

Design and Fabrication of a Miniaturized Reconfigurable Antenna Based on a PIN Diode for IoT Applications

Huda Ismail Khalil¹, and Riyadh Khlf Ahmed²

¹Department of Communications, College of Engineering, University of Diyala, Diyala, Iraq;
Email: eng_grad_communication2509@uodiyala.edu.iq

²Department of Communications, College of Engineering, University of Diyala, Diyala, Iraq;
Email: riyadh_alazawi_eng@uodiyala.edu.iq

*Correspondence: eng_grad_communication2509@uodiyala.edu.iq; Tel.: +9647705283919

ABSTRACT- This paper describes a frequency-reconfigurable antenna that uses PIN diodes and a biasing circuit integrated into the same substrate. Designing compact frequency-reconfigurable antennas with stable multiband performance remains an important challenge for modern wireless and IoT applications. The proposed antenna is small and flexible, enabling operation over multiple frequency bands and modes. The antenna is $26 \times 14 \times 1.524$ mm³ in size and printed on a Rogers 4350 substrate ($\epsilon_r = 3.66$, $\tan \delta = 0.0037$). Two PIN diodes are used to change the operating frequency. The antenna operates in four switching states and covers seven different frequency bands. The first mode is single-band (3.88 GHz), the second is dual-band (3.4 GHz, 4.9 GHz), the third is tri-band (3.5 GHz, 5.3 GHz, 6.8 GHz), and the fourth is dual-band (3.4 GHz, 6.7 GHz). The antenna has a simulated radiation efficiency of about 94% and a peak gain of 2.7 dBi. The simulated results are in good agreement with the experimental measurements, showing close agreement. The main contribution of this work is achieving seven operating bands using only two PIN diodes while maintaining a compact antenna size. The suggested antenna works well for small wireless and IoT applications.

Keywords: Reconfigurable Antennas, Microstrip Antennas, PIN Diodes, Multiband Antennas, Internet of Things (IoT).

ARTICLE INFORMATION

Author(s): Huda Ismail Khali, and Riyadh Khlf Ahmed;
Received: 24/05/26; **Accepted:** 27/08/26; **Published:** 30/09/26;
E- ISSN: 2347-470X;
Paper Id: IJEER260119;
Citation: 10.37391/ijeer.140309
Webpage-link:
<https://ijeer.forexjournal.co.in/archive/volume-14/ijeer-140309.html>



Publisher's Note: FOREX Publication stays neutral with regard to jurisdictional claims in Published maps and institutional affiliations.

1. INTRODUCTION

The rapid growth of wireless communication technologies, such as Wi-Fi, WLAN, and sub-6 GHz IoT networks, are already growing exponentially, and this has created a demand in the marketplace for smaller-sized, versatile antenna systems that can work across a variety of different frequency bands. The single-band antennas that were used previously cannot be used in such a dynamic environment because of the requirement of spectrum reuse of spectrum, convergence of devices, and the requirement of quick response to applications [1], [2]. The Reconfigurable Antennas (RAs) have the capability of modifying the radiation properties of frequency, polarization, or radiation pattern in real-time. RAS, then, is a solid solution to such dynamic needs and has numerous strengths compared to other reconfigurability techniques. Namely, FRAs (far-field) offer effective spectral flexibility without being bulky and difficult to use. The latter features render FRAs especially appropriate to the requirements of modern multi-standard wireless systems [3]. Recently, PIN diodes as tuning elements have been attracting the interest of antenna designers because

they are small, economical, and can switch rapidly, not to mention that they are relatively simple to bias in DC [4]. Relative to RF-MEMS switches, where many elaborate fabrication techniques are typically used and actuation speeds are sometimes slow, or to varactor diodes, where nonlinearity is a problem and tuning ranges are limited, PIN diodes offer a good trade-off between structural simplicity and functionality. A single PIN diode can be used in patch or slot-based radiating structures to achieve discrete frequency reconfigurability through changing the effective electrical length of the radiating element when used tactically as a radiating element [5]. The recent advances have shown that the microstrip antennas with the PIN diodes can be used to implement dual- or multi-bands with the minimum design complexity and acceptable impedance matching. These configurations can also offer gain stability and omnidirectional radiation patterns, which are critical needs of IoT and Sub-6 GHz wireless communication systems [6], [7]. In addition, the use of economical substrates like FR-4 or low-loss dielectric materials like Rogers RT/duroid 5880 to reduce the amount of backward radiation can also play a significant role in the determination of the most important parameters of the antenna design, like the radiation efficiency, the bandwidth of the antenna, and its size in small reconfigurable antenna systems. The most recent studies are guiding the development of small, flexible frequency-design antennas that can be dynamically tuned based on a PIN-diode switching strategy over the wide frequency range of the 5G networks, WLAN systems, and IoT operate under sub-6 GHz device types. A table of organization of the same is provided in the next section. One of the chosen designs is displayed, as is the case with some of them. Characterization of their prominent

characteristics according to their operating frequency, substrate material, gain, and reconfiguration technique capabilities. Nguyen et al. [8] suggested a small-sized frequency reconfigurable antenna, which has the ability of wideband sensing and narrowband communication of sub-6 GHz 5G cognitive radio. Two PIN diodes and three varactors were used as the antenna, giving a range of 3.45-5.32 GHz that is tunable and with gains of 6.02dB (WB) and 5.37dB (NB). Its efficient switching was compensated for by the power control and complexity of many active devices in the system. Then Kumari et al. [9] made a small presentation monopole antenna (FR4) monopole (35x35x1.6mm³): 4reconfigurable modes with the help of RF PIN diodes. It worked at frequencies up to 6GHz, such as Wi-Fi (2.4GHz), Sub-6GHz 5G (3.5 GHz), Vo5G (4.7 GHz), V2X (5.8GHz), and C-band (6.25 GHz) of low VSWR (<1.5), and a significant number of locations attained the profit of up to 79%. Although it is functional in nature and is also too big in size, which is a problem with respect to miniaturized platforms. In [10], a frequency-reconfigurable antenna was developed using an FR4 substrate with overall dimensions of 15 × 21 × 1.6 mm³ and integrated with two PIN diodes to achieve six distinct operating frequency bands. The antenna was capable of supporting wideband, dual-band, and tri-band modes at multiple operating frequencies, including (2.47,3.2,5.29,5.42,7.2,7.29) while maintaining an acceptable omnidirectional radiation pattern suitable for multi-mode applications. In [11], a compact antenna with dimensions of 22 × 22 × 0.762 mm³ was implemented on a Rogers 5880 substrate and incorporated four PIN diodes to generate multiple operating frequency bands spanning from 7.5 GHz to 13.6 GHz. The antenna demonstrated a peak measured gain of 5.34 dBi with a return loss of -34.73dB. Although the high total and radiation efficiencies highlight its performance capabilities, its primary operation within higher frequency bands limits its suitability for low-power IoT or Sub-6 GHz 5G applications. In [12], the antenna was fabricated on an FR4 substrate with dimensions of 50 × 45 × 1.6 mm³ and featured a sixth-order nested fractal radiator fed through coplanar waveguides, enabling an extended operating bandwidth from 3.67 GHz to 6.70 GHz with a maximum gain of up to 5.50 dBi. Despite offering wide frequency coverage and satisfactory gain performance across the desired spectrum, the relatively large physical size of the antenna may limit its applicability in modern compact wireless communication devices. In this context, the proposed antenna was designed to address the need for a compact and frequency-reconfigurable antenna capable of supporting multiple wireless communication bands with a simple switching mechanism. The use of PIN diodes enables the operating frequency to be controlled by modifying the effective current path of the radiating structure, allowing different frequency bands to be obtained from the same compact antenna. The proposed design therefore provides several practical advantages, including compact dimensions, four switching states, multiband operation, and a simplified biasing circuit using only two PIN diodes. The resulting operating bands are relevant to wireless applications such as IoT, WLAN, WiMAX, C-band, and short-range radar systems. Thus, the proposed antenna is intended to provide a practical balance between frequency reconfigurability, structural compactness, and switching simplicity for compact wireless

communication devices. Consequently, it provides a scalable energy-efficient solution to future generations of programmable wireless networks. Moreover, recent works have highlighted the significance of the compact and miniaturized reconfigurable antenna to cater to a variety of frequency bands and retain effective radiation properties for contemporary wireless devices [13], [14]. Chi et al. [15] proposed a compact frequency-reconfigurable microstrip antenna for 5G, WiMAX, and WLAN applications. The antenna was fabricated on an FR-4 substrate with overall dimensions of 30×37× 1.6 mm³. The proposed design employed two PIN diodes to achieve frequency reconfigurability, providing four operating modes, including single-band, dual-band, and two triple-band configurations. The antenna was designed using a trident-shaped radiating element with meandered branches to reduce the overall size while maintaining stable operation. The fabricated prototype validated the simulated results, achieving a measured peak gain of 3.9 dBi with satisfactory radiation characteristics. However, the relatively large antenna dimensions and the limited gain may reduce its suitability for highly miniaturized wireless and IoT devices.

Galaba et al. [16] presented a conformal frequency-reconfigurable antenna for Wi-Fi 7 applications operating in the 2.4, 5, and 6 GHz bands. The antenna was fabricated on a Rogers RT/duroid 5880 LZ substrate and employed two PIN diodes to achieve frequency reconfigurability. The proposed antenna provided operating bandwidths of 2.6 GHz (4.5–7.1 GHz) and 480 MHz (2.23–2.71 GHz) while maintaining stable radiation characteristics with good gain and radiation efficiency. The measured results confirmed the effectiveness of the proposed design for conformal wireless communication applications. Despite these recent advances, there is still a need for antenna designs that simultaneously achieve compact size, simple switching circuitry, and stable multiband performance for modern IoT applications. In particular, achieving a compact antenna size while maintaining stable multiband performance, simplified switching circuitry, and reliable radiation characteristics across multiple operating bands continues to be a significant design challenge. These limitations motivate the development of the proposed antenna presented in this work.

The novelty of this work lies in the development of a compact frequency-reconfigurable antenna that achieves seven distinct operating frequency bands using only two PIN diodes and a simplified biasing circuit. The two PIN diodes provide four switching states, enabling the antenna to operate in single-, dual-, and tri-band configurations without requiring a large number of switching elements. The proposed antenna has compact dimensions of 26 × 14 × 1.524 mm³ and integrates the switching mechanism and biasing network within the antenna structure. Compared with the previously reported designs discussed above, the proposed approach focuses on achieving a practical balance among compact size, the number of reconfigurable operating bands, and switching complexity. In addition, the proposed design is experimentally validated through S11 measurements for all four switching states, while the gain and radiation efficiency are evaluated through simulation. These features constitute the main contribution of

this work and demonstrate the potential of the proposed antenna for compact IoT and wireless communication applications. The remainder of this paper is organized as follows. *Section 2* presents the materials and methods used in the proposed antenna design. *Section 3* discusses the simulation and measurement results. *Section 4* presents a comparative analysis of the proposed antenna against recently reported antennas. Finally, *sections 5* and *6* present the conclusions and future research directions, respectively.

2. Materials and Methods

2.1. Proposed Antenna Design

The section gives the basic design theory and structural design of the proposed multiband frequency-reconfigurable antenna. The PIN diodes are modelled by an RLC equivalent circuit that allows the diodes to be reconfigured in the simulation environment. The antenna can be used to work in various frequency bands by regulating the ON/OFF state of the PIN diodes. More so, the partial ground plane is used, which adds to better radiation efficiency and provides acceptable far-field performance.

2.2. Structural Geometry

Figure 1 shows the top, bottom, and side views of the systematic geometry of the proposed frequency reconfigurable antenna. Rogers RO4350B dielectric $\tan \delta = 0.0037$, with a dielectric of $\epsilon_r = 3.66$ and a height of $h_s = 1.524$ mm, is employed as the antenna substrate in this design. The antenna is manufactured using a conventional copper cladding of 0.035 mm. In addition, we introduced a partial ground cut (DGS) to enhance impedance matching and reduce surface wave losses. This provided additional inductive and capacitive loading, adjusting the guided wavelength and enhancing electromagnetic coupling. Furthermore, the addition of three slots in the ground plane not only improved impedance matching but also contributed to increasing the gain. The PIN diode switches will be inserted with a gap of one millimeter. The antenna is also supplied with a microstrip line with a width of 2.94 mm and an impedance of 50 ohms. The simulations are performed with switching that is achieved with the help of an SMP1340-079LF PIN diode. The optimized geometrical dimensions of the proposed antenna are summarized in table 1.

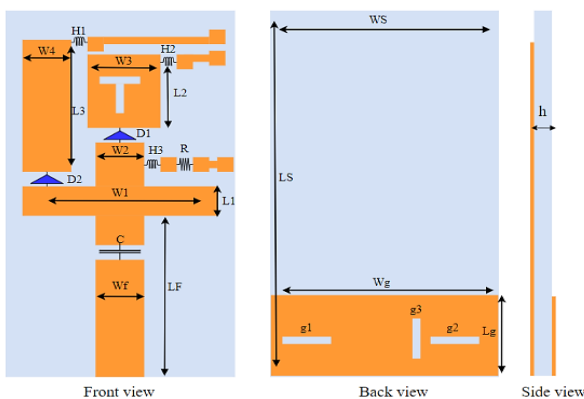


Figure 1. Suggested antenna geometry

Table 1. Optimized Antenna Parameters

Parameters	Value (mm)	Parameters	Value (mm)
WS	14	LS	26
Wf	2.94	Lf	12
Wg	14	Lg	5
L1	2	W2	2.8
L2	3.5	W3	4.5
L3	9	W4	2.5
W1	13	hs	1.524

The effective resonant lengths for the target frequencies are obtained using the transmission line model theory. [17] For the intended operating frequency f , the effective resonant length L_f and the effective permittivity ϵ_{eff} are determined through eqs. (1) and (2),

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

$$L_f = \frac{c}{4f\sqrt{\epsilon_{eff}}} \quad (2)$$

where c is the speed of light in ϵ_r is the relative permittivity, h denotes the substrate thickness, and w is the substrate width.

2.3. Switching Techniques

Two-PIN diodes (SMP1340-079LF) are frequently employed in switching because they have almost RF characteristics of a variable resistor. They can have the ability to operate regularly over the range of frequencies, 1 GHz-10 GHz. When the PIN diodes are connected, the resonant length of the antenna is altered, and the frequency of the antenna is changed in the process. These PIN diodes are open- and short-circuit PIN diodes. Figure 2 represents equivalent circuits of a PIN diode switch in the ON and the OFF state. When the circuit is in the ON state, it is simply a resistor-inductor (RL) of low value and an inductor (L). An inductor is in series with a high-value resistor named R_H , and in parallel with the other three components is a capacitor named C . Two Skyworks SMP1340-079LF PIN diodes have been used in this project [18]. The datasheet provides the following values of $RL = 0.85 \Omega$, $L = 0.7$ nH, and $C = 0.20$ pF.

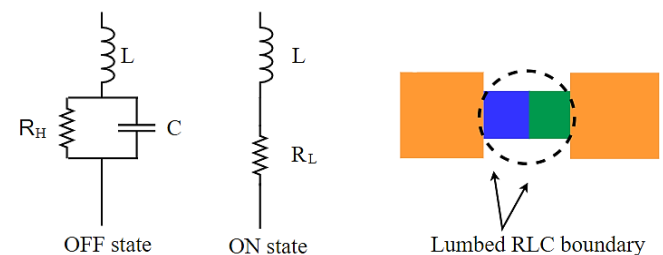


Figure 2. The circuit models of the PIN diode and the CST model

3. RESULTS AND DISCUSSION

The proposed structure was designed and evaluated using CST Microwave Studio 2021. Excitation of the radiating structure was done by allocating a waveguide port of standard size. The standard performance was obtained by using the CST microwave studio under the conditions of the boundary. Attributes, including S-parameter, gain, and surface current plots.

3.1. Frequency Reconfigurability

The proposed antenna achieves frequency reconfiguration via the ON and OFF states of each PIN diode, creating either an open or short circuit between radiating patches. This allows the antenna to switch between four distinct operational states. In the first scenario, when both diodes are OFF, the antenna resonates at 3.88 GHz. Similarly, when the first diode is OFF and the second is ON (Mode 2), the antenna exhibits resonances at 3.4 GHz and 4.9 GHz. In another condition, where the first diode is ON and the second is OFF (Mode 3), the antenna resonates at 3.5 GHz, 5.3 GHz, and 6.8 GHz. Finally, when both diodes are active (Mode 4), the antenna resonates at 3.4 GHz and 6.7 GHz. These results demonstrate the frequency-reconfigurable capability of the proposed antenna. The four switching states provide single-, dual-, and tri-band operation, resulting in seven distinct operating frequency bands using only two PIN diodes. The obtained frequency bands are relevant to wireless applications such as IoT, WiMAX, C-band, WLAN, and short-range radar systems, as discussed in the Introduction. Therefore, the results confirm that the proposed configuration provides multiple operating bands while maintaining a simple two-diode switching scheme. The PIN diode states for each mode and their corresponding resonances are detailed in *table 2*.

Table 2. States of the PIN diodes for various operating modes

MODE	D1	D2	Frequency band (GHz)
MODE1	OFF	OFF	3.88
MODE2	OFF	ON	3.4 and 4.9
MODE3	ON	OFF	3.5, 5.3, and 6.8
MODE4	ON	ON	3.4 and 6.7

3.2. Printed Antenna Design Steps

In the initial step, we planned a primary copper component in the form of a cross, which is placed at the center of the dielectric substrate. This is an element that acts as the primary radiating structure of the antenna. In the second step, we inserted a rectangular shape of copper on top of the cross, which served as a parasitic element to increase the gain and bandwidth. On the third step, we added small rectangular-shaped copper pieces on the upper-left part of the antenna. These elements were employed in matching impedance and frequency tuning. We used a T-shaped slot in the upper zone in the fourth step. The purpose of introducing this T-slot was to enable us to change the resonant frequencies and have multiple modes. This was to help us not have all the modes with similar frequencies so that we could give flexibility to obtain different resonant behavior of each mode.

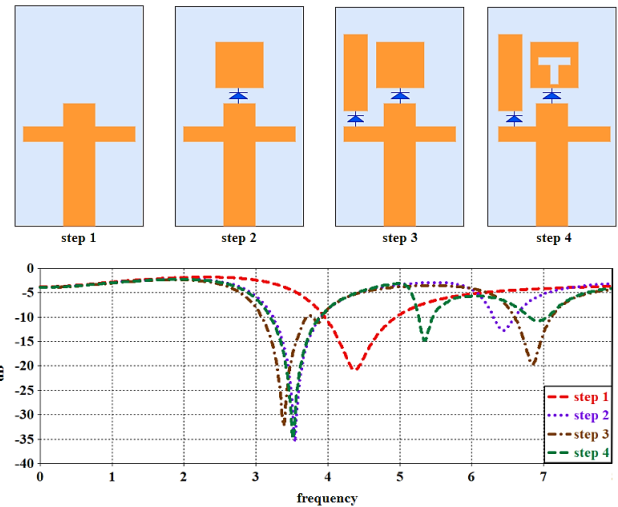


Figure 3. Antenna steps designed

3.3. S-parameter and Bandwidth

Figure 4 shows the S-parameter of all the modes of the proposed antenna. Mode 1: The antenna is in a single frequency band of 3.88 GHz (bandwidth, 860 MHz) when both switches (D1 and D2) are in the OFF state. Mode 2: When the first diode is OFF and the second one is ON, the antenna resonates at two frequency bands, 3.4 GHz and 4.9 GHz, with a bandwidth of 560 MHz (3.17-3.73 GHz) and 580 MHz (4.6-5.18 GHz), respectively. Mode 3: The same antenna functions in three different bands of 3.5 GHz, 5.3 GHz, and 6.8 GHz in the ON condition of the first diode and the OFF condition of the second diode with a bandwidth of 680 MHz (3.2-3.88 GHz), 260 MHz (5.2-5.46 GHz) and 380 MHz (6.68-7.06 GHz), respectively. Lastly, Mode 4: all switches are on, the antenna is on 3.4 GHz and 6.7 GHz with bandwidth 660 MHz (3.09-3.75GHz) and 950 MHz (6.05-7 GHz), respectively.

The S11 results confirm the resonant frequencies obtained for the four operating modes, with distinct resonance points observed for each switching configuration. The low S11 levels at the corresponding resonant frequencies indicate good impedance matching and confirm that the antenna can effectively operate at the reported frequency bands. The obtained bandwidths also show that each switching state provides a different operating range, supporting the frequency-reconfigurable capability of the proposed antenna. Overall, the S11 and bandwidth results demonstrate that the proposed antenna can provide multiple operating bands with acceptable impedance matching under different switching conditions.

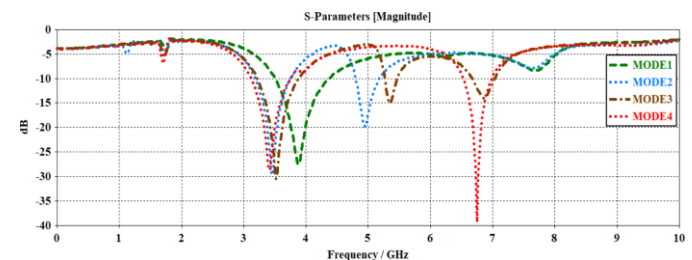


Figure 4. S 11 for all operating modes in the antenna

3.4. Bias Circuit

Figure 5 represents the control circuit of the biasing circuit that indicates the practical realization of the DC bias network to provide control over the switching state of the two PIN diodes (SMP1340-079LF). The figure shows the physical design of the antenna prototype, with the positioning of the PIN diodes, RF choke inductors, resistor, and capacitor and how they are interconnected to a 3 V DC power supply using a DIP switch, which allows the ON/OFF state of the diodes to be controlled manually. Continuing this physical implementation.

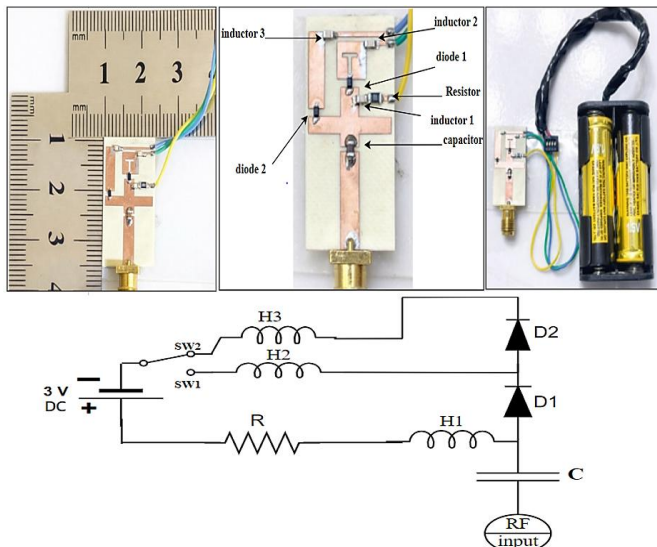


Figure 5. The fabrication of the suggested antenna and biasing circuit

Figure 6 shows the respective operational behaviour of the biasing circuit and its impact on antenna performance. The bias network uses RF chokes (47 nH inductor), 1 nF capacitor, and 1 k oh resistor to provide the appropriate DC bias and isolate the RF signal. The inductors enable a DC current to flow in the direction of the diodes but prevent RF signals, whereas the capacitor prevents unwanted DC interference along the microstrip line and enhances stability and the resistor controls the current to limit the diodes. A distance of 1 mm is kept between the radiating patch and the bias pad on which the inductors are loaded with a capacitor placed along the microstrip line with a spacing of about 0.2 mm to avoid much interference with the RF propagation. Also, there is a 1 mm spacing between the pad lines that the resistor is placed in which offers stability electrically in the bias network. The switching is regulated by applying a DC voltage, with each diode being ON when forward-biased to 3 V (low-resistance path) and OFF when no bias (0 V) is applied (high-resistance path). The antenna, therefore, has four modes of operation as shown in fig. 6. In figure 6(a) (Mode 1), the two diodes remain off and cause an interrupted current flow and a resonance at 3.88 GHz. Fig. 6(b) (Mode 2) has D1 = OFF, D2 = ON, and this lets current flow through D2, changing the effective current path, which resonates at about 3.4 GHz and 4.9 GHz. Fig. 6(c) (Mode 3) shows that D1 is ON and D2 is OFF, which diverted the current through D1, producing resonances around 3.5 GHz, 5.3 GHz and 6.8 GHz. Lastly, in Fig. 6(d) (Mode 4) the two diodes are

on and both current paths are active leading to dual-band operation at approximately 3.4 GHz and 6.7 GHz. This shows that the biasing circuit is effective in controlling the current distribution allowing the frequency to be reconfigured with constant performance.

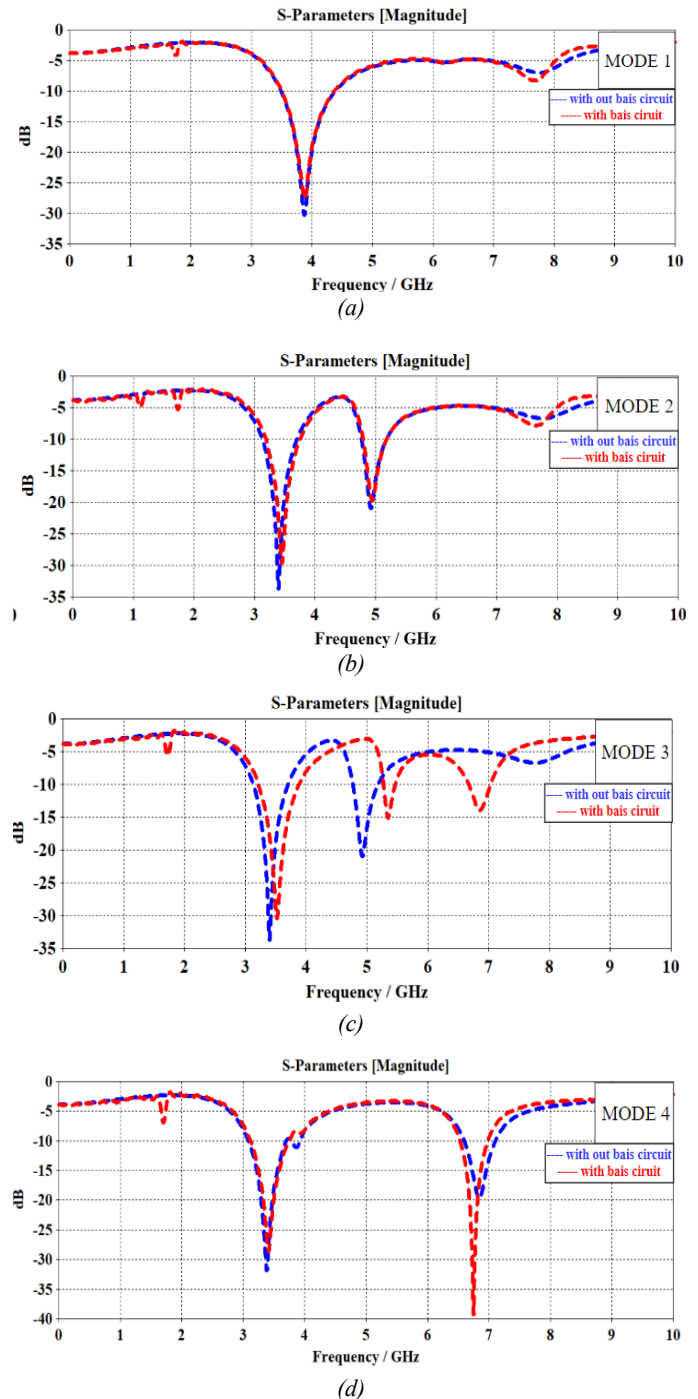


Figure 6. (a), (b), (c), (d) S11 characteristics with and without the bias circuit

Figure 7 depicts the constructed antenna when the laboratory measurement setup was done to measure the S11 parameter of the 4 operating modes, which justified the practicability of the antenna and the accuracy of the measured values.

Figures 8(a)–(d) show the simulated and measured S-parameters for the proposed antenna in its different operating modes. When you look closely at the simulated and experimental results, they match up well, which shows that the antenna design and measurement process are both reliable. After being properly calibrated to ensure accuracy, the Vector Network Analyzer (VNA) was used to measure the antenna that was made. A 50-ohm SMA connector was used to make sure the impedance was right. A DC biasing circuit with the right bias voltages was used to control the PIN diodes and switch them on and off. We used RF chokes and DC blocking capacitors to separate the RF signal from the DC path. We took measurements in a controlled lab setting that reduced the effects of cables and connectors. It is important to remember that the measurement system was recalibrated every time the operating mode changed. This helped keep things consistent and cut down on measurement mistakes. Small differences between simulated and measured results are due to differences in materials, tolerances in fabrication, and the fact that measurement equipment is not as good as ideal simulation conditions.

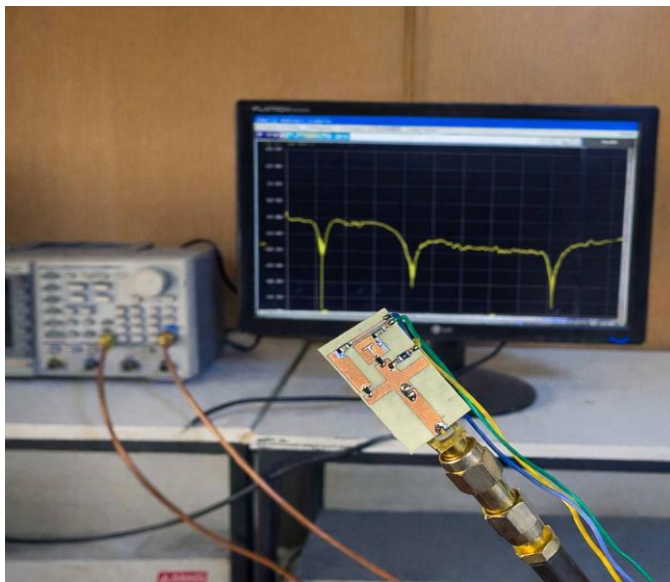
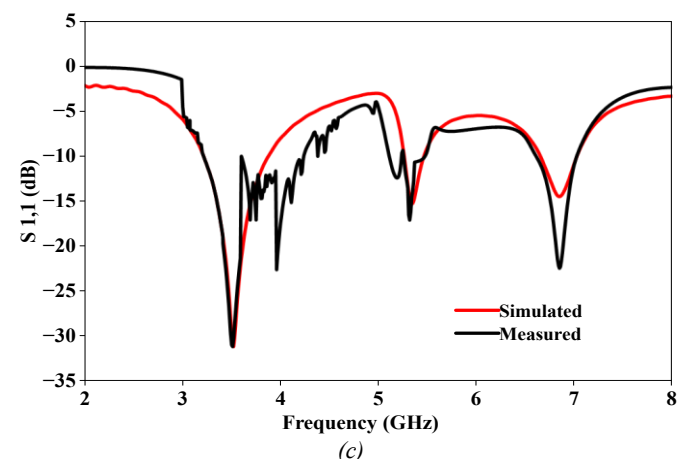
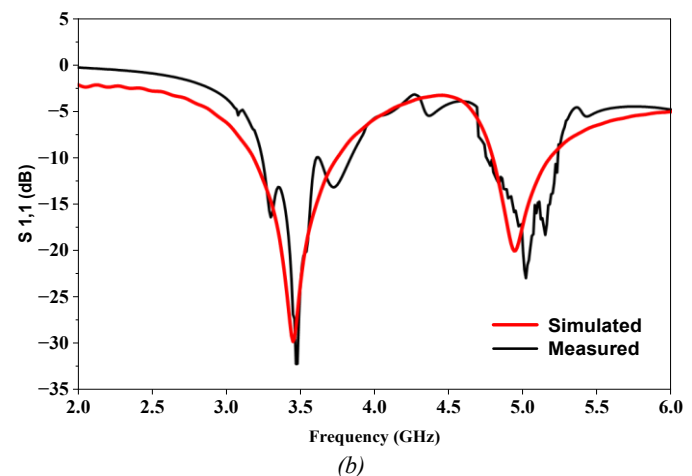
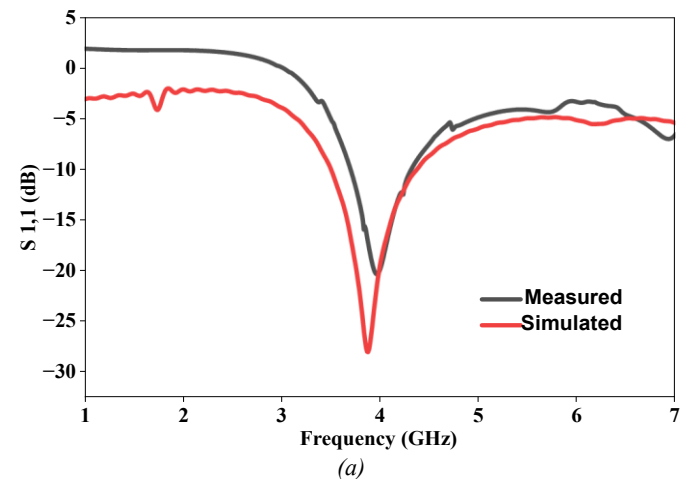


Figure 7. The reflection coefficient, setup of antenna used to determine the reflection coefficient of (S11)

Figure 8 shows the simulated and measured S11 results for the proposed antenna in different operating modes. A quantitative analysis shows that the difference in frequency between the simulated and measured results stays within about 3% for most operating bands. In some cases, the difference can be as much as 6%. Also, there are clear differences in the S11 and bandwidth values between the simulated and experimental results. The measured responses are not quite the same as what was expected from the simulation.

These differences are mostly due to real-world factors that affect how things are made, such as manufacturing tolerances, small changes in substrate properties, parasitic effects from the PIN diodes and biasing circuits, and losses from connectors and

soldering. The Vector Network Analyzer (VNA) measurements are also affected by how things are set up in the lab, while the simulation environment assumes perfect materials and boundary conditions. So, the observed differences are normal and are still within acceptable limits for real-world antenna implementations. The following table 3 shows the operating frequencies, S11 values, and bandwidth results for all operating modes, both from simulations and experimental measurements. This comparison shows even more clearly that the simulated and measured antenna performance is in good agreement.



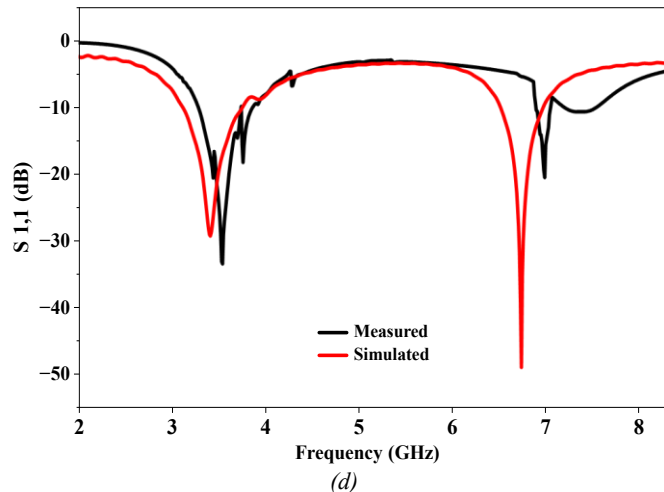


Figure 8. shows the S11 parameter, comparing simulated versus measured results

Table 3. Comparison of S11 and bandwidth between simulated and experimental results

MODE	Simulated Frequencies	S11 (dB)	Bandwidth (MHz)	Experimental Frequencies	S11 (dB)	Bandwidth (MHz)
Mode 1	3.88 GHz	-27.5	860	3.9 GHz	-20.2	400
Mode 2	3.4 GHz	-22.8	560	3.5 GHz	-32	600
	4.9 GHz	-19.7	580	4.98 GHz	-24	440
Mode 3	3.5 GHz	-28.8	680	3.72 GHz	-31	1030
	5.3 GHz	-15.7	260	5.2 GHz	-17.11	330
	6.8 GHz	-14	380	6.8 GHz	-22.4	390
Mode 4	3.4 GHz	-27.6	660	3.75 GHz	-31.5	860
	6.7 GHz	-37	950	7.12 GHz	-13.5	780

Overall, the measured results generally follow the main resonant behavior predicted by the simulations, confirming the practical realization of the proposed frequency-reconfigurable antenna and the effectiveness of its switching states.

3.5. Parametric Analysis

An important aspect of antenna design is parametric analysis to make sure that it has stable performance even under geometric conditions. variations. A parametric study on width, w_1 , was done in *figure 9(a)*. In the third-mode (when diode 1 is ON and diode 2 off), optimum width was found to be 13 with a resonant frequency of 6.8 GHz which is. important to IoT applications. To continue, *figure 9(b)* investigated the length parameter L_3 . In the first mode (both diodes = OFF), the optimal length was 9, and the resonant frequency was maximum along. with the best S11 values. Then in *figure 9(c)*, we plotted the ground length, in which the optimal was analyzed. The length was determined to be 5, which offered the best frequency among the tested values. Finally, in *figure 9(d)*, we compared materials used as the substrate, comparing Rogers 4350 (1.524 mm thick) and three FR4 substrates. (1.4, 1.5, and 1.6 mm). FR4 at 1.4 mm offered slightly higher S11, but Rogers 4350 offered a lower

one. Excellent balance, providing high-quality S11 values and higher and stable resonant frequencies.

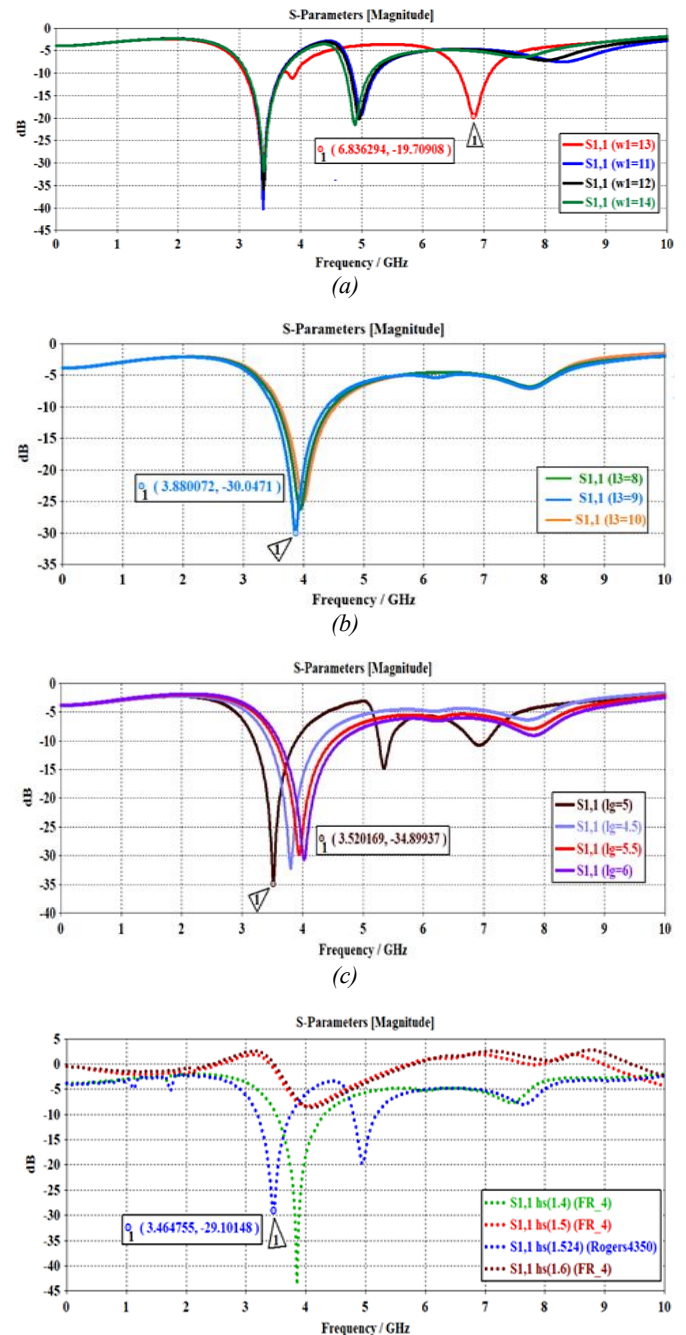


Figure 9. The simulated return loss is presented across all operational modes: (a) Mode 4, (b) Mode 1, (c) Mode 3, (d) Mode 2

3.6. Physical Interpretation of the Parametric Variations

In this section, the physical implications of the study parameters are discussed in detail. The investigation focuses on how modifications to various structural components of the antenna affect its resonant frequency. Several critical variables that significantly influence antenna performance were analyzed, with particular emphasis on the length of the partial ground plane (L_g) and its impact on wave reflection. Attention was also

directed toward the patch, which serves as the primary radiating element, along with the surrounding regions and radiating parts connected to the feed line. It was observed that altering the ground plane length notably impacts the resonant frequency, especially across all modes, particularly in mode 3 when D1 ON, D2 OFF. Increasing the ground plane length makes the current path's effective electrical length longer, which moves the resonant frequency to lower values. This behavior is in line with the fact that the resonant frequency and the effective electrical length are inversely related. The fundamental resonance principle offers a mathematical expression of the relationship between the resonant frequency f_r and the effective electrical length L_{eff} , where

$$f_r = \frac{v}{2L_{eff}} \quad (3)$$

The wave propagation speed (v) depends on the effective permittivity of the substrate ϵ_{eff} and is given by:

$$v = \frac{c}{\sqrt{\epsilon_{eff}}} \quad (4)$$

$$\lambda_{eff} = \frac{v}{f_r} \quad (5)$$

Thus, increasing the ground plane length causes a slight reduction in the effective length L_{eff} , which consequently increases the resonant frequency due to their inverse relationship. Furthermore, the magnitude of the frequency shift is directly tied to the wave propagation speed within the medium. An increase in the wave propagation speed results in a reduction of the effective resonant length, thereby raising the resonant frequency. Since wave velocity is inversely proportional to the square root of the effective permittivity, any factor that enhances propagation speed will manifest as an increase in resonant frequencies. In our design, increasing the slot length L_3 shortens L_{eff} , raising the resonant frequency. Conversely, increasing the ground plane length L_g increases L_{eff} , lowering the resonant frequency. S_{11} is determined by impedance matching between the antenna impedance $Z_{antenna}$ and the feed line Z_0 through the relation:

$$S_{11} = \frac{Z_{antenna} - Z_0}{Z_{antenna} + Z_0} \quad (6)$$

A lower S_{11} means better impedance matching and less reflected power. The introduction of T-slots in our design alters the current distribution, improving impedance matching and shifting the frequency. Finally, the use of rectangular shapes in our design provides precise control over L_{eff} , enabling fine-tuning of resonant frequencies, simplifying fabrication, and ensuring uniform current distribution, which enhances overall performance.

3.7. VSWR Performance

Voltage Standing Wave Ratio (VSWR) of the antenna is maintained at acceptable values, 1.1 in the majority of the frequency bands, and this indicates that it is being properly

matched to impedance and power is being transferred efficiently. *figure 10* illustrates VSWR to be less than 2 in all the frequencies that are studied, and this indicates that the radiation is effective in the various modes. The VSWR is calculated using the following relation [19].

$$VSWR = \frac{1 + |S_{11}|}{1 - |S_{11}|} \quad (7)$$

The low VSWR value indicates the lowest possible reflective losses, and the free space offers a high efficiency of the antenna, which proves the credibility of the antenna in terms of its efficiency in all resonant modes.

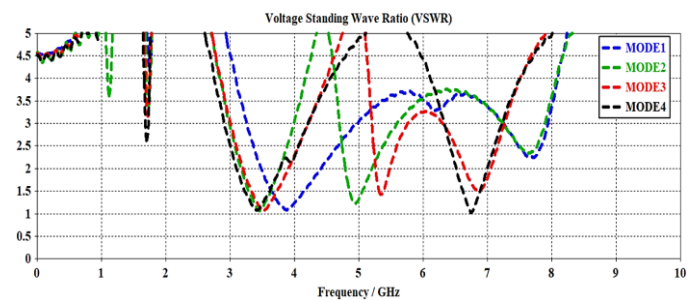


Figure 10. VSWR of the proposed antenna in different operating modes

3.8. Analysis of Far-Field Radiation Patterns, Gain, and Efficiency

The radiation properties of the proposed antenna in both H-plane and E-plane at the operating frequency bands were checked through the simulated far-field patterns depicted in *figure 11*. *Figure (8)* radiation pattern at resonant frequencies in mode 1 of 3.88 GHz, mode 2 of 3.4 GHz, mode 3 of 3.5 GHz, and mode 4 of 3.4 GHz in H-plane as shown in *figure 11(a), (b), (d), (g)*. The antenna shows an almost omnidirectional behavior in the H-plane across most of the operating bands, which reflects quasi-isotropic radiation behavior. On the other hand, at 4.9 GHz in mode 2, 5.3 GHz in mode 3, 6.8 GHz in mode 3, and 6.7 GHz in mode 4, respectively, the response of the E-plane is more distorted and irregular, as shown in *figure 11(c), (e), (f), and (h)*, respectively. The far-field radiation test shows that the antenna can offer sufficient radiation coverage at any frequency of operation, and that there is an acceptable amount of deviation in beam shape across the various reconfigurable modes. *Figure 12* shows the gain at every single frequency of the four different modes. Mode 1 had a frequency of 3.88 and a 94% efficiency. In Mode 2, there were 2 frequencies: the first with a frequency of 3.4 and an efficiency of 89.9%, and the second with a frequency of 4.9 and an efficiency of 88%. Mode 3 recorded three frequencies, namely: 3.5 with an efficiency of 92.6%, 5.3 with an efficiency of 83.6%, and 6.8 with an efficiency of 87.6%. Mode 4, lastly, the frequency found was 3.4 with an efficiency of 93%, and another frequency of 6.7 with an efficiency of 82%. The figure will simply illustrate the gain of each such frequency.

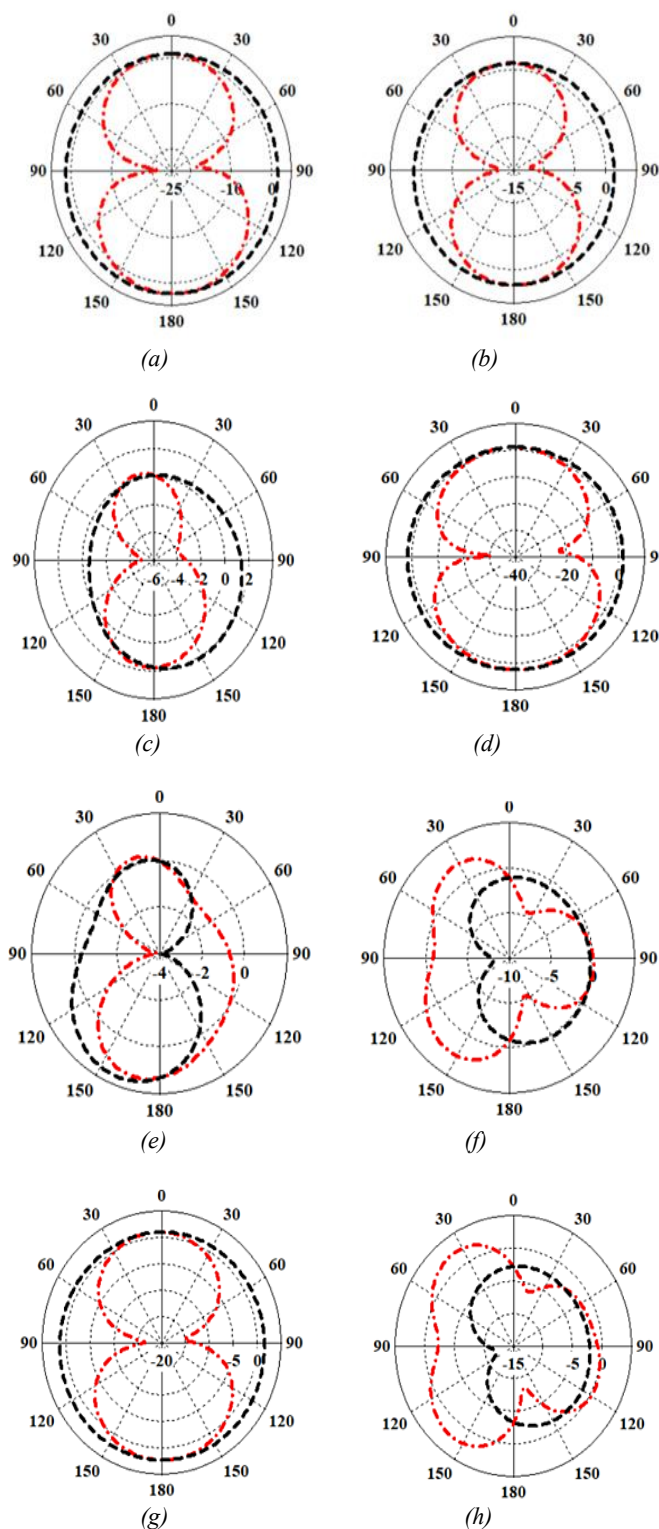


Figure 11. Simulation findings of radiation pattern of proposed antenna at varying frequencies and switching states; (a) 3.88 GHz (MODE 1), (b) 3.4 GHz (MODE 2), (c) 4.9 GHz (MODE 2), (d) 3.5 GHz (MODE 3), (e) 5.3 GHz (MODE 3), (f) 6.8 GHz (MODE 3), (g) 3.4 GHz (MODE 4), (h) 6.7 GHz (MODE 4)

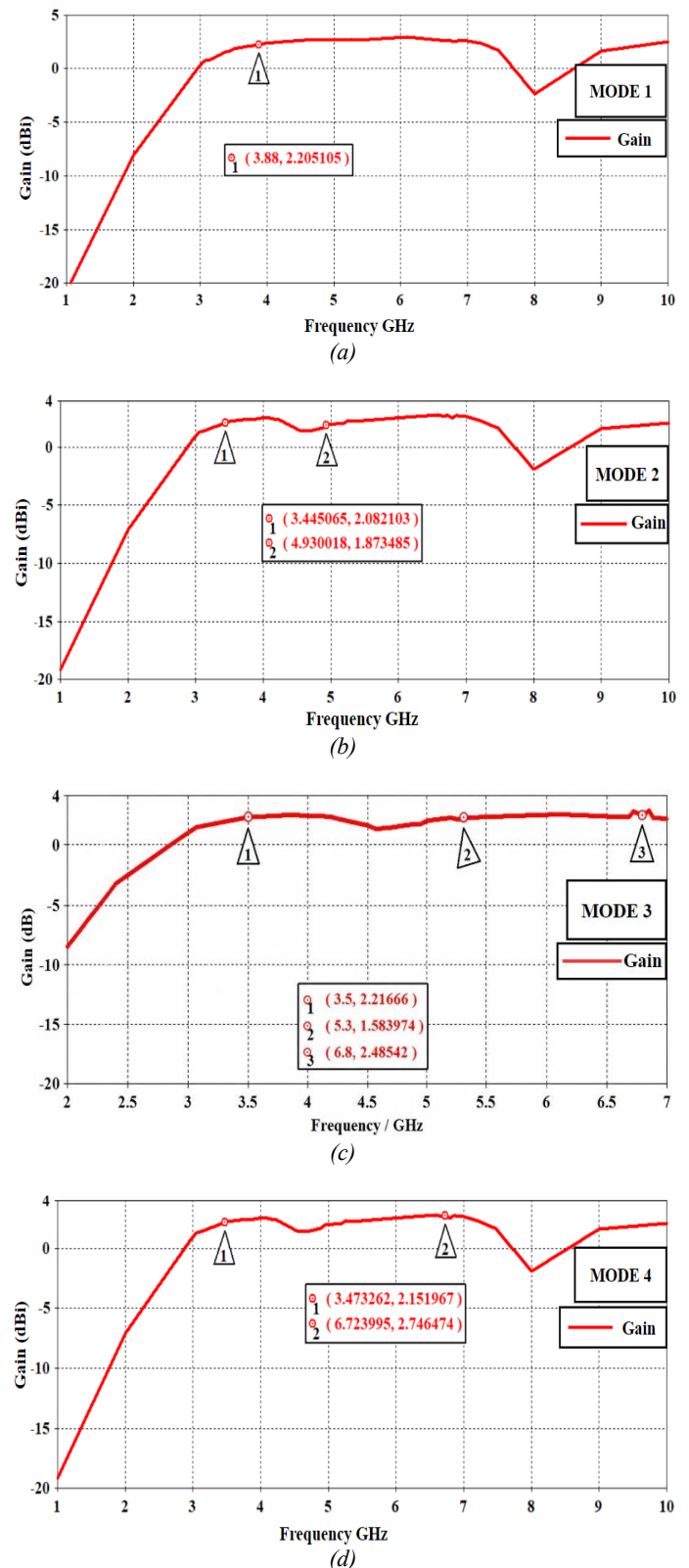


Figure 12. shows how the proposed antenna would work in seven different bands: 3.4 GHz, 3.5 GHz, 3.88 GHz, 4.9 GHz, 5.3 GHz, 6.7 GHz, and 6.8 GHz, with different switching setups

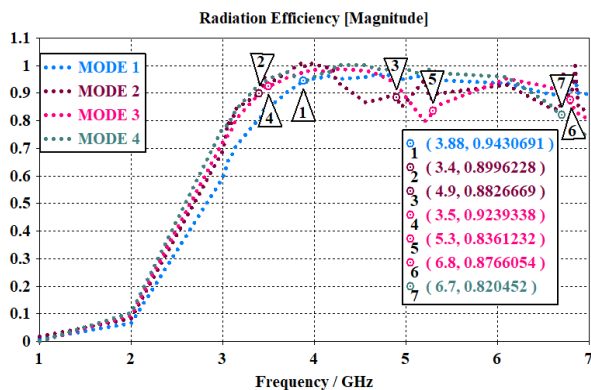
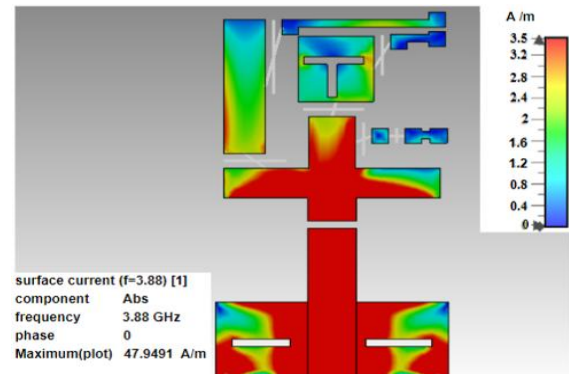


Figure 13. Efficiency of the proposed antenna (simulated)

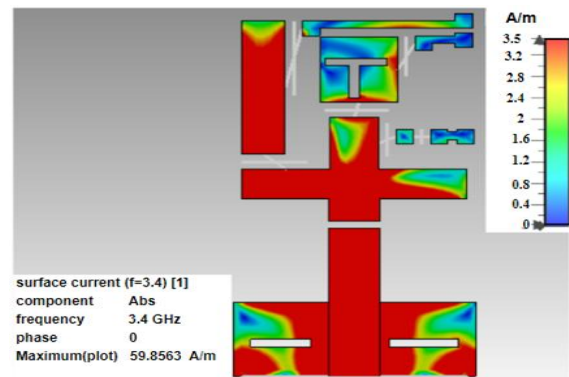
3.9. Surface Current Distribution

To apprehend the behavior and performance of the antenna, one has to examine the current regions of distributions and important flow points between the feed line and the radiating patch. To better understand the operating mechanism of the proposed antenna, the surface current distributions at the main resonant frequencies are illustrated in figure 14. These distributions provide insight into the active radiating paths and the resonant behavior associated with each operating frequency. At 3.88 GHz (figure 14(a)), the surface current is primarily concentrated along the central vertical strip and the horizontal radiating arm, indicating that the main resonant path is formed by the central monopole structure. The strong current concentration at the intersection of the vertical strip and the horizontal arm proves that this area is of predominance in radiation at this frequency. In the resonance at 3.4 GHz (figure 14(b)), the current was found to be distribution is further towards the upper radiating part, especially around the T-shaped element and the neighboring conducting paths. This means that the effective electrical length of the antenna increases as a result. to the addition of the upper radiating branch, which causes the resonance to extend into a lower frequency band. When the frequency is 4.9 GHz (figure 14(c)), the current concentration becomes more localized on the bottom arms and the central. feed region, and it is implied that that is the primary contribution of the resonance. The present distribution trend. indicates that the antenna is powered by shorter current paths than the lower frequency modes. For 3.5 GHz, a comparatively high current distribution is observed along the left vertical strip and the center in (figure 14(d)), which is GHz. radiating structure, which means that the left branch is an extra resonant path. This extension of the current trajectory is effective in increasing the electrical length, which can operate in this frequency band. At 5.3 GHz, the current density (figure 14(e)) is concentrated near the central horizontal and the feed junction, arm, but weaker currents are observed in the outer metallic parts. This type of conduct suggests that the resonance is overpowered by the central radiating element that has a relatively shorter effective path. Finally, at 6.8, the upper strip and the feed area are heavily concentrated sources of current at GHz (figure 14(f)) with localization of currents at noticeable values on the discontinuities and edge of the radiating elements. This distribution implies that the current resonant modes of higher order are aroused at this frequency, leading to reduced

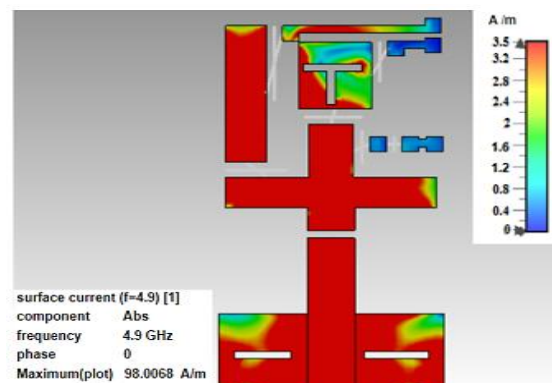
current paths. between the antenna structure. On the whole, the distribution of the surface currents in the various resonant. frequency proves that the antenna can operate in multiple bands and that this is made possible through a change in the effective current paths. in the radiating structure, which is steered by the switching states of the PIN diodes.



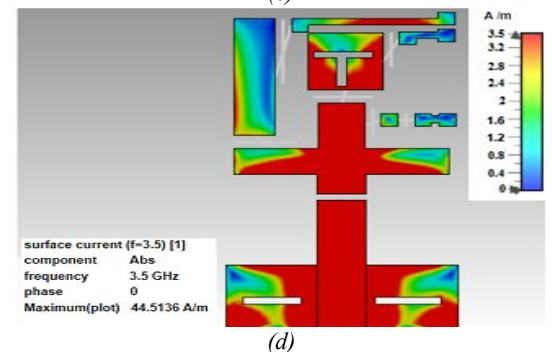
(a)



(b)



(c)



(d)

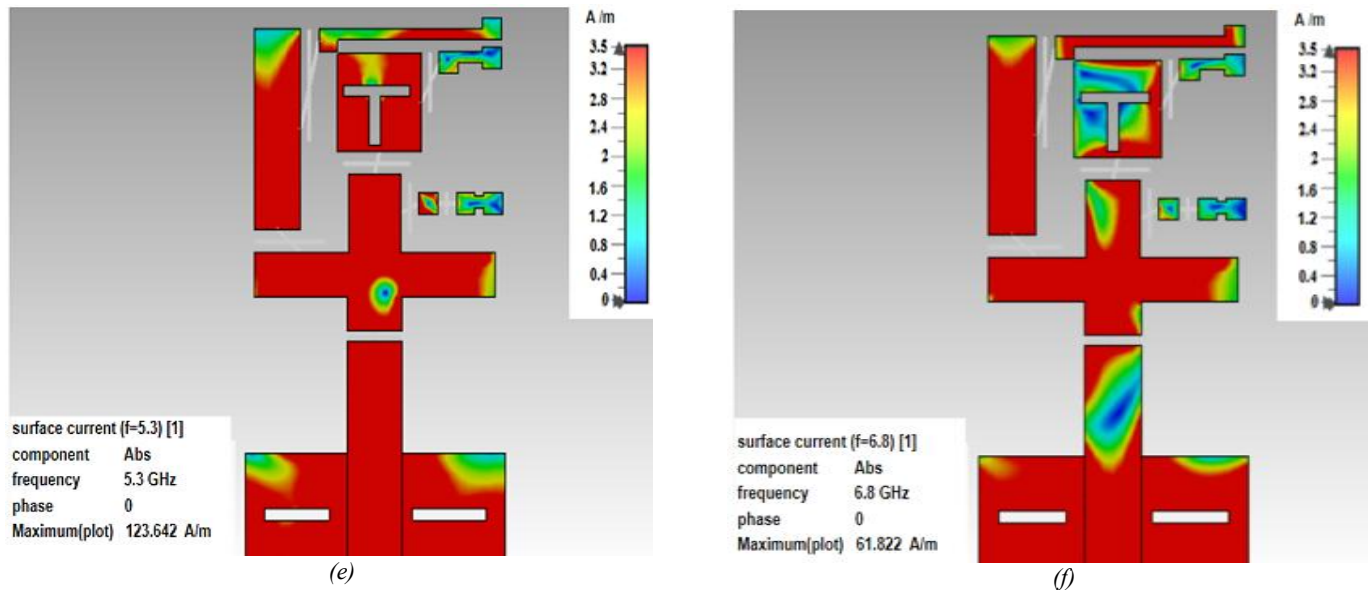


Figure 14. presents the distribution of the surface currents of the proposed antenna at various frequency modes. (a) Mode 1 is 3.88 GHz, (b) Mode 2 is 3.4GHz, (c) Mode 2 is 4.9 GHz, (d) Mode 3 is 3.5 GHz, (e) Mode 3 is 5.3 GHz, and (f) Mode 3 is 6.8 GHz

Table 4. Comparison between the suggested Antenna and other designs

Ref.	Antenna size mm ³	Substrate	Frequency bands (GHz)	Antenna type	No. of switches	Max Gain (dBi)	Max Efficiency (%)	Applications
[10]	15 × 21 × 1.6	FR-4	2.47/3.2/5.29/ 5.42/7.2/7.29	CPW-fed Rectangular monopole	2 PIN diodes	3.38	—	IoT, WLAN, WiFi
[11]	22× 22 × 0.762	Rogers 5880	7.4/7.5/8.1/8.2/8 .6/9/10.14/11.6/ 11.7/12/12.1/13. 2/13.6	Monopole	4 PIN diodes	5.34	88.4	IoT, sub-6 GHz (5G)
[12]	50× 45 × 1.6	FR-4	Bands (3.67-6.7)	CPW waveguide	2 PIN diodes	5.5	—	WiMAX, IoT, sub-6 GHz (5G)
[14]	27.8× 14 × 0.508	Rogers 5880	3.5/28	Patch	1 PIN diode	6.2	93.5	WiMAX, IoT
[20]	22 × 18 × 1.6	FR-4	3.16/3.2/3.3/7.8/ 7.6/7.7/7.5/10.5/ 11.5	Patch	2 PIN diode	1.9	—	WiMAX, and IOT
[21]	20 × 15 × 1.4	FR-4	2.4/6.04	Printed monopole	1 PIN diodes	4.8	95.6	IoT, Bluetooth, WiFi
[22]	38 × 21 × 1.6	Rogers 5880	1.8/2.3/3/5/4.2/6 .4	fed microstrip line	2 PIN diodes	2.5	98.9	IoT, Bluetooth, WiFi, WiMax
[23]	30 × 15 × 1.52	Rogers RO3003	2.4/ 2.9/ 3.5 /4.2 /5.6	microstrip patch	2 PIN diodes	5.8	—	modern wireless systems like WLAN and 5G.
[24]	45 × 45 × 1.5	Rogers RT5880	1.9/ 2.45/ 3.5/ 5.4/ 5.9	microstrip patch	3 PIN diodes	3.5	89	IoT, Bluetooth, WiFi, WiMax
This work	26×14×1.524	Rogers 4350	3.88/3.4/4.9/3.5/5 .3/6.7/6.8	Wave-guide monopole	2 PIN diodes	2.7	94	IoT, WiMAX, C-band, WLAN, short- range radar.



Reference [10] uses two switching elements to get six operating bands, but the proposed antenna has a smaller structure and achieves seven operating bands. Reference [11] supports more operating bands, but it needs four PIN diodes, which makes switching and control harder. Reference [12] has a wide range of frequencies it can work with, but the antenna is bigger than the one we suggest. Reference [14] shows good gain performance, but it only works in two frequency bands. Reference [20] has more operating bands, but the gain values that were reported are lower. Reference [21] uses a single PIN diode that is small, but it only works at two frequency bands. Reference [22] also gets similar gain performance, but the proposed antenna is smaller. Reference [23] supports multiple operating bands with good gain performance, but the proposed antenna has a smaller structure and operates over more frequency bands. Reference [24] uses more switching elements and has a larger antenna structure, while the proposed antenna achieves a simpler switching mechanism with a more compact design. In general, the proposed antenna strikes a good balance between size, operating bands, switching complexity, and efficiency performance. The studies that were compared were done under different conditions for simulation, fabrication, and measurement. These include differences in substrates, biasing configurations, gain definitions, and efficiency calculation methods. The comparison is meant to give a general analytical overview rather than a definitive ranking of performance.

4. COMPARATIVE ANALYSIS

The proposed antenna performance is compared with some of the recently reported reconfigurable antenna designs as summarized in *table 4*. The comparison is based on such important parameters as frequency bands, switching elements number, antenna size, gain, efficiency, antenna type, and applications. For Reference [10], the antenna is a CPW-fed rectangular monopole using two PIN diodes. It operates at six frequency bands: 2.47, 3.2, 5.29, 5.42, 7.2, and 7.29 GHz. The antenna size is $15 \times 21 \times 1.6$ mm³, and it achieves a maximum gain of 3.38 dBi. Although the gain is moderate, the design is compatible with IoT, WLAN, and WiFi applications. FR4 is the substrate, and its dielectric constant is 4.4, and its loss tangent is 0.022. The PIN diode biasing switches the antenna to 'ON' at +2V and 'OFF' at 0V. A VNA was used to measure, and CST MWS was used to simulate. Efficiency is not reported in the paper, thus, this aspect cannot be compared. In Reference [11], the antenna is a monopole antenna with four PIN diodes. It operates over multiple frequency bands: 7.4, 7.5, 8.1, 8.2, 8.6, 9, 10.4, 11.6, 11.7, 12, 12.1, 13.2, and 13.6 GHz. The antenna dimensions are $22 \times 22 \times 0.762$ mm³, with a peak gain of 4.3 dBi and a peak efficiency of 85.38%. The substrate is Rogers 5880 with a dielectric constant of 2.2 and a loss tangent of 0.0009. PIN diodes are switched at certain bias voltages (not mentioned here when not mentioned), and measurements were made with a VNA (or mentioned instrument). The simulations were done in CST Microwave Studio. This design is aimed at IoT and sub-6 GHz 5G. No additional biasing or testing environment is described.

In Reference [12], the antenna is a design of an ACPW waveguide with two PIN diodes. It is $50 \times 45 \times 1.6$ mm³ and

works on a continuous band of 3.67 GHz to 6.7 GHz. The highest gain simulated is 5.5 dBi, although no gain is measured. Efficiency values are not indicated in the paper. The antenna is designed to be used in IoT and sub-6 GHz 5G. In the case of Reference [14], the antenna is fabricated based on Rogers 5880 substrate which is chosen because of its high frequency characteristics. The substrate has a dielectric constant of 2.2 and a low loss tangent of 0.0009, which helps in maintaining high radiation efficiency, especially at millimetre-wave frequencies. The dimensions of the antenna are small ($27.8 \times 14 \times 0.508$) and the antenna works in two frequency bands: 3.5 GHz and 28 GHz. It is designed in the form of patch antenna and uses a single PIN diode to reconfigure the frequencies. The design has a gain of 6.2 dBi maximum, and high efficiency of 93.5%, which is a good radiation performance.

In [20], the dimensions of the antenna are $22 \times 18 \times 1.6$ millimeters. FR4 is the substrate, its dielectric constant is 4.4 and its loss tangent is 0.02. It is a patch antenna, which has two PIN diodes. It has nine frequency bands. The peak gain is 1.9 dBi. Although efficiency was not specified, the antenna is suitable for WiMAX and IoT applications. CST Microwave Studio was used to do simulations.

In [21], the dimensions of the antenna are $20 \times 15 \times 1.4$ millimeters, with an FR4 substrate. It has a relative permittivity of 4.3 and a loss tangent value of 0.025. The antenna is a monopole which is printed at 2.4 and 6.04 GHz. It has a single SMP1340-079LF PIN diode. The highest gain achieved is 4.8 dB and the efficiency is 95.6%. The bias circuit has a value of 2.2 mA, with a 1k ohm resistor and a Duracell alkaline battery of 1.5 V. The gain is IEEE-compliant, the gain realized. VSWR and S11 were measured and simulations done with CST Microwave Studio.

In [22], the antenna size is $38 \times 21 \times 1.6$ millimeters, and the substrate is Rogers 5880 ($\epsilon_r = 2.2$, loss tangent = 0.0009). It works with six frequency bands and is a fed microstrip line antenna with two SMP1340-079LF PIN diodes. The highest gain achieved is 2.5 dB and the efficiency is 98.9%. It can be used in the IoT, Bluetooth, WiFi and WiMAX applications. The design was completely simulated in CST Microwave Studio.

Reference [23] presents a compact frequency-reconfigurable microstrip patch antenna fabricated on a Rogers RO3003 substrate ($\epsilon_r = 3.0$, loss tangent = 0.0013) with overall dimensions of $30 \times 15 \times 1.52$ mm³. The antenna employs two PIN diodes to achieve frequency reconfigurability and operates at 2.4, 2.9, 3.5, 4.2, and 5.6 GHz. It is intended for WLAN and 5G wireless communication applications and provides a peak gain of 5.8 dBi. The radiation efficiency was not reported in the study.

Reference [24] proposes a frequency-reconfigurable microstrip patch antenna implemented on a Rogers RT5880 substrate ($\epsilon_r = 2.2$, loss tangent = 0.0009) with dimensions of $45 \times 45 \times 1.5$ mm³. The design utilizes three PIN diodes to provide operation at 1.9, 2.45, 3.5, 5.4, and 5.9 GHz. The antenna is designed for Bluetooth, Wi-Fi, WiMAX, and IoT applications, achieving a peak gain of 3.5 dBi and a radiation efficiency of 89%.

In our work, the antenna dimensions are $26 \times 14 \times 1.524$ millimeters, using a Rogers 4350 substrate ($\epsilon_r = 3.66$, loss tangent = 0.0037). It is based on seven frequency bands. It is designed as a waveguide monopole antenna in which two SMP1340-079LF PIN diodes have been used. The peak gain is 2.7 dB and the efficiency is 94%. Although we measured S11 in simulation and experiment, we could not measure gain and efficiency experimentally due to equipment limitations in our region. A 3V DC source is used in the bias circuit. The entire simulation has been done in CST Microwave Studio.

5. CONCLUSION

This paper presents a compact, multiband, frequency-reconfigurable antenna for wireless communication and Internet of Things (IoT) applications. The antenna provides seven different operating frequencies through two PIN diodes. The combination of compact geometry, controlled surface current distribution, and a well-designed partial ground plane enables the antenna to achieve low reflection coefficients, reaching -37 dB at 6.7 GHz in Mode 4, with satisfactory radiation efficiency across the investigated modes and a compact size of only $26 \times 14 \times 1.524$ mm³.

The results demonstrate that the proposed antenna provides flexible frequency operation through its different switching states. The antenna exhibits a VSWR below 2 at the reported operating bands, indicating acceptable impedance matching. The differences between the simulated and experimental results are mainly attributed to fabrication tolerances, equipment limitations, and environmental effects. The measured results generally follow the main resonant behavior predicted by the simulations, supporting the practical realization of the proposed antenna. Furthermore, the ability to switch between single-, dual-, and tri-band operation provides additional flexibility for wireless communication applications requiring frequency adaptability and a compact form factor. The proposed antenna is currently limited to the targeted operating bands and requires a PIN-diode biasing circuit for frequency reconfigurability.

6. FUTURE WORKS

Future work will focus on improving the radiation performance and expanding the operating bandwidth of the proposed antenna. In addition, future studies will investigate further antenna miniaturization, simplified PIN-diode biasing circuits, and the integration of intelligent control techniques for adaptive frequency reconfiguration. Experimental validation of additional antenna characteristics and extension of the proposed design to emerging wireless communication applications will also be considered.

REFERENCES

- [1] A. K. Abd, J. M. Rasool, Z. A. S. Rahman, and Y. I. Al-Yasir, "Design and analysis of a novel reconfigurable monopole antenna using a DIP switch and covering 5G-sub-6-GHz and C-band applications", *Electronics*, Vol.11, No.20, pp.3368, 2022.
- [2] A. Kumar, M. Aljaidi, I. Kansal, K. Alshammari, G. Gupta, and S. M. Alenezi, "Recent Trends in Reconfigurable Antennas for Modern Wireless Communication: a Comprehensive Review", *International Journal of Antennas and Propagation*, Vol.2024, No.1, 2024.
- [3] A. K. Abd and J. M. Rasool, "Octa-band reconfigurable monopole antenna frequency diversity 5G wireless", *International Journal of Electrical and Computer Engineering (IJECE)*, Vol.13, No.2, pp. 1606-1617, 2023.
- [4] M. S. Yahya, S. Soeung, S. K. A. Rahim, U. Musa, S. S. Ba Hashwan, and M. A. Haque, "Machine Learning-Optimized Compact Frequency Reconfigurable Antenna with RSSI Enhancement for Long-Range Applications", *IEEE Access*, Vol.12, 2024.
- [5] A. Kadhum Abd and J. M. Rasool, "Triple Band Frequency Reconfigurable mmWave Antenna Design for 5G Applications", *Proc. of 2022 2nd International Conference on Advances in Engineering Science and Technology (AEST)*, pp.521-526, 2022.
- [6] A. H. Ali and J. M. Rasool, "Design of a Tri-band Reconfigurable Antenna Using Metamaterials for IoT Applications", *Open Engineering*, Vol.15, No.1, pp.20240076, 2025.
- [7] S. Shrimal, R. Agrawal, I. B. Sharma, and M. M. Sharma, "Dual wideband circularly polarized reconfigurable antenna using gap-loaded annular ring", *AEU - International Journal of Electronics and Communications*, Vol.178, pp.155296, 2024.
- [8] T. K. Nguyen, C. D. Bui, A. Narbudowicz, and N. Nguyen-Trong, "Frequency-Reconfigurable Antenna with Wide- and Narrowband Modes for Sub-6 GHz Cognitive Radio", *IEEE Antennas and Wireless Propagation Letters*, Vol.22, No.1, pp.64-68, 2022.
- [9] K. Thenkumari, K. S. Sankaran, and J. M. Mathana, "Design and Implementation of Frequency Reconfigurable Antenna for Wi-Fi Applications", *Engineered Science*, Vol.23, 2023.
- [10] O. Benkhadda et al., "A Miniaturized Reconfigurable Antenna for Modern Wireless Applications with Broadband and Multi-band Capabilities", *Progress in Electromagnetics Research M*, Vol.127, pp.93-101, 2024.
- [11] A. Tiwari, G. K. Soni, D. Yadav, S. V. Yadav, and M. V. Yadav, "Rectangular loaded ring-shaped multiband frequency reconfigurable defected ground structure antenna for wireless communication applications", *Results in Engineering*, Vol.25, pp.104339, 2025.
- [12] A. Reha, O. Benkhadda, A. Oulad Said, A. El Amri, and A. Jamal Abdullah Al-Gburi, "Design of Sub-6GHz and Sub-7GHz DRAGON Fractal Antenna for 5G Applications with Enhanced Bandwidth", *International Journal of Intelligent Engineering and Systems*, Vol.18, No.2, pp.14-22, 2025.
- [13] A. Varshney et al., "Design process of a miniaturized reconfigurable antenna for 5G sub-6 GHz applications", *Journal of Electromagnetic Engineering and Science*, Vol.23, 2025.
- [14] A. Salisu et al., "Machine learning-optimized compact wearable frequency-reconfigurable antenna for sub-6 GHz/mm-wave 5G integration", *Scientific Reports*, 2025.
- [15] R. T. Chi and H. F. Zhang, "Frequency-reconfigurable antenna with multimode operation for 5G/WiMAX communication platforms," *Physics Letters A*, vol. 591, Art. no. 131924, 2026.
- [16] S. R. Galaba, R. C. Kasoju, and L. N. Meda, "Design and Analysis of Conformal and Frequency-Reconfigurable Antennas for Wi-Fi 7 APs and Routers," *Proc. SPIE*, vol. 14163, Art. no. 1416812, 2026.
- [17] C. A. Balanis, "Antenna Theory: Analysis and Design", Vol.4, Wiley, 2016.
- [18] Skyworks Solutions Inc., "SMP1340 Series: Fast Switching Speed, Low Capacitance, Plastic Packaged PIN Diodes", Datasheet, Feb.2006. [Online]. Available: <https://www.skyworksinc.com/Products/Diodes/SMP1340-Series>.
- [19] D. M. Pozar, "Microwave Engineering", 4th Edition, 2012.
- [20] S. E. El Aoud, H. Abbaoui, O. Benkhadda, et al., "Design of a crescent moon-shaped reconfigurable patch antenna using a PIN diode for 5G sub-6 GHz and multistranded wireless applications", *Progress in Electromagnetics Research B*, Vol.109, pp.81-93, 2024.
- [21] A. H. Ali et al., "A compact dual-band reconfigurable antenna with metamaterial for IoT applications", *Scientific Reports*, Vol.15, No.1, pp.21039, 2025.
- [22] J. M. Rasool and A. K. Abd, "A reconfigurable antenna for IoT applications with enhanced performance by adding metamaterial", *J. Commun*, Vol.19, No.4, pp.198-203, 2024.

[23] I. S. Idris, S. H. Lawan, B. D. Bala, S. A. Babale, U. Musa, and A. Y. Muhammad, "Design and Simulation of Frequency Reconfigurable Microstrip Patch Antenna for 5G and IoT Applications," *Int. J. Latest Technol. Eng., Manag. Appl. Sci.*, vol. 15, no. 2, 2026.

[24] V. Subashini, S. Chitra, and S. Ramesh, "Performance Analysis of Multiband Frequency-Reconfigurable Antenna for Cognitive Radio Applications," *Journal on Wireless Communications and Networking*, vol. 2026, Art. no. 5, 2026.



© 2026 by the Huda Ismail Khalil, and Riyadh Khlf Ahmed. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).