

A Miniaturized Reconfigurable Antenna for Modern Wireless Applications with Broadband and Multi-Band Capabilities

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ABSTRACT: A miniaturized frequency reconfigurable antenna, designed with a simple geometric layout on an FR-4 substrate measuring $15 \times 21 \text{ mm}^2$, offers versatility for various wireless applications is proposed in this paper. By adjusting biasing conditions of integrated PIN diodes, the antenna can operate in three distinct modes: wideband, dual band, and triband configurations. The antenna demonstrates satisfactory gain and presents an omnidirectional radiation pattern. Verification of the antenna's functionality involved building a prototype and subjecting it to testing. The confirmed compatibility of the antenna with modern wireless requirements, including the need for small antennas capable of operating across multiple bands and modes, is substantiated by the close agreement between simulated and measured results.

1. INTRODUCTION

The progress in wireless technology, coupled with constraints in the electromagnetic spectrum, has spurred the creation of devices capable of supporting multiple standards and applications simultaneously. Consequently, there is a growing need for antennas adaptable to different standards and practical applications. Reconfigurable antennas have garnered considerable interest lately owing to their dynamic qualities, including the ability to change parameters such as frequency, radiation pattern, and polarization, to meet various system requirements [1–7]. Particularly, a frequency-adaptable antenna proves beneficial across a spectrum of applications. Various methods such as electrical switches [8–10], PIN diodes [11–13], varactor diodes [14, 15], and RF-MEMS [16, 17] can be employed for frequency reconfigurability. The positive aspect of electric switching technology is its low voltage requirement, while RF-MEMS has longer switching times. Due to their tiny size and fast switching times (ranging from 1 to 100 ms), PIN diodes have found widespread application in reconfigurable technologies. In reconfigurable antennas, RF-MEMS switches excel with their extremely low power consumption, owing to negligible static power needs and minimal actuation energy, making them ideal for power-sensitive applications. In contrast, PIN diodes consume more power due to continuous cur-

rent requirements but offer faster switching speeds and cost advantages.

A variety of frequency-reconfigurable antenna structures are outlined in the literature. In [8], the authors propose a flexible antenna for multiband applications with a total area of $25 \times 35 \times 0.254 \text{ mm}^3$ and a frequency-reconfigurable method. In [9], a lightweight frequency-reconfigurable antenna capable of operating in four dual-band modes and eight distinct frequencies is developed. In [11], the authors propose the use of a single PIN diode to facilitate frequency reconfigurability, enabling a miniaturized flexible antenna to operate at three distinct frequencies or within the UWB spectrum as needed. In [18], an innovative approach to designing a frequency-reconfigurable antenna tailored for IoT applications is introduced, achieving a compact form factor measuring $40 \times 40 \text{ mm}^2$. In [19], a frequency-reconfigurable multi-band antenna operating across nine distinct bands is presented, utilizing four PIN diode switches for reconfigurability. In [20], the authors introduce a frequency-adaptable antenna designed for various common wireless communication systems. Their design incorporates three strategically positioned PIN diodes on the ground plane to facilitate multi-resonance frequency switching capabilities.

In [21], the authors introduce a fork-shaped antenna capable of adjusting frequency. The proposed antenna's size is $29 \times 23 \text{ mm}^2$, achieving frequency variation through the inte-

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gration of four PIN diodes. In [22], a reconfigurable antenna radiating in seven distinct bands and adjusted using PIN diode switches is developed. In [23], a reconfigurable dual-band antenna using four PIN diodes is presented. In [24], the authors propose a reconfigurable fractal antenna with RF MEMS switches, with dimensions of $40 \times 45 \text{ mm}^2$. In [25], a “9”-shaped reconfigurable antenna with three distinct operating frequencies is introduced. In [26], a Koch snowflake fractal reconfigurable antenna with four PIN diodes and dimensions of $40 \times 80 \text{ mm}^2$ is proposed. In [27], a versatile IFA antenna with adjustable frequency capabilities is introduced. By employing a dynamic circuit featuring a Digitally Tunable Capacitor (DTC), the antenna can seamlessly shift its resonant frequency across 32 different settings, spanning from 600 MHz to 960 MHz. In [28], to achieve multiband operation, the design employs antenna boosters paired with reconfigurable matching networks. These networks utilize a combination of passive components, such as capacitors and inductors, along with active devices, ensuring versatile performance across various frequency bands.

Nevertheless, the antennas proposed in the aforementioned papers exhibit deficiencies in either operating frequency, bandwidth, dimensions, or complexity, primarily due to the number of switches employed.

This study introduces a miniaturized frequency-reconfigurable antenna utilizing two PIN diodes, enabling multi-mode behavior. By manipulating the configurations of the two PIN diodes, the antenna transitions among UWB, dual-band, and tri-band operation modes.

2. ANTENNA DESIGN METHODOLOGY

This section outlines the design of a compact reconfigurable antenna, well suited for diverse applications including C-band, X-band WLAN, WiMAX, and LTE. The suggested antenna utilizes two PIN diodes to transition between different frequency band modes, including ultra-wideband, dual-bands, and tri-bands. Fabricated within an inexpensive FR-4 substrate, the antenna features a small footprint of $15 \times 21 \times 1.6 \text{ mm}^3$, making it suitable for integration into small electronic devices. Simulation results indicate that the suggested antenna achieves good performance in terms of S_{11} , radiation patterns, and gain across different frequency bands. The combination of frequency adaptability and small footprint positions the proposed antenna as a promising option for a variety of uses in wireless communication.

2.1. Antenna Configuration Process

For a clearer understanding of the evolution of the aforementioned antenna, Figure 1 outlines the various stages that led from the basic rectangular antenna to the studied reconfigurable antenna structure. Figure 2 illustrates the results of the S_{11} simulation for the different stages of the designed antenna evolution.

Antenna 1 (Figure 1(a)) represents the foundational structure of the designed antenna. It consists of a rectangular radiating patch with dimensions $L_p = 13.5 \text{ mm}$ and $W_p =$

14.5 mm , printed on an FR4-type dielectric substrate ($\epsilon_r = 4.4$ & $\tan(\delta) = 0.022$). The antenna is fed using a coplanar waveguide (CPW) feed. Figure 2 illustrates that Antenna 1 demonstrates a bandwidth spanning from 5.33 GHz to 6.3 GHz, with a resonant frequency of 5.8 GHz.

Next, the structure of Antenna 2 was modified by incorporating a symmetrical ground plane in the form of a quarter ellipse, as indicated in Figure 1(b). The antenna exhibits a resonant frequency of 5.6 GHz and a bandwidth spanning from 4.7 GHz to 7.45 GHz.

In step 3 (Figure 1(c)), a rectangular slot was positioned at the center of the radiating patch to extend the surface currents on Antenna 3, thereby creating the ability to increase the electrical length and reduce the size of the antenna. Figure 2 shows that Antenna 3 has a bandwidth of 4.1 GHz to 5.36 GHz with a resonant frequency of 4.6 GHz.

After this, Antenna 4 was designed by inserting three rectangular slots onto the radiating element (Figure 1(d)), aiming to shift the frequency band towards lower frequencies. As depicted in Figure 2, Antenna 4 exhibits a resonant frequency of approximately 3.9 GHz, covering a bandwidth from 3.6 GHz to 4.36 GHz.

Then, as shown in Figure 1(e), two “C” slots were added to generate an additional frequency band (Antenna 5). According to Figure 2, Antenna 5 provides two operating bands and exhibits resonances at both 3.6 GHz and 5.9 GHz.

Antenna 6 was formed by cutting two triangular shapes on the lower corners of the radiating patch (Figure 1(f)) to improve the bandwidth of the second band. It can be seen from Figure 2 that Antenna 6 has two bands of 3.2 GHz to 3.6 GHz and 4.8 GHz to 6.4 GHz with resonant frequencies at 3.4 GHz and 5.4 GHz.

Figure 3 depicts the geometry of the designed frequency-reconfigurable antenna. Two slots, each 1 mm long, have been etched into the radiating element of Antenna 6, incorporating two PIN diodes, D1 and D2, positioned between the poles of each slot to ensure frequency-reconfigurable functionality.

Based on the activated and deactivated states of the diodes, different frequency band modes are produced, including ultra-wideband, dual-band, and triple-band. Table 1 lists the suggested ideal dimensions for the structure.

TABLE 1. Dimensions of the designed frequency reconfigurable.

Parameters	Dimensions (mm)	Parameters	Dimensions (mm)
W	15	g	0.6
L	21	X	1
W_p	14	X_1	6.5
W_c	6	X_2	4
L_c	4.5	X_3	2
W_f	2	Y	1
L_f	6.5	Y_1	8
W_g	5.9	Y_2	2
L_g	5.2	Y_3	1

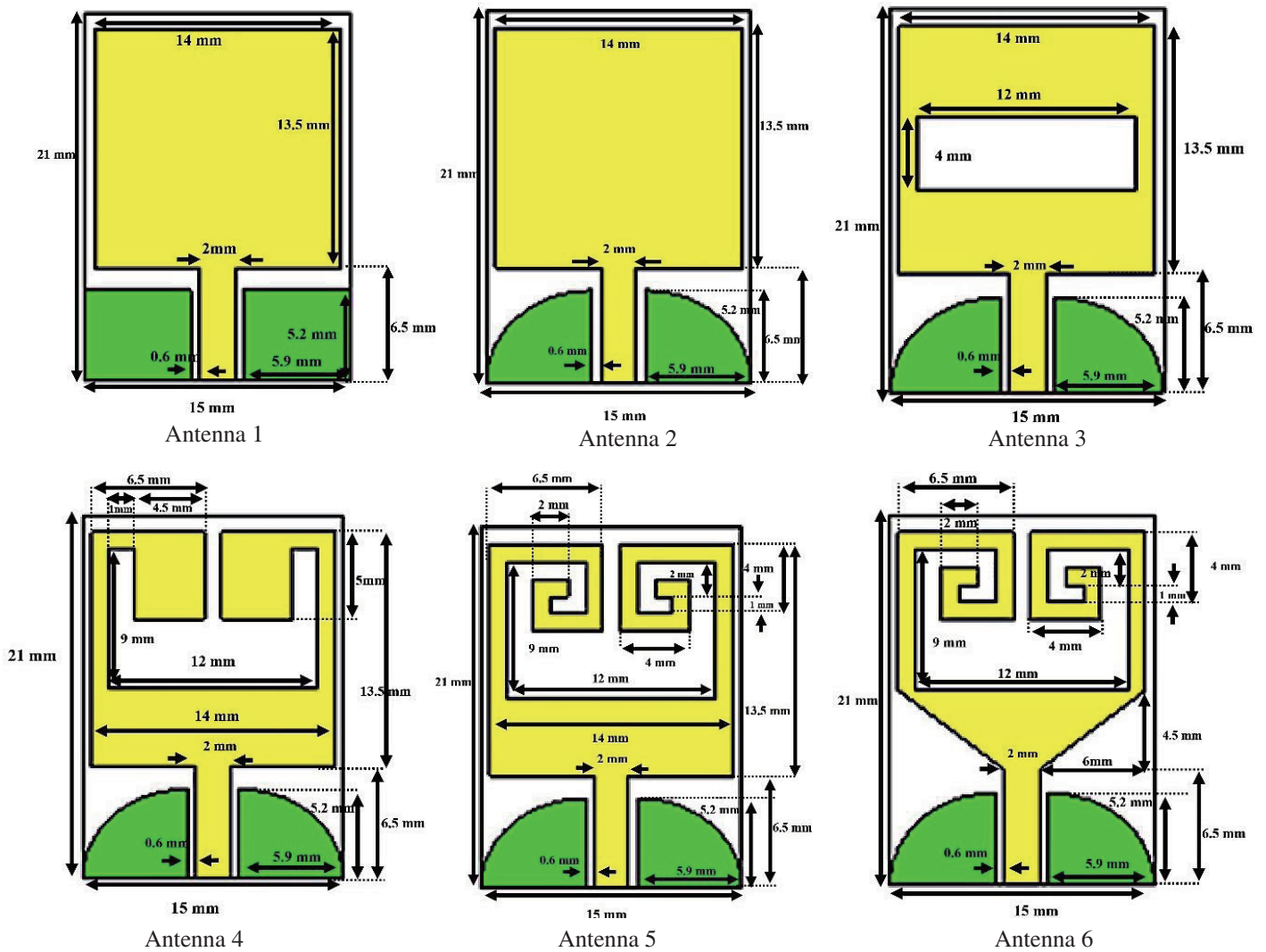


FIGURE 1. Proposed antenna evolution process.

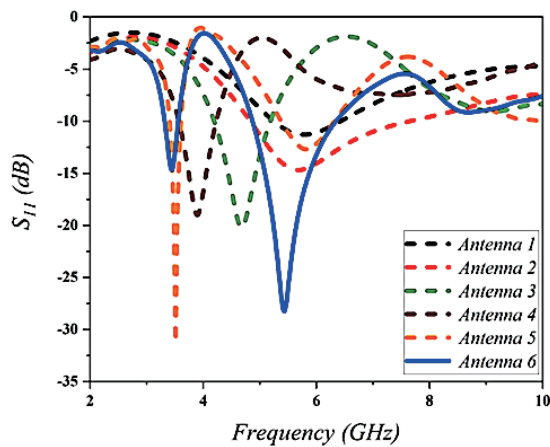


FIGURE 2. Reflection coefficient of six antennas.

The primary objective of our work is to design and develop an antenna capable of covering multiple frequency bands, specifically targeting LTE, WiMAX, WLAN, and the C and X bands.

2.2. Switching Techniques

The illustration in Figure 4 depicts a simplified RLC model equivalent to the PIN diode. For simulation purposes, the PIN diode is replaced by this simplified model, obtained from the manufacturer’s data sheet. The inductance L has a value of 0.15 nH in both the OFF and ON states. When the PIN diode is activated, the equivalent model can be depicted as a series combination of the 4.7Ω resistor and the L inductance. Alternatively, when the PIN diode is in the deactivated state, the equivalent model consists of two parallel elements: a 0.017 pF capacitor and a $7 \text{ k}\Omega$ resistor, which are in series with the L inductance. Table 2 summarizes the values of these passive components of the PIN diode.

TABLE 2. Values of pin diode equivalent circuit components.

State of the diode	Components			
	L (nH)	R_s (Ω)	R_p (k Ω)	C_p (pF)
ON	0.15	4.7	-	-
OFF	0.15	-	7	0.017

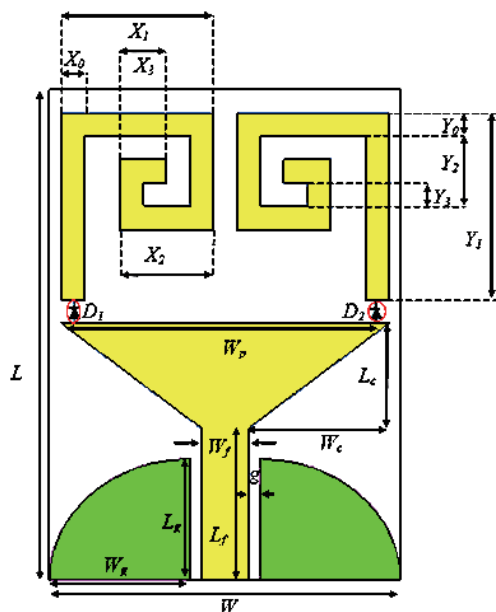


FIGURE 3. Frequency-reconfigurable antenna structure.

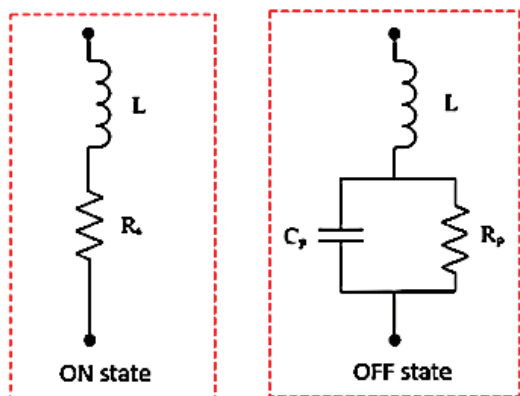


FIGURE 4. PIN diode equivalent circuit.

The CST MWS simulation software is utilized to model the PIN diode using lumped elements, as depicted in Figure 5.

To enable frequency reconfigurability in Antenna 6, two PIN diodes are employed, as shown in Figure 3. These diodes can be in either ON or OFF state, facilitating three modes of operation, as summarized in Table 3. It is worth noting that the ON/OFF and OFF/ON modes of diodes D1 and D2 yield the same results. During simulation, the PIN diode is substituted

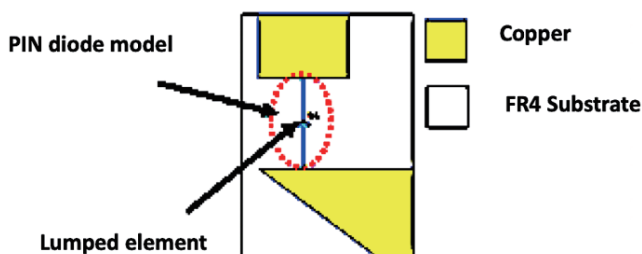


FIGURE 5. Modeling PIN diode behavior in CST MWS.

TABLE 3. Values of PIN diode equivalent circuit components.

Mode	State of the PIN diode	
	D1	D2
Mode 1	OFF	OFF
Mode 2	ON	OFF
Mode 3	ON	ON

by its equivalent circuit, derived from the manufacturer’s data sheet (Figure 5). In order to create a frequency-reconfigurable antenna that satisfies the needs of WLAN, WiMAX, C-band, and X-band applications, the diode placements have been optimized.

3. RESULTS AND DISCUSSIONS

A prototype of the antenna is constructed and tested to confirm the feasibility of the proposed design. The depicted design in Figure 6 showcases both the top and bottom perspectives of the fabricated frequency-reconfigurable antenna. The measurement setup is illustrated in Figures 6(a) and (b), where the lower part of the radiating patch is connected to the positive terminal of the PIN diode positioned upward and to the VDC battery below through the decoupling RF choke. The signal path is established by connecting one side of the respective upper part of the radiating patch to the negative terminal of the PIN diode at the top and the other side to ground below, as depicted in Figure 6(c). To control the states of the PIN diodes, DC bias circuits were used. By toggling the ON-OFF states of the PIN diodes, the designed antenna achieves frequency reconfigurability. To avoid altering the current circulating in the bias circuit on the patch element, an inductance of 47 nH is required. The states of the PIN diodes are switched by monitoring the DC voltages. At a VDC input of 2 V, the PIN diode switches to an active state, while at 0 V, it is deactivated.

The S_{11} characteristics are assessed using an E5071C VNA, while the radiation patterns are analyzed utilizing an anechoic chamber. The outcomes are depicted in the following subsections.

3.1. Reflection Coefficient (S_{11})

By toggling the state of the diodes D1 and D2, it becomes feasible to either connect or disconnect the two upper sections of the radiating patch, consequently leading to a shift in operating frequencies. Figures 7, 8, and 9 depict the outcomes of the S_{11} reflection coefficients for the various operating modes. The comparison of resonant frequency and bandwidth outcomes achieved for each operating mode is presented in Table 4, while the results obtained by the CST MWS solver and measurement for each operating mode are delineated below:

MODE 1: During this mode, both D1 and D2 are turned off, so the two upper parts of the radiating patch act as parasitic elements. Looking at Figure 7, we can see that when the antenna is configured in mode 1, it has a resonant frequency of 7.29 GHz. Moreover, its bandwidth extends over a broad frequency span, covering from 5.39 GHz to 9.4 GHz. The antenna offered in this mode operates in the WLAN.

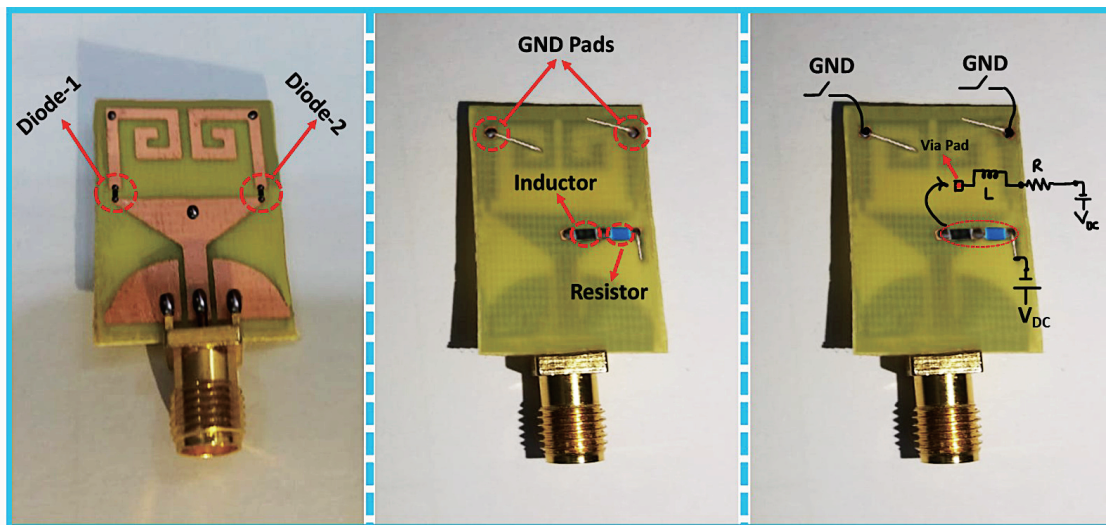


FIGURE 6. Constructed antenna prototype: (a) Top view, (b) Bottom view, and (c) Bottom view with illustration of electric circuit for switching.

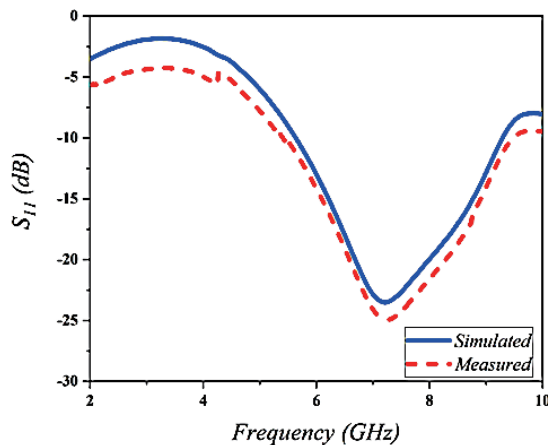


FIGURE 7. Reflection coefficient of the constructed frequency reconfigurable antenna in mode 1.

MODE 2: During mode 2, the upper right-hand part of the radiating patch is parasitic because PIN diode D2 is OFF. Looking at the results of the S_{11} in Figure 8, the reconfigurable antenna in this mode will produce three resonant frequencies of 2.47 GHz, 5.29 GHz, and 7.2 GHz, as well as three frequency bands extending from 2.37 GHz to 2.64 GHz, 4.87 GHz to 5.68 GHz, and 6.04 GHz to 9.2 GHz. This makes the designed antenna a good candidate for applications in LTE, WiMAX, WLAN, and C-band and X-band wireless communication systems.

MODE 3: Figure 9 illustrates the variation of the simulated and measured reflection coefficients (S_{11}) of the reconfigurable antenna for mode 3. Referring to Figure 9, we can see that the antenna in this mode has two bands: the first is between 3.04 GHz and 3.5 GHz, while the second is between 4.63 GHz and 6.04 GHz. The resonant frequencies are 3.2 GHz and 5.42 GHz. In this mode, the constructed reconfigurable antenna is operational for WLAN, WiMAX, and C-band standards.

The design of the constructed reconfigurable antenna enables switching between different operating bands to meet the demands of WLAN, WiMAX, C-band, and X-band standards, based on the state of the diodes. The three operating modes of the constructed antenna are assessed for bandwidth and resonant frequency in Table 4, which summarizes the simulation and measurement results.

3.2. Current Distribution

To elucidate the frequency reconfigurability mechanism and understand the origin of each operating mode, an examination of the antenna's current vectors was conducted. Figure 10 displays the surface current distribution in various operating modes. It is noteworthy that the state of PIN diodes D1 and D2, whether in ON or OFF mode, alters the flow of current on the antenna's radiating element.

In mode 1 (Figure 10(a)), the current is mainly concentrated around the lower part of the radiating patch. Moreover, the very limited current flowing from the upper parts of the radiating patch also indicates that these parts do not contribute significantly to the antenna's broadband response at 7.29 GHz.

In mode 2, on the other hand, only the upper left part of the radiating patch is excited by the switching of diode D1. This left-hand part redistributes the current flowing over the surface of the patch, resulting in three-band operation. In this case, when the upper left part of the single radiating patch is connected to the patch, current flows partially to this part, as shown in Figure 10(b), causing resonance in the lower 2.47 GHz band.

3.3. Radiation Pattern and Gain

Figures 11 and 12 depict the measurement setup and the results obtained from the simulation and measurement of the radiation pattern in the E and H planes. The suggested antenna configuration exhibits an omnidirectional radiation pattern in both the H -plane and E -plane. This symmetry in the radiation patterns

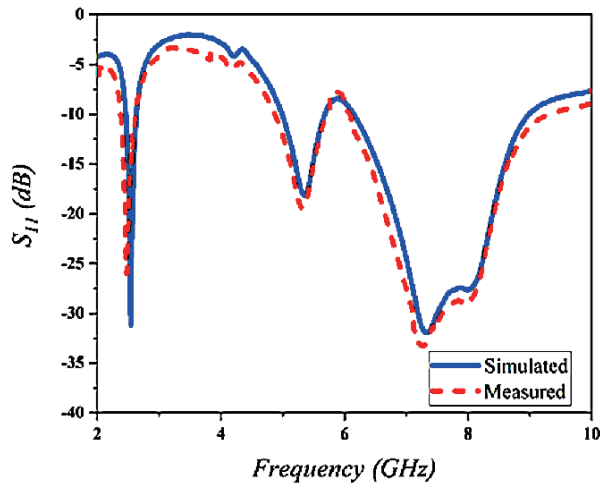


FIGURE 8. Reflection coefficient of the constructed frequency reconfigurable antenna in mode 2.

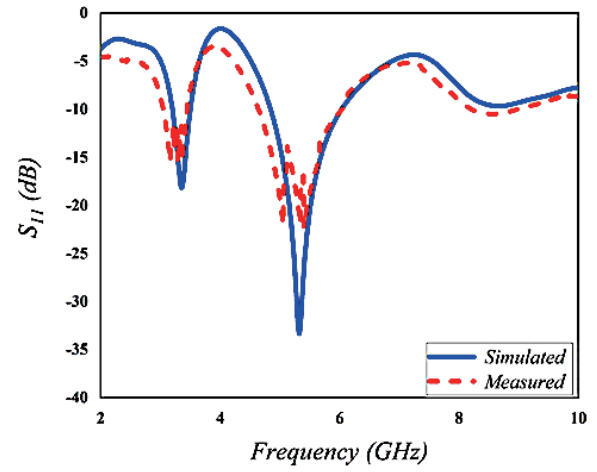


FIGURE 9. Reflection coefficient of the constructed frequency reconfigurable antenna in mode 3.

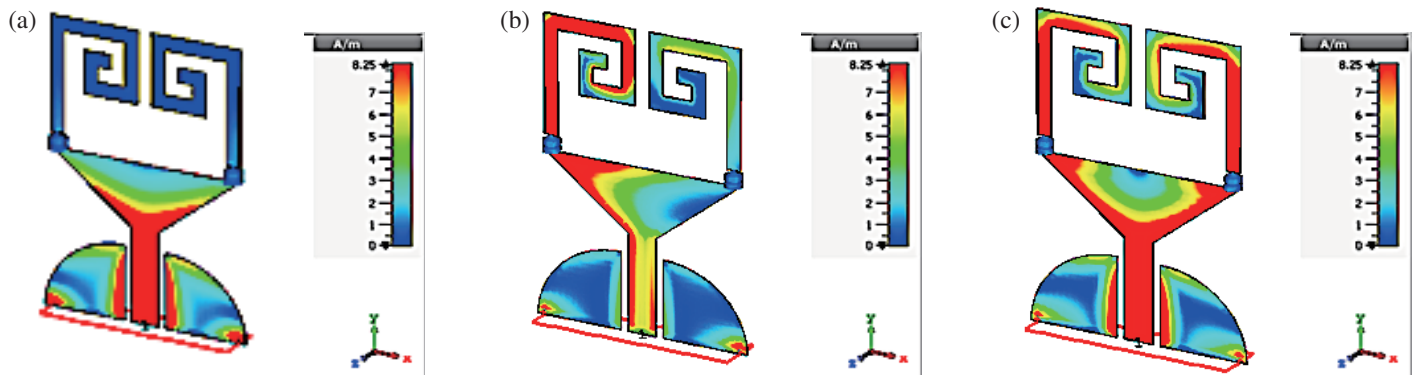


FIGURE 10. Surface current distribution at the three different operating modes. (a) Mode 1 at 7.29 GHz. (b) Mode 2 at 2.47 GHz. (c) Mode 3 at 3.2 GHz.

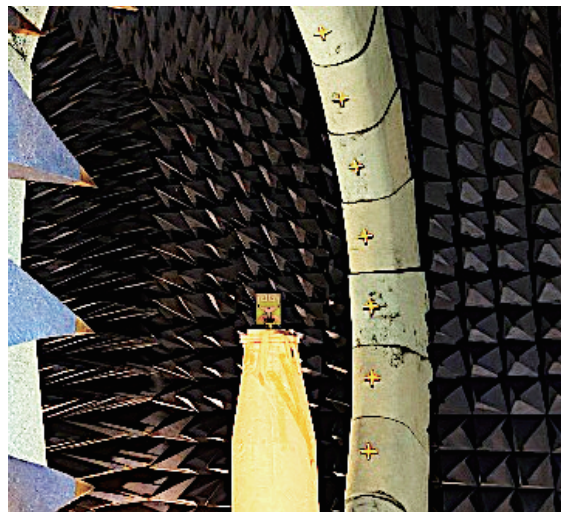


FIGURE 11. Measurement setup of radiation pattern.

TABLE 4. Operating modes of the proposed reconfigurable antenna.

	Simulated (CST)		Measured	
	f_r (GHz)	Operational band (GHz)	f_r (GHz)	Operational band (GHz)
Mode 1	7.3	5.67–9.3	7.29	5.39–9.4
	2.55	2.46–2.64	2.47	2.37–2.64
Mode 2	5.3	4.98–5.7	5.29	4.87–5.68
	7.3	6.2–8.97	7.2	6.04–9.2
Mode 3	3.36	3.2–3.5	3.2	3.04–3.5
	5.4	4.84–6.02	5.42	4.632–6.04

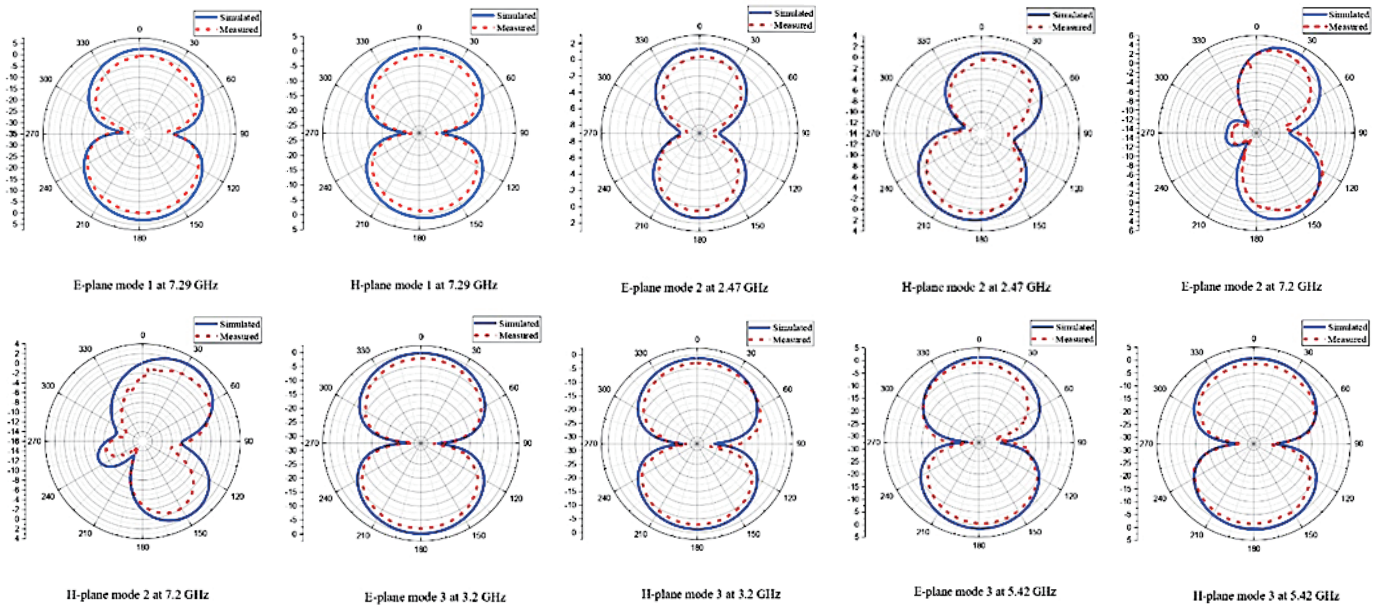


FIGURE 12. Simulated and measured radiation pattern.

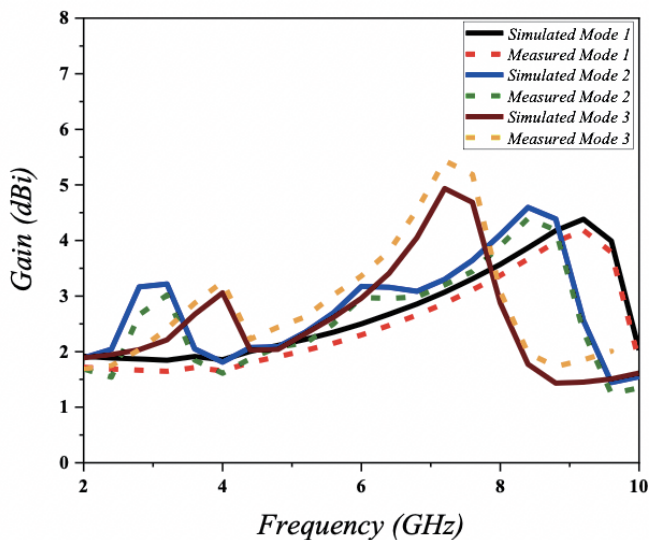


FIGURE 13. Simulated and measured gain at the three operating modes.

is attributable to the symmetric structure of the antenna’s radiating element.

Figure 13 displays both simulated and measured gains of the reconfigurable antenna for the three switching states. Note from the figure that in mode 1, the gain at 7.29 GHz is 3.21 dBi, while in mode 2, the gains at resonant frequencies 2.47 GHz, 5.29 GHz, and 7.2 GHz are 2.07 dBi, 2.41 dBi, and 3.38 dBi, respectively. In mode 3, gains are 2.3 dBi and 2.4 dBi at resonant frequencies 3.2 GHz and 5.42 GHz.

3.4. Comparative Study with Other References

The performance of the constructed frequency-reconfigurable antenna is evaluated against that of alternative reconfigurable antennas already described in the literature, as presented in Table 5. It should be emphasized that the suggested frequency-reconfigurable antenna is capable of operating in six distinct operating bands thanks to a minimal number of PIN diodes. The constructed antenna has the advantage of reducing circuit bias complexity, and manufacturing costs. Additionally, its compact size makes it particularly suitable for miniature wireless systems.

TABLE 5. Comparative performance evaluation of the proposed antenna against some previously published reconfigurable antennas.

Ref	Size (mm ³)	Switch number	Operating band number	Bandwidth (GHz)	Gain (dBi)
[23]	40 × 37.2 × 1.6	4	2	(2.2–2.7) & (4.7–5.33)	0.65 & 1.92
[24]	45 × 40 × 1.6	10	4	(1.75–1.99) & (2.50–4.50) & (6.05–6.79) & (2.28–6.67)	0.68 & 1.50 & 1.38 & 1.96
[25]	30 × 26 × 1.6	4	3	(2.1–2.6) & (2.9–4.5) & (4.98–5.6)	1.48 & 2.47 & 3.26
[26]	40 × 80 × 1.6	4	3	(3.34–4.52) & (2.2–3.4) & (1.45–4.1)	2.23 & 2.91 & 2.42
[29]	23 × 42.9 × 51.3	2	3	(2.6–3.19) & (3.07–3.42) & (3.55–3.795)	2.46 & 3.2 & 2.78
[30]	19 × 40 × 1.6	2	3	(1.56–2.5) & (2.8–3.39) & (2.26–3.9)	-
[31]	83 × 89 × 1.6	1	2	(2.35–2.52) & (3.28–3.38)	-
This work	15 × 21 × 1.6	2	6	(5.39–9.4) & (2.37–2.64) & (4.87–5.68) & (6.04–9.2) & (3.04–3.5) & (4.632–6.04)	3.21 & 2.07 & 2.41 & 3.38 & 2.3 & 2.4

4. CONCLUSIONS

This article describes the design, simulation, and measurement of a miniature multi-band frequency-reconfigurable antenna. The antenna integrates a CPW-fed rectangular monopole antenna with slots and utilizes just two PIN diodes to provide a band-reconfigurable feature. Based on the PIN diodes' ON-OFF state, three modes are obtained: wideband, dual-bands, and tri-bands. The antenna demonstrates significant alignment between simulated and measured outcomes, coupled with satisfactory gain and an omnidirectional radiation pattern. Furthermore, a comparative analysis with related works indicates that the proposed antenna surpasses existing antennas in the literature, establishing its viability as a robust option for heterogeneous applications demanding a miniature, versatile antenna capable of operating across various frequency ranges and modes.

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