

A Compact Frequency-Reconfigurable Antenna Using a Single PIN Diode for IoT and Sub-6 GHz Applications

Huda Ismail Khalil ^{1*}, Riyadh Khlf Ahmed ¹

¹Department of Communication Engineering, University of Diyala, 32001, Iraq
eng_grad_communication2509@uodiyala.edu.iq, riyadh_alazawi_eng@uodiyala.edu.iq

Abstract

This research article introduces a compact, frequency-reconfigurable microstrip radiating element featuring a PIN diode for multiband wireless communications. The proposed radiating element is simulated on an FR-4 substrate measuring 22.5 x 13 x 1.6 mm³ and is designed to operate below 6 GHz. The antenna design features a U-shaped radiating element with additional folded sections to improve current distribution and multiband performance. The arrangement uses a single PIN diode as a dynamic switching device between two operating modes, without complex circuitry. When the switch is OFF, the radiating element resonates at 2.4 GHz and 5 GHz; in the ON state, the frequencies shift to 2.16 GHz and 4.5 GHz, enabling support for multiple operating frequencies for IoT, WLAN, and other modern systems. The suggested antenna shows good impedance matching across all operating frequencies, with S₁₁ values of -22 dB, -37 dB, -32.9 dB, and -16.5 dB at 2.4, 5, 2.16, and 4.5 GHz, respectively. The bandwidths are 300 MHz and 800 MHz in OFF mode and 200 MHz and 600 MHz in ON mode, respectively. VSWR was below 1.5 in all operating modes. The antenna has stable gains of 1.5 to 2.5 dBi and a high efficiency of 86% to 95%. Radiation patterns are mostly bidirectional and omnidirectional in the E-plane and H-plane, respectively, ensuring good communication performance. The findings affirm the claim that the proposed radiator element offers a small, cost-effective, and efficient role for multiband and reconfigurable wireless systems, especially in the IoT and sub-6 GHz bands.

Keywords: Reconfigurable antenna, PIN diode, Small size, Frequency Switching, Wireless Communication

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1. Introduction

The rapid development of modern wireless communication systems has created a growing need for compact, efficient, and multifunctional antennas. These antennas must operate across multiple frequency bands while maintaining high performance and simple design. As a result, frequency reconfigurable antennas have become a promising solution because they can adapt dynamically to different communication needs and offer smaller sizes and lower costs.

The rapid advancement of small electronic devices such as smartphones, GPS receivers, smartwatches, and wireless internet access points has created a strong need for small, multifunctional communication systems [1] and [2]. Achieving these

improvements relies on using compact, efficient, and multi-frequency antennas in modern wireless systems. Frequency reconfigurability is crucial, allowing a single antenna to support multiple communication standards and reducing hardware complexity and cost [3]. Antennas that operate across multiple frequency bands with broad bandwidth are highly preferred for boosting system performance and spectrum efficiency [4].

Reconfigurable antennas can dynamically adjust their operating frequency, radiation pattern, and polarization by controlling the distribution of surface currents using methods such as PIN diodes, varactors, and shorting pins. They can be applied in IoT applications [5-13]. Metamaterials have also been shown to enhance antenna performance by reducing antenna size, increasing bandwidth, and reducing

radiation [1] and [2]. As suggested, combining metamaterials with reconfigurable antennas improves thermal stability and minimizes performance degradation caused by switching devices [14].

It has been demonstrated that loading metamaterials can help reduce antenna size, structural complexity, and system cost [15] and [16]. A small fractal monopole with a semi-elliptical ground plane was introduced, offering super-wideband performance and a reasonable VSWR [17]. A notch-loaded wideband fractal antenna is demonstrated, with a large bandwidth ratio and stable behavior [18]. To obtain multiple resonant frequencies, a multiband fractal antenna using metamaterial structures and slots has been presented [19]. A frequency-reconfigurable microstrip based on a PIN diode has been proposed for operation across several bands [20].

A metamaterial-based reconfigurable sub-6 GHz microstrip antenna has been reported to have improved performance [21]. A frequency-reconfigurable, high-radiation-efficiency planar monopole antenna has been demonstrated across multiple bands [22]. Multiband operation suitable for the IoT has been demonstrated with a compact frequency-reconfigurable antenna made using metamaterials [23]. IoT researchers have also designed compact dual-port antennas with multiband characteristics, small size, and acceptable gain. Multiband and MIMO antenna systems have been used to support multiple wireless standards; with more advanced substrate materials, performance has improved [24] and [25].

The proposed design balances structural simplicity with high performance. It uses low-cost, readily available materials. In addition, the design employs a single PIN diode for frequency reconfiguration, significantly reducing overall design complexity and implementation cost. The proposed antenna exhibits stable radiation characteristics, satisfactory gain, and high radiation efficiency while maintaining a low-profile structure. Therefore, the design offers a practical, cost-effective solution for modern wireless systems. Furthermore, complementary studies have highlighted the growing importance of compact antennas that support

multiple frequency bands while maintaining desirable radiation characteristics, making them well suited to meet the increasing demands of contemporary wireless communication applications.

2. Methodology

2.1 Antenna Structure

The proposed radiator will be a U-shaped radiating element with one arm shorter and the other arm horizontal to the left. A section that resembles a C is created from this horizontal extension, with one arm being longer than the other. This section is connected to another section that extends vertically downward via a PIN diode. The antenna dimensions are $22.5 \times 13 \times 1.6$ mm. It is mounted on an FR4 substrate with a dielectric constant of 4.3, a loss tangent of 0.025, and a thickness of 0.035 mm.

For the copper radiating layer, a $50\text{-}\Omega$ feed line with a width of 2.5 mm feeds the antenna, ensuring effective excitation and appropriate impedance matching. The feed point connects to a 50-ohm microstrip feeding line via a waveguide port in CST to provide efficient excitation and an appropriate impedance match. The design has also been streamlined to support four resonant frequencies at 2.16, 2.4, 4.5, and 5 GHz, providing critical bands for IoT, Wi-Fi, and wireless systems. Fig. 1 depicts the geometric arrangement.

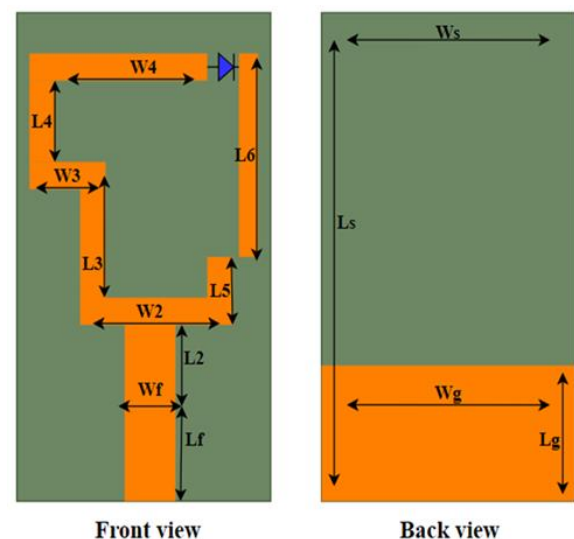


Fig. 1 The geometry of the suggested antenna.

The effective resonant length can be determined at the required frequencies using transmission line model theory [26]. Effective dielectric constant (ϵ_{eff}) Furthermore, the effective resonant length (L_f)

at the working frequency (f) is calculated using formulas (1) and (2).

$$\epsilon_{\text{eff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 12 \left(\frac{h}{w} \right) \right)^{-0.5} \quad (1)$$

$$Lf = \frac{C}{4f\sqrt{\epsilon_{\text{eff}}}} \quad (2)$$

Where c is the speed of light, ϵ_r is the dielectric constant, h is the altitude of the substrate, and w is the patch width.

Table 1: Geometrical parameters and size of the proposed printed antenna

Parameter	Value (mm)	Parameter	Value (mm)
Wf	2.5	Lf	4.5
Ws	13	Ls	22.5
Wg	13	Lg	7.6
W4	10.3	L4	4
L2	4	L5	3.5
L3	5	L6	8

Table 1 summarizes the optimized geometrical parameters and dimensions of the printed antenna. These values define the dimensions of the feeding geometry, substrate, ground plane, and radiating elements used to achieve the desired antenna characteristics.

2.2 Switching Techniques

Fig. 2 shows the electronic circuits for the two biasing states: forward (ON) and reverse (OFF) bias for the PIN diode. The switch-ON State is represented by a simple series connection of an inductor with a small resistance (RL). Conversely, the OFF condition is represented by a parallel circuit that includes a capacitor (C), an inductor (L), and a high-value resistor (RH). The PIN diode used in this paper is Skyworks SMP1340-079LF, with the following values: L = 0.7 nH, RL = 0.85 ohms, and C = 0.21 pF. For simulation, the capacitance was set to 0.2 pF, since this value is very close to the actual capacitance.

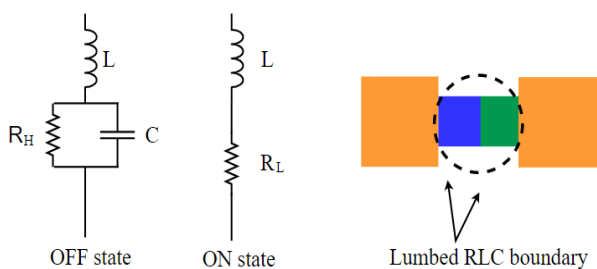


Fig. 2 Circuit models of the PIN diode and the CST model.

2.3 Antenna Design Process.

The antenna design process is presented as an evolution of six consecutive designs, as depicted in Fig. 3. Each design improves on the previous one through selective structural changes to enhance the overall frequency response. Fig. 4 illustrates the reflection-coefficient performance for all stages. The original antenna had a rectangular radiating element with a microstrip feed, with a vertical element added on the left-hand side to make the antenna resonate at 3.2 GHz. In the second antenna, a horizontal section was placed over the vertical section, which resulted in a 2.9 GHz resonance. The third antenna added a vertical component on top of the first horizontal component, attaining a 2.6 GHz resonance.

In the fourth design, an additional horizontal strip was added above the existing vertical section, altering the current distribution and producing a resonance at 2.12 GHz. The fifth antenna resulted in a side-sectioned extension on the right, generating two operating frequencies at 2.4 and 5 GHz. Lastly, the sixth structure featured a PIN diode on its top, connected to a rectangular piece that provided resonances at 2.16 and 4.5 GHz. In the last antenna performance, the four important frequencies in the on and off states were observed: 2.4 and 5 GHz, and 2.16 and 4.5 GHz. These were obtained through a systematic, gradual overlay of rectangular segments, which were horizontally and vertically positioned and complemented with precision geometric control and the application of methods such as PIN diodes. This led to an adjustable antenna suitable for high-tech communication.

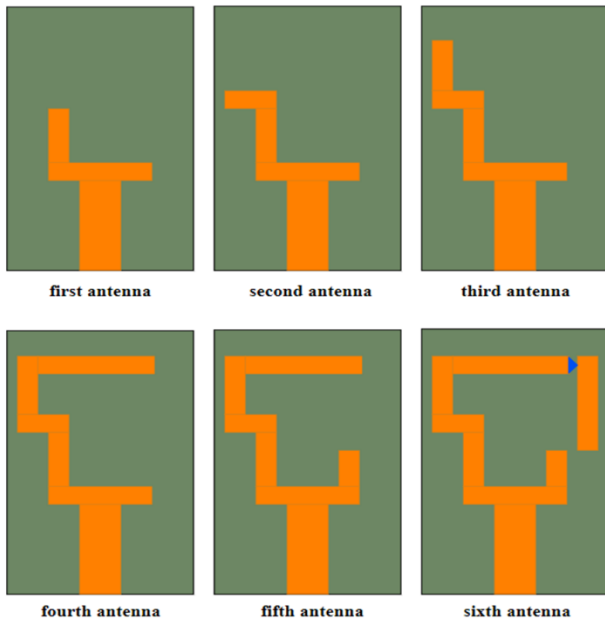


Fig. 3 The evolution of the antenna design.

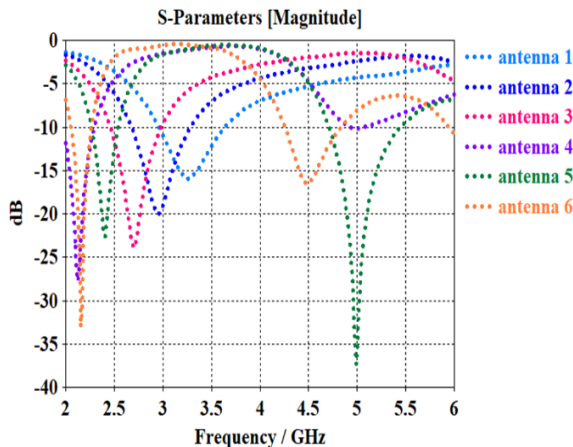


Fig. 4 S_{11} responses of Antennas.

3. Results and Discussion

Antenna structures were built and analyzed using CST Microwave Studio 2021. The radiating element was excited via a waveguide port on the microstrip feed line in CST. Under standard simulation conditions, CST Microwave Studio provides essential performance metrics, including S-parameters, gain, and surface current distributions.

3.1 Reconfigurable frequency switching

The antenna will use one PIN diode to implement dynamic frequency control with two operational states. When the device is in the OFF state, the diode acts as an open circuit, resulting in a shorter effective current path and weaker coupling between the radiating segments. In this State, resonances of 2.4 GHz and 5 GHz exist in the fundamental modes of

operation (Mode 1 and Mode 2) of the antenna. However, when the diode is turned ON, it is treated as a short circuit, providing the electrical connection between the various components of the structure. This bonding extends the effective current path and enhances the inductive-capacitive (LC) interaction between the antenna. Particularly, the inductive elements in the current paths are enhanced, and other capacitive couplings are added between elements close to each other.

This forces the resonance condition to vary with the LC relationship, resulting in lower resonant frequencies at 2.16 GHz and 4.5 GHz. These are called modified higher-order modes, in which the energy is spread out over a long current path. This effect demonstrates that the antenna can dynamically reconfigure its resonant properties by adjusting the corresponding LC network, enabling flexible multiband operation, which is appropriate for modern wireless systems. The switching states and resonant frequencies are summarized in Table 2.

Table 2: States of the PIN diodes for two operating modes.

MODE	D1	Frequency(GHz)
MODE1	OFF	2.4, 5
MODE2	ON	2.16, 4.5

Table 2 summarizes the PIN diode switching states and the corresponding resonant frequencies of the proposed radiating element. In Mode 1, the diode is OFF, and the structure operates at 2.4 and 5 GHz. In contrast, in Mode 2, the diode is ON and the operating frequencies shift to 2.16 and 4.5 GHz, demonstrating the frequency reconfigurability of the proposed design.

3.2 S-parameter and Bandwidth

The S-parameter (S_{11}) characteristics and bandwidth performance of the proposed antenna under various operating states are presented in Figure 5. Mode 1 (OFF state): The antenna works at two resonant frequencies of 2.4 GHz and 5 GHz. The corresponding bandwidths are 300 MHz (2.2–2.5 GHz) and 800 MHz (4.6–5.4 GHz), with minimum S_{11} values of -22 dB and -37 dB, respectively. Mode 2 (ON state): The antenna exhibits two resonant frequencies at 2.16 GHz and 4.5 GHz. The

corresponding bandwidths are 200 MHz (2–2.2 GHz) and 600 MHz (4.2–4.8 GHz), with minimum S11 values of –32.9 dB and –16.5 dB, respectively. The results indicate that the antenna can dynamically adapt its operating bands while retaining good impedance over the entire range of configurations. Fig. 5 shows the reflection coefficient (S11)

properties of all modes. VSWR is kept less than 1.5 across all operating bands, making it an excellent match. The radiating element operates at 2.4 GHz and 5 GHz in Mode 1, and at 2.16 GHz and 4.5 GHz in Mode 2. The VSWR values are less than 1.5 in all cases, as shown in Fig. 6.

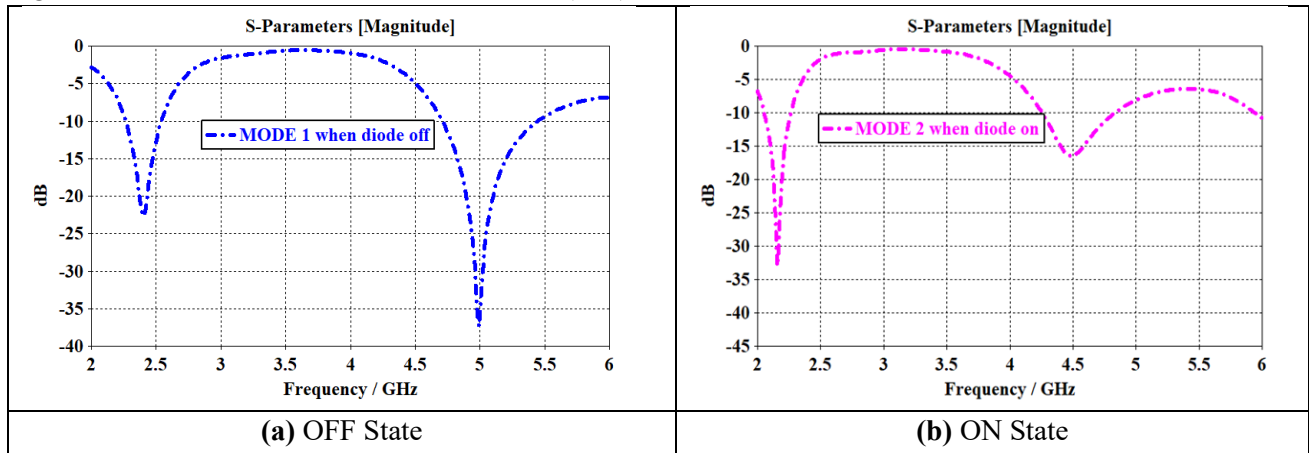


Fig. 5. Simulation S11 of the proposed antenna

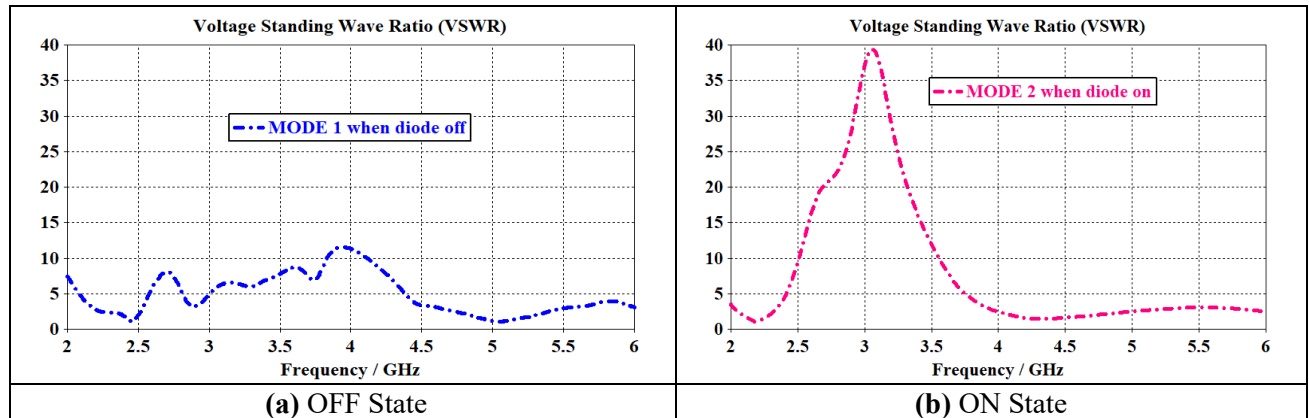


Fig. 6 Simulation VSWR of the proposed antenna

3.3 Performance Evaluation

To provide further insight into the proposed antenna behavior, a detailed parametric analysis is conducted to examine how progressive structural changes affect the resonance mechanism and impedance-matching characteristics. The reflection coefficient (S11) of all configurations is provided in Fig. 4. This resonance behavior of the antenna is explainable through an equivalent LC model, in which the resonance condition is obtained when the input reactance is zero, i.e., the inductive reactance of the antenna is equal to the capacitive reactance of the antenna, as shown in Equation (3) [26].

$$x_{in} = wL - \frac{1}{wc} = 0 \quad (3)$$

The first design has a single resonance at 3.2 GHz and is based on a simple structure. The existing path is relatively short at this stage, so (L) and (C) are low, resulting in a higher resonant frequency. The resonant frequency of a circuit, according to the resonance relationship, is proportional to the square root of the product of L and C; hence, the lower the value of L and C, the higher the resonant frequency, as shown in Equation (4) [26].

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad (4)$$

When a horizontal rectangular element is added to the second configuration, an effective current path is formed, and consequently, (L) increases.

According to the inverse linearity between L and resonant frequency, the resonant frequency decreases with increasing L , reaching 2.9 GHz. The third configuration adds another vertical element to enhance the effective current value and enhance capacitive coupling between adjacent elements. This increases the inductive coupling (L) and capacitive coupling (C). Therefore, and in proportion to the inverse, an increment in either L or C will lead to an additional decrease in the resonant frequency to 2.6 GHz.

In the fourth step, another horizontal rectangular section was added to the antenna structure, increasing the electromagnetic interaction between the radiating elements. This increased the capacitance (C), consequently lowering the resonant frequency to 2.12 GHz. This also enhances the power coupling within the structure and strengthens the resonance condition. In the fifth configuration, a rectangular side element is added, and several current paths are introduced, each associated with a specific effective electrical length. This leads to multi-resonant operation, with two frequencies at 2.4 GHz and 5 GHz. The formation of several parallel LC resonant paths within the structure may explain such behavior. The sixth configuration is reconfigurable, with a PIN diode included to switch between two electrical states. This directly impacts the effective current path and the equivalent inductance (L) and capacitance (C).

When the diode is in the ON state, it acts as a short circuit; current flows through a longer circuit, thereby increasing L and shifting the resonant frequencies. In the OFF case, the diode acts as an O/C, reducing the current path length, and the resonant frequencies are 2.4 GHz and 5 GHz. As far as impedance matching is concerned, it is achieved if the input impedance Z_{in} is close to the feed line impedance (50), thus reducing the reflection coefficient. When the input impedance Z_{in} closely matches the characteristic impedance z_0 The reflected power is minimized, thereby improving antenna performance. Conversely, any impedance mismatch

increases the reflected power. The gradual structural adjustments help in enhancing impedance matching by adjusting the equivalent inductive and capacitive elements, as illustrated by Equation (5) [26].

$$\Gamma = \frac{Z_{in} - z_0}{Z_{in} + z_0} \quad (5)$$

In general, the decrease in resonant frequencies with design stages is primarily explained by the prolongation of the effective path length, the augmentation of (L) and (C), and the strengthening of electromagnetic coupling. Because the resonant frequency decreases as the number of rectangular elements increases, the proposed design shows that stepwise addition of rectangular elements, combined with a PIN diode, easily controls resonance characteristics. This leads to a very small, high-performance, and reconfigurable radiating element that is compatible with modern communication applications.

In addition, the influence of substrate material and thickness on antenna performance is also explored. For an FR-4 substrate height of 1.4 mm, the antenna resonant frequencies are 2.4 GHz and 4.6 GHz. With an increase in substrate thickness to 1.6 mm, the impedance matching improves, and the resonant frequencies shift to 2.4 GHz and 5 GHz. The behavior is explicable depending on the variation of the effective permittivity ϵ_{eff} and the equivalent (L) and (C) of the antenna structure. A slight increase in the substrate thickness causes a slight adjustment in the electromagnetic field distribution and results in a decrease in the effective dielectric loading, resulting in a shift in the resonant frequency according to:

$$f_r \propto \frac{1}{\sqrt{\epsilon_{eff}}} \quad (6)$$

Therefore, as the effective permittivity decreases, the resonant frequency increases, shifting from 4.6 GHz to 5 GHz. Moreover, the antenna works at 2.6 GHz and 5.52 GHz using the Rogers RT5880 substrate. This improvement can be attributed to the lower (ϵ_r) and loss tangent of Rogers RT5880 compared to FR-4, which minimizes dielectric losses and improves impedance matching.

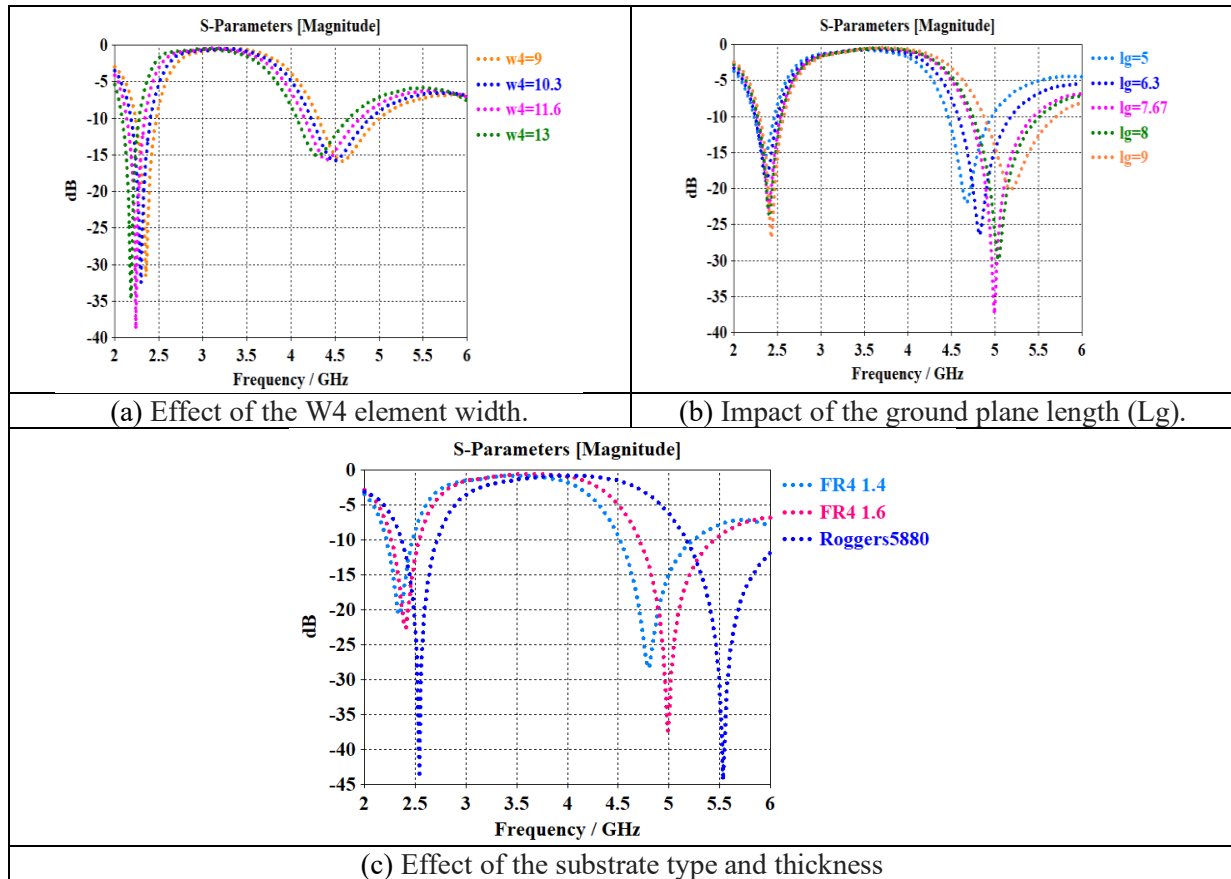


Fig. 7 Parametric study: (a) Effect of the width of the W4 element, (b) Effect of the ground plane length (Lg), and (c) Effect of the substrate type and thickness.

3.4 Gain and Efficiency

Both gain and radiation efficiency of the reconfigurable antenna were evaluated under both switching conditions (ON and OFF). The antenna demonstrated stable and efficient performance across the working frequency bands. In the OFF State, the antenna operates at 2.4 GHz and 5 GHz, with realized gains of 2.5 dBi and 2.2 dBi, respectively. The radiation efficiencies are 95 percent at 2.4 GHz and 86 percent at 5 GHz, indicating efficient power radiation, especially at the lower band.

In the ON state, the antenna operates at 2.16 GHz and 4.5 GHz, with gains of 1.5 dBi and 2.3 dBi, respectively. The radiation efficiency of this design is quite high, at 90% and 91% at 2.16 GHz and 4.5 GHz, respectively. On balance, the antenna demonstrates uniform radiation and high efficiency in both switching states across its entire operating frequency range. The obtained results confirm that the proposed design provides reliable

Gain and high radiation efficiency. The efficient conversion of input power into radiated energy demonstrates its suitability for multiband wireless applications. The radiation Equations (7) and (8) can be used to give efficiency (η) and gain (G) [26].

$$\eta = \frac{P_{in}}{P_{rad}} \times 100\% \quad (7)$$

$$G = \eta * D \quad (8)$$

Fig. 8 shows the gain and radiation efficiency of the proposed antenna under both switching conditions. In particular, Fig. 8 (a) shows the obtained antenna gain in the OFF case, whereas Fig. 8 (b) shows the gain properties in the ON state. Similarly, the radiation efficiency is illustrated in the same figure: Fig. 9(a) depicts the radiation efficiency in the OFF state, and Fig. 9(b) shows it in the ON state. This representation provides a pictorial view of the antenna's characteristics for different operating conditions.

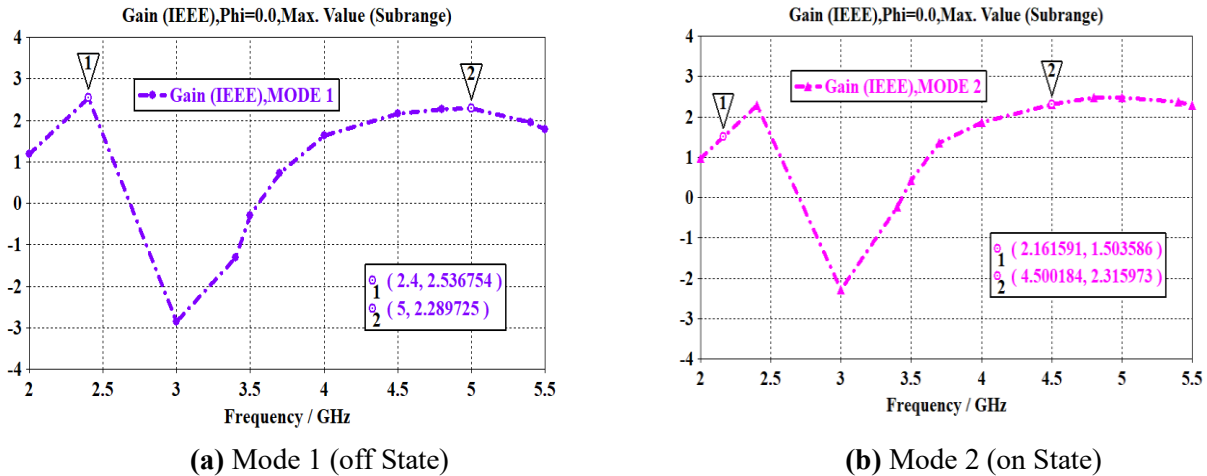


Fig. 8 represents the gain of this dual-mode antenna in Mode 1 (off State) and Mode 2 (on State).

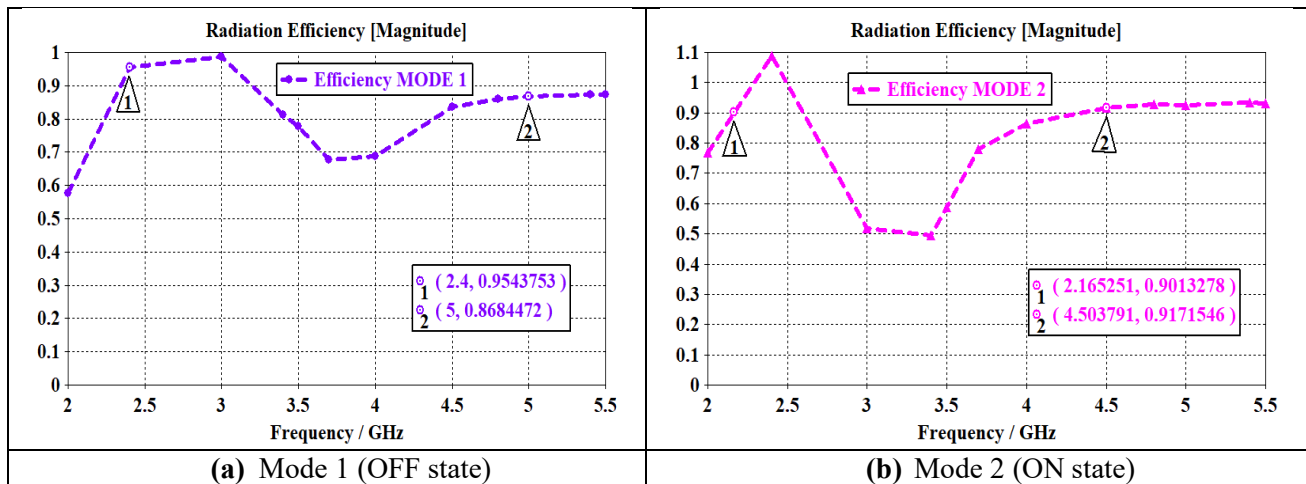


Fig. 9 The radiation efficiency of the suggested antenna in Mode 1 (OFF state) and Mode 2 (ON state).

3.5 Radiation Pattern and Surface Current Distribution

The suggested radiating characteristics are shown in Fig. 10 at the working frequencies of 2.16 GHz, 2.4 GHz, 4.5 GHz, and 5 GHz. The radiation patterns are evaluated based on the far-field response, which characterizes the antenna's performance across various frequency bands. At 2.16 GHz, the antenna exhibits a bidirectional radiation pattern in the E-plane, with two major lobes at 0° and 180° , indicating stable radiation behavior and high symmetry. The H-plane presents almost omnidirectional properties, implying homogeneous radiation in the azimuth plane. At 2.4 GHz, there is a similar pattern of bidirectionality; however, with a better gain and more defined lobes. It is symmetric with respect to radiation and maintains H-plane omnidirectional behavior, which is preferable for wireless communication applications. At 4.5 GHz, the radiation pattern remains bidirectional. However,

some distortions and slight differences in the shape of the lobes start to emerge as a result of higher-order mode excitation.

Nevertheless, the antenna still exhibits stable radiation characteristics with acceptable directivity. The radiation pattern shows greater variation at 5 GHz, with a minor asymmetry. and variation in the lobe intensity. This is because, as the frequency increases, electromagnetic interactions increase as well. However, the antenna still exhibits good radiation performance, with a quasi-omnidirectional pattern in the H-plane. Overall, the antenna can be used in multiband wireless systems, as it exhibits coherent radiation characteristics across the frequency bands under consideration and stable bidirectional patterns in the E-plane and almost omnidirectional patterns in the H-plane.

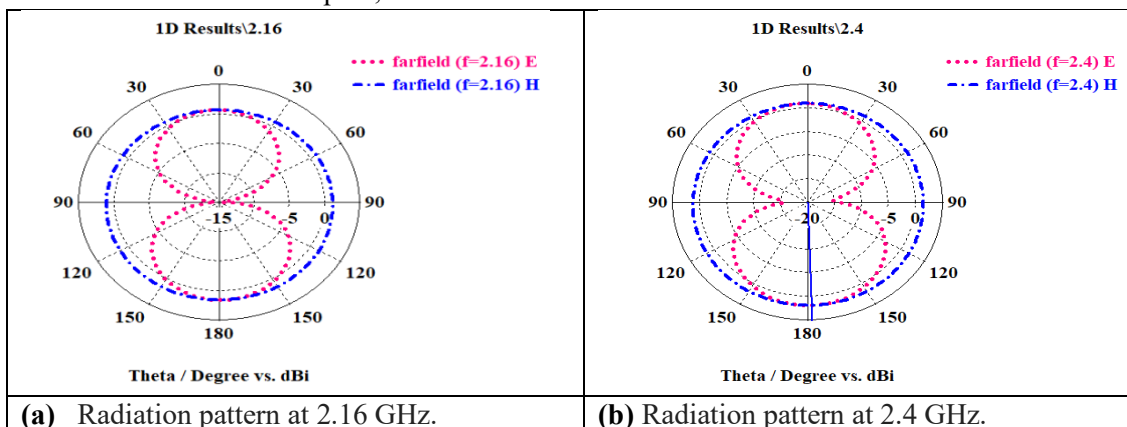
Another important parameter is surface current distribution analysis, as it provides a first-hand understanding of the radiation mechanisms, resonant

behavior, and the effective current paths that emit electromagnetic waves. By analyzing the surface current distribution, the active radiating regions, the impedance-matching mechanism, and the multiband operation of the proposed antenna can be identified. The distributions of the surface currents in the proposed antenna at 2.16 GHz, 2.4 GHz, 4.5 GHz, and 5 GHz are presented in Fig.11. The currents are mostly confined along the feeding and the lower radiating section at 2.16 GHz and are continuous and highly defined. This mode is associated with the basic resonant mode in which the effective path length of the current is about 0.5 times the wavelength (0.5). Physically, this suggests that a standing wave forms, with a maximum current at the feed and a minimum at the open ends, resulting in stable, efficient radiation.

The current at 2.4 GHz is broader along the radiator, especially on the edges and corners. This distribution enhances excitation of the entire radiating structure and electromagnetic coupling between the various sections. Physically, the lower frequency of this wavelength allows more antenna elements to contribute to the resonance, increasing radiation efficiency and bandwidth. At 4.5 GHz, the current distribution is more complex, with two or

more paths observed in the upper and side radiators. This denotes higher-order resonant mode excitation. The antenna is no longer structurally a single half-wavelength resonator; rather, it is now a multiple-resonant structure with currents flowing and phase variations throughout. This complexity also directly causes more lobes in the radiation pattern. The current at 5 GHz is also spread across most of the antenna surface, with high current density at edges, corners, and discontinuities. These areas of field concentration result from sudden impedance changes, leading to current crowding. Physically, these discontinuities in radiation are driven by increased localized electromagnetic fields. The presence of several strong current paths confirms that the antenna exhibits higher-order resonance and supports its multiband characteristics.

The surface current analysis generally shows an evident transition from a fundamental mode at lower frequencies to a complex higher-order mode at higher frequencies. The same transition can be attributed to both the constant radiation performance at lower frequencies and the more complex pattern at higher frequencies, validating the proposed antenna for multiband wireless applications.



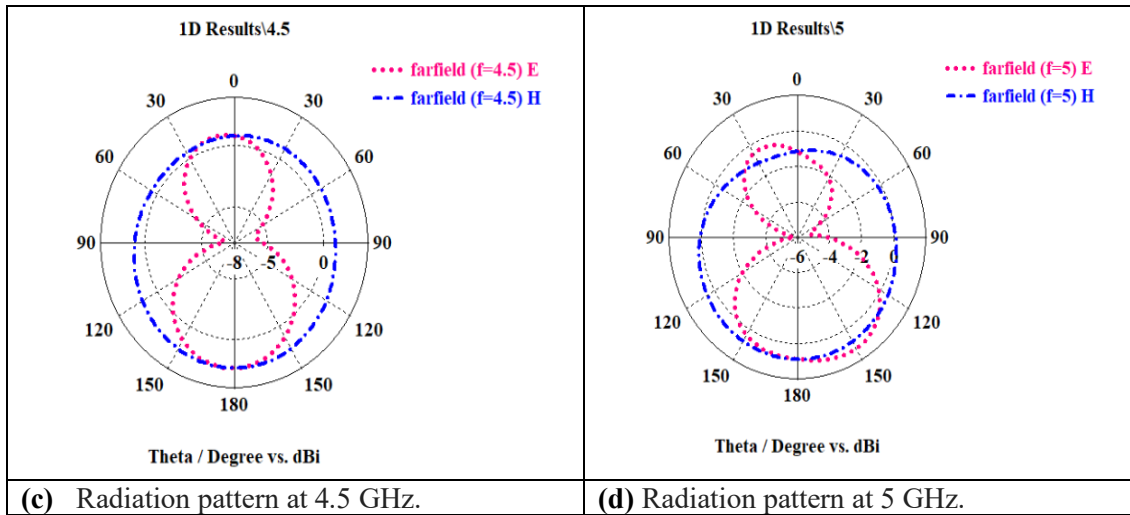


Fig. 10 Radiation patterns at (a) 2.16 GHz, (b) 2.4 GHz, (c) 4.5 GHz, and (d) 5 GHz.

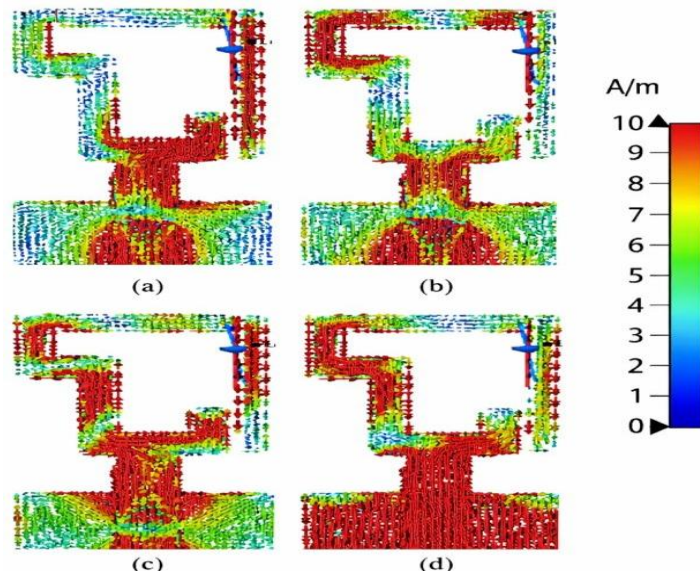


Fig. 11 Simulation of surface current distributions at (a) 2.16 GHz, (b) 2.4 GHz, (c) 4.5 GHz, and (d) 5 GHz.

Table 3. Comparative Evaluation of the Proposed Antennas against State-of-the-Art Designs.

References	Years	Dim. (mm ³)	Substrate	No. of switches	Operating band number	Operating Frequency (GHz)	Peak Gain (dBi)	Radiation Efficiency (%)
Ali et al. [12]	(2025)	20 × 15 × 1.4	FR-4	1-PIN diode	2	6.04, 2.4	4.82	-
Thenkumari et al. [22]	(2023)	35×35×1.6	FR-4	3-PIN Diode	5	5.8,4.7,3.5,2.4, 6.23	2.3-4.91	73-79
Kumar et al. [27]	(2019)	37.8×40.4×1.6	FR-4	4 PIN Diode	2	2.4, 5.6	1.92	-
Dildar et al. [28]	(2021)	40 × 32 × 1.6	FR-4	4-PIN Diode	9	1.8, 2.1, 2.6, 3.5, 4.8, 5.0,5.6, 6.4, 6.5	1.25–3.6	71-84
Benkhadda et al. [29]	(2024)	15 × 21 × 1.6	FR-4	2-PIN Diode	6	7.3,2.55,5.3, 3.36,7.3,5.4	2.07-3.38	-

Tiwari et al. [30]	(2025)	$22 \times 22 \times 0.762$	RT/duroid 5880	4-PIN Diode	13	7.25, 7.5, 8.1, 8.2, 8.7, 9.2, 10, 11.5 ,11.9,12.1, 12.2,13.4, 5.34	13.5	63-87
This work	(2026)	$22.5 \times 13 \times 1.6$	FR-4	1-PIN diode	4	2.16,2.4,4.5,5	2.5	86-95

The suggested antenna and recently published frequency-reconfigurable antennas are contrasted in Table 3. Several PIN diodes and/or larger antenna dimensions are typically needed, even though some reported designs offer more operating bands or higher peak gain. On the other hand, the suggested antenna has a small profile of $22.5 \times 13 \times 1.6 \text{ mm}^3$ on a cheap FR-4 substrate while achieving four operating bands (2.16, 2.4, 4.5, and 5 GHz) with just one PIN diode. Additionally, it has a high radiation efficiency of 86–95%, which is on par with, or better than, that of most reported designs. These features show that the suggested antenna offers a good trade-off between radiation performance, operating-band coverage, structural simplicity, and compact size, making it a suitable candidate for practical multiband wireless communication applications.

4. Conclusions

The results demonstrate that the frequency-reconfigurable antenna (FRA), with a compact design measuring $22.5 \times 13 \times 1.6 \text{ mm}^3$ and a conventional single PIN diode for switching, is a robust and effective solution for adaptive multiband performance with a small physical footprint. It employs a design approach grounded in controlled current redistribution and electromagnetic coupling to enable stable resonance across various operating states. The switching element greatly eases the reconfiguration procedure without compromising stable switching to the operating modes. This process eliminates the complex biasing networks and the multiplicity of switching components, thereby increasing design feasibility and minimizing implementation cost. The results obtained demonstrate that the antenna exhibits consistent impedance and radiation behaviour under various switching conditions. The design has good operational characteristics, meaning it is robust to structural variations and reliable over its operating

frequency range. In addition, radiation properties are acceptable in real-world wireless communication settings, providing consistent coverage and reliable operation. The overall electromagnetic performance indicates the proposed design's efficiency in balancing these factors. The adaptability and stability of performance are also considered. Besides its small size and low-cost design, the suggested antenna is a potential solution for integration into the current wireless communication platform, especially given the need for a flexible frequency response and efficient resource use. The practical DC biasing network was not included in the CST simulation model. This limitation will be addressed in future fabrication and experimental validation. In general, this work proposes a feasible, adaptable design method for frequency-reconfigurable antennas, demonstrating that high-performance multiband operation can be achieved with low hardware complexity and is highly applicable to next-generation IoT and sub-6 GHz wireless systems.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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