneficial due to their high data rates and extended detection ranges [8-9]. Advancements in microelectronic technologies have increased the demand for smaller, high-performance antennas. Printed Patch Structures (PPS) are ideal for this demand, offering benefits, involving compact size, lightweight construction, low production costs, and compatibility with microwave circuits [10]. A key challenge is to design compact, efficient antennas, especially for dual-band devices in space-constrained environments [11-12]. Achieving dual-band functionality in a single antenna reduces the need for multiple antennas and facilitates the integration of diverse applications. Several methods have been employed to solve these problems, such as metamaterials [13], multilayer substrates [14], Artificial Magnetic Conductor (AMC) surfaces [15], fractal structures [16], and etching slots in the radiating plane and/or ground [17–24]. Among these, slot techniques have been particularly effective due to their ability to achieve multi-band operation, enhance bandwidth, and enable antenna miniaturization while maintaining design simplicity and cost efficiency. Slots embedded within the antenna structure or the ground plane, extend the return current path, lowering the resonant frequency without increasing the antenna's physical dimensions. This creates distinct resonant paths, enabling dual resonances. As a result, slot-based antennas offer a more compact form factor, improved bandwidth, and consistent electromagnetic performance, making them ideal for the RFID systems. Recent advancements in the RFID antenna design have aimed to improve compactness, performance, and efficiency for dual-band operations. However, many existing dual-band antenna designs still face limitations related to fabrication challenges, size constraints, and inconsistent performance in real-world conditions, indicating the need for further optimization and innovation in this field. For example, the antennas in [13, 17-19] achieve dual-band functionality but often have larger dimensions, limiting their integration into compact systems. Similarly, the designs in [25-27] address dual-band performance but encounter trade-offs, such as lower gain or less efficient impedance matching, particularly at the target frequencies. This work addresses these challenges by proposing a compact dual-band antenna that combines simplified fabrication with optimized performance, constituting an efficient solution for RFID applications. A detailed comparative analysis of these recent works is provided to highlight the innovative aspects of the proposed design and its contributions to the field of the RFID antenna technology. To overcome the aforementioned limitations, this paper presents an innovative compact dual-band antenna operating at 2.45 GHz and 5.8 GHz, specifically designed for mobile RFID microwave reader applications. The proposed antenna combines miniaturization and dual-band functionality by utilizing a slotted structure on a single dielectric layer. With dimensions of 28×26×1.6 mm³, it achieves reliable impedance matching (S11 of -25.8 dB at 2.45 GHz and -38.28 dB at 5.8 GHz) and competitive gain values of 1.52 dBi and 4.48 dBi, making it highly suitable for space-constrained RFID systems.

II. ANTENNA CONFIGURATION

A. Structure of the Compact Dual-Band Antenna

The suggested miniaturized antenna is depicted in Figure 1. It is constructed by engraving a 0.035 mm copper layer onto an 1.6 mm thick FR4 substrate. The FR4 dielectric material offers a favorable balance of electrical properties, cost, and availability, making it a popular choice for antennas operating below 6 GHz. The design embraces a rectangular radiating patch with embedded slots. A rectangular feed line, precisely tuned to optimize coupling with the radiating patch, attaches the patch, ensuring efficient signal transmission and enhanced performance. The ground plane includes a rectangular loop, a square loop, and a rectangular radiating element attached to the rectangular loop. The slotting technique enables the creation of two distinct resonance frequencies, facilitating dual-performing bands and contributing to the miniaturization of the radiator, which occupies an area of 28×26×1.6 mm³. Moreover, the slots optimize the current distribution, broaden the bandwidth, and improve impedance matching at both target frequencies. These advantages make the antenna ideal for space-constrained applications while ensuring superior overall performance. The finalized geometrical attributes are outlined in detail in Table I.

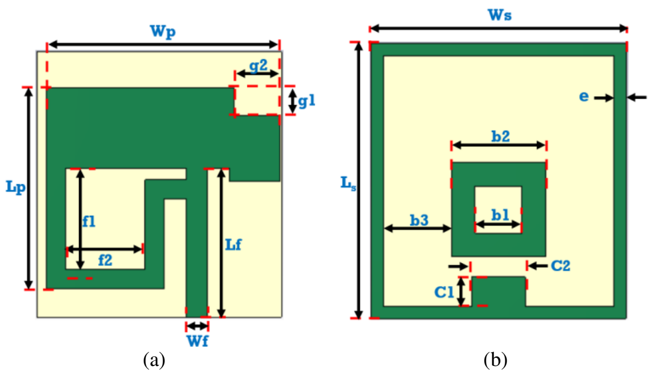


Fig. 1. Proposed antenna configuration: (a) front side, and (b) rear side.

TABLE I. ANTENNA OPTIMIZED DIMENSIONS

Parameters	Dimensions (mm)	Parameters	Dimensions (mm)
Ls	28	f1	10.75
Ws	26	f2	8.5
Lp	21.2	e	1.25
Wp	24.8	b1	4.8
Lf	15.75	b2	9.61
Wf	2.2	b3	6.945
g1	2.9	C1	3
g2	4.8	C2	5.46

B. Development Process

This section analyzes the design progression through three distinct stages: Ant 1, Ant 2, and Ant 3, showcased in Figure 2. These stages reflect a significant structural evolution to achieve the desired dual-band operation at 2.45 and 5.8 GHz. The incorporated slots are crucial for fine-tuning the resonance frequencies and improving impedance matching. The results (S11) for each design iteration are shown in Figure 3.

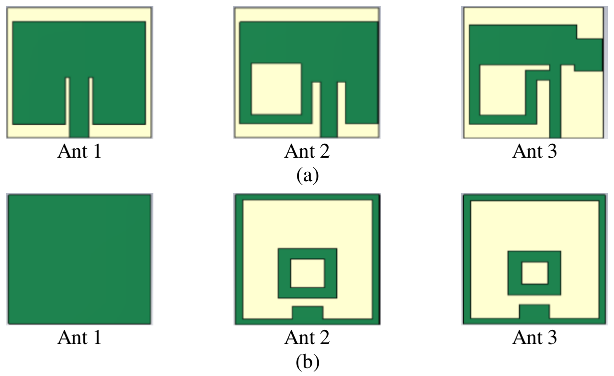


Fig. 2. Antenna design process: (a) top plane, (b) bottom plane.

The initial design (Ant 1) features a simple rectangular radiating patch and a rectangular ground plane. This configuration yields only one resonant frequency at 5.8 GHz with an S11 value of -12.66 dB. Although the antenna performs well at this frequency, it does not cover the lower target frequency f1, indicating the need for further modifications. In the second design (Ant 2), a slot is introduced in the radiating patch and the microstrip feed line is placed in the correct position. Additionally, the ground plane is modified by inserting several slots, forming a rectangular loop and a square loop, and integrating a rectangular radiating element. These changes create a new resonance at 2.37 GHz with an S11 of -17 dB, alongside a slight shift of the second resonance towards lower frequencies (5.53 GHz) with an S11 of -45.73 dB. This design successfully enables dual-band operation, but still requires further refinement to precisely align the resonances at the target frequencies. The final design (Ant 3) includes three additional slots into the radiating patch with an adjustment in the dimensions of the microstrip feed line, which improves its performance by aligning the resonances at the intended frequencies of 2.45 and 5.8 GHz, while widening the bandwidth at the second resonance. The final results demonstrate a substantial improvement in the reflection parameters, with S11 of -25.8 dB at 2.45 GHz and -38.28 dB at 5.8 GHz, indicating excellent impedance matching and efficient radiation at both frequencies.

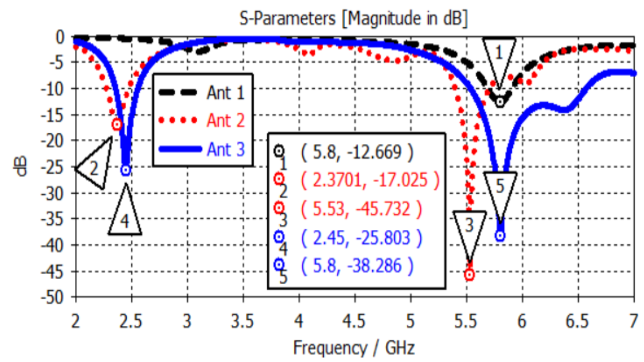


Fig. 3. Simulated reflection coefficient for each antenna.

III. PARAMETRIC STUDY

The antenna's performance is intrinsically linked to its geometrical parameters. A comprehensive parametric analysis was performed using the CST MWS through multiple simulation iterations to optimize the prescribed radiator design. This study focuses on assessing the influence of varying key parameters, such as the interior measurements of the square loop (b1), the width (Wf) of the feed line, and the width of the rectangular slot (g1), on its performance. Each geometric parameter is systematically varied during optimization while all other parameters are held constant.

A. Impact of Parameter b1 of the Square Loop

The first simulation study analyzes how the square loop's design parameter b1 affects the antenna's resonant frequencies. Figure 4 illustrates the reflection coefficient for different values of b1, ranging from 1.6 mm to 6.4 mm. Increasing b1 does not affect the first operating frequency f1, while the second operating frequency f2 experiences a significant shift towards lower frequencies. This indicates that the second resonant frequency can be tuned by the inner dimensions of the square loop. Notably, when b1 is 4.8 mm, the resonant frequency of 5.8 GHz is achieved.

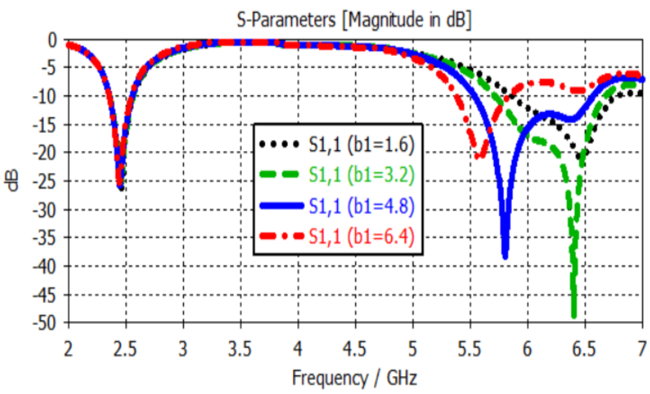


Fig. 4. Simulated reflection coefficient of the proposed structure for different values of b1.

B. Effects of Changing the Feed Line Width Wf on the Reflection Coefficient

To assess the influence of the feed line width Wf on the reflection coefficient, it was adjusted from 1.4 to 2.6 mm in increments of 0.4 mm, while holding other parameters constant, as depicted in Figure 5. Each increase in Wf causes both resonant frequencies to shift towards higher values. This shows that Wf can effectively tune the resonant frequencies f1 and f2. Based on the analysis, the final value of Wf is set to 2.2 mm to achieve the desired resonant frequencies.

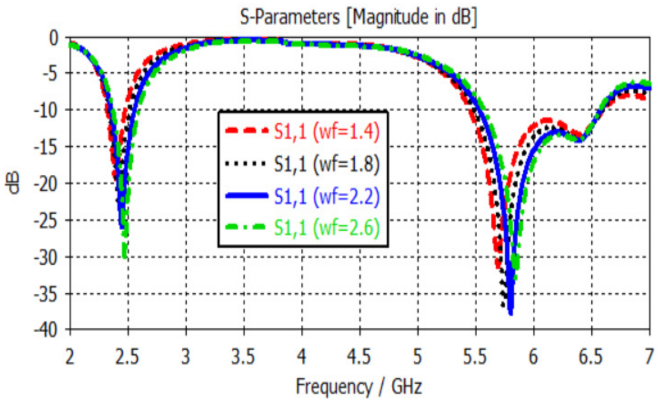


Fig. 5. Effect of varying Wf on parameter S11.

C. Effects of Changing the Rectangular Slot Width g1 on the Reflection Coefficient

The last important parameter in the parametric study is the slot width g1, which is adjusted between 0 mm and 4.35 mm to examine its influence on parameter S11. As portrayed in Figure 6, an increment in g1 results in a widening of the impedance bandwidth for the second operating band f2. However, the variation of g1 has no significant effect on the impedance bandwidth of f1. Based on the analysis, a slot width g1 of 2.9 mm provides optimal performance, balanced bandwidth, and impedance matching at 2.45 and 5.8 GHz.

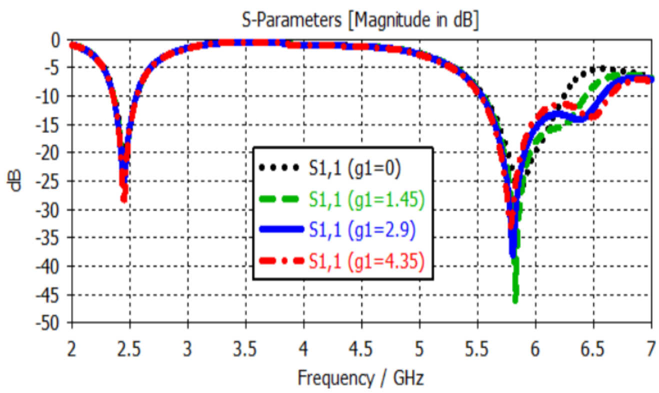


Fig. 6. Effect of varying g1 on parameter S11.

IV. RESULTS AND DISCUSSION

The following section presents the optimal simulation results including the reflection coefficient, Voltage Standing Wave Ratio (VSWR), radiation pattern, gain, and surface current distributions for the proposed RFID antenna. Figure 7 exhibits the simulation outcome of the S11 of the suggested antenna. The antenna provides two operating bands. For the lower band, the S11 reaches -25.8 dB with 199 MHz bandwidth ranging from 2.354 GHz to 2.553 GHz at the operating frequency of 2.45 GHz. For the upper band, the S11 reaches -38.28 dB with 1037 MHz bandwidth from 5.532 GHz to 6.569 GHz at an operating frequency of 5.8 GHz.

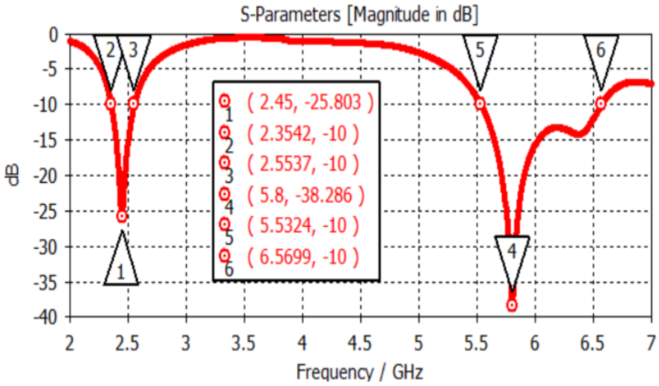


Fig. 7. Simulated reflection coefficient S11 of the proposed antenna.

VSWR is an essential metric that reflects the accurate alignment of the antenna's input impedance with the impedance of the transmission line. This ratio is determined by comparing the highest and lowest voltages along the transmission line, with values approaching 1 indicating excellent impedance matching. In this investigation, the simulated VSWR results, as depicted in Figure 8, were 1.1 at 2.45 GHz and 1.02 at 5.8 GHz, demonstrating effective impedance matching for the antenna at these frequencies.

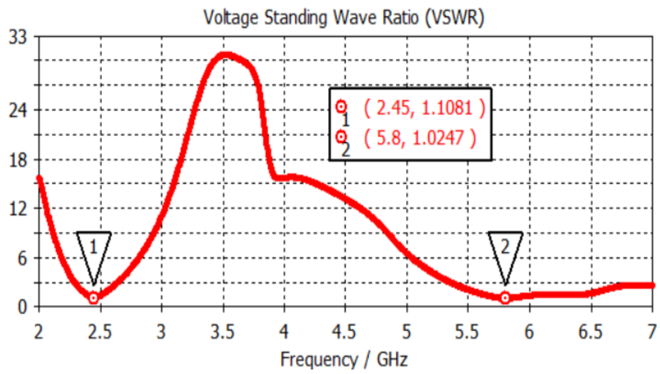
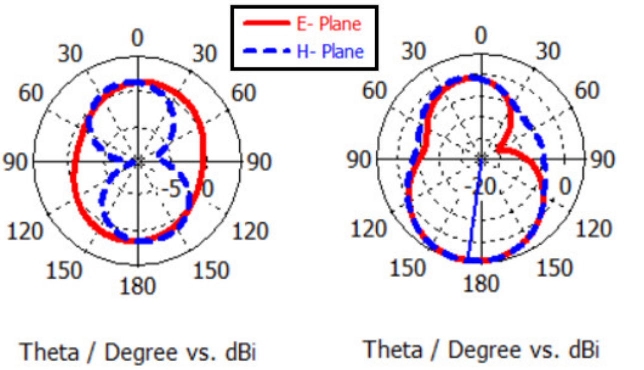


Fig. 8. Simulated VSWR of the proposed antenna.

The simulated 2D radiation pattern of the proposed antenna at resonance points is examined, as shown in Figure 9. The antenna gives a figure-eight radiation pattern in the E-plane at 2.45 GHz, indicating bidirectional radiation. The radiation pattern in the H-plane at 2.45 GHz is more omnidirectional, suggesting uniform energy distribution across different angles. At 5.8 GHz, the E-plane exhibits a highly directional radiation pattern with a focused main lobe and a narrower beamwidth, indicating an efficient concentration of the radiated power. In the H-plane at 5.8 GHz, a nearly isotropic radiation pattern is observed, implying consistent and uniform radiation in all directions. This pattern highlights the antenna's strong radiation properties at both resonant frequencies. The simulated peak gain is shown in Figure 10. The graph displays that the maximum gain at 2.45 and 5.8 GHz is 1.52 and 4.48 dBi, respectively.



(a) (b)

Fig. 9. Radiation patterns in a two-dimensional plane at (a) 2.45 GHz and (b) 5.8 GHz.

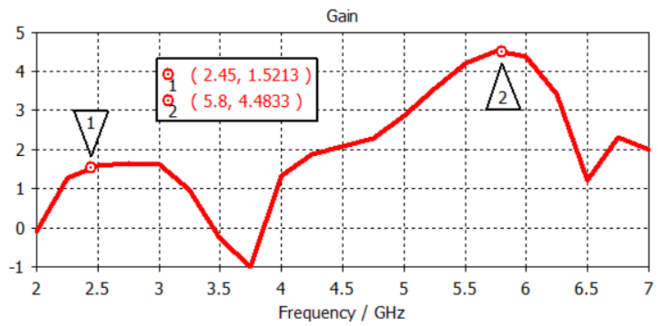


Fig. 10. Gain vs frequency.

The distributed surface current indicates the critical areas of the radiator responsible for generating resonances at the desired frequencies. At 2.45 GHz (Figure 11a), the current is widely distributed along the feedline, the outer edges of the radiating patch, and the rectangular loop on the ground plane, whereas at 5.8 GHz (Figure 11b) the current is more concentrated around the embedded slots in the radiating patch and along the square loop of the ground plane. This behavior is consistent with the theory that a longer current path lowers the resonant frequency, whereas a shorter path raises it, explaining the observed frequencies at 2.45 and 5.8 GHz, respectively [24].

Table II presents a performance comparison of the proposed dual-band antenna with some recently developed designs, focusing on size, reflection coefficient S11, and gain, to highlight the potential of the suggested antenna. The antenna (26×28×1.6 mm³) is more compact than the antennas proposed in [13, 17-19, 25-27], which significantly reduces the overall system size, which is crucial for space-constrained applications. In terms of the reflection coefficient, the proposed antenna demonstrates superior performance, with S11 values of -25.8 dB at 2.45 GHz and -38.28 dB at 5.8 GHz, outperforming the antennas in [17–19, 25, 27]. Even though the antenna in [13] offers comparable S11 values, its larger size (32×26×1.6 mm³) reduces the space efficiency. The antenna proposed in [26], although similar in size (34×34×1.5 mm³), has higher S11 values, indicating less favorable reflection characteristics. In terms of gain, the proposed antenna achieves 1.52 dBi at 2.45 GHz and 4.48 dBi at 5.8 GHz. While the antennas in [17–19, 26] exhibit a higher gain at 2.45 GHz, their larger dimensions result in a trade-off between gain and size. At 5.8 GHz, the proposed antenna outperforms all others, except for the antenna in [18], which offers a higher gain (5 dBi) but at the expense of a much larger size. The antenna introduced in [27] has a notably lower gain, highlighting the efficiency of the proposed design. Hence, the proposed antenna balances compactness, performance, and efficiency, establishing it as a promising solution for dual-band RFID applications.

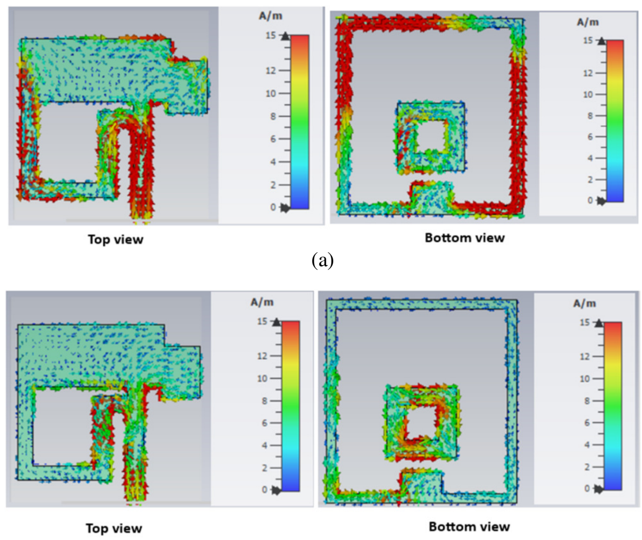


Fig. 11. Surface current circulation at (a) 2.4 GHz and (b) 5.8 GHz.

TABLE II. PERFORMANCE COMPARISON

Ref.	Dimensions (mm^3)	Resonant frequency (GHz)	S11 (dB)	Gain (dBi)
[13]	32×26×1.6	2.45/5.8	−25/−46	1.3/3.8
[17]	24×34×1.6	2.45/5.8	−16/−36.5	1.8/4.15
[18]	34×35×1.5	2.4/5.8	−18.95/−12.09	1.7/5
[19]	20×35×1.6	2.4/5.5	−15/−37	1.8/3.6
[25]	30×38×1.52	2.45/5.8	−13.47/−19.51	N/A
[26]	34×34×1.5	2.4/5.8	−18.95/−12.09	1.7/5
[27]	30×30×1.5	2.45/5.8	N/A	−0.7/2.21
This work	26×28×1.6	2.45/5.8	−25.8/−38.28	1.52/4.48

V. CONCLUSION

This paper presents a compact dual-band antenna for 2.45/5.8 GHz Radio Frequency Identification (RFID) applications, with dimensions of 28×26×1.6 mm³. The antenna utilizes a slot-based design on a single dielectric layer, enabling miniaturization and dual-band functionality. Simulations show that the impedance matching is optimized (S11 of -25.8 dB at 2.45 GHz and -38.28 dB at 5.8 GHz) and that the gain is competitive (1.52 dBi at 2.45 GHz and 4.48 dBi at 5.8 GHz). This demonstrates its suitability for space-constrained applications, such as portable and wearable RFID devices. The proposed design effectively integrates dual-band operation and miniaturization, addressing key challenges in RFID antenna development. Its compact form factor and simplified fabrication ensure efficient performance without compromising functionality. The antenna's consistent electromagnetic behavior across both frequency bands highlights its potential for real-world deployment in RFID systems, contributing to the advancement of the antenna technology for wireless communications.

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