A Compact Reconfigurable Antenna for Sub-6 GHz Frequency Bands

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Abstract

This paper presents the design and analysis of a compact, frequency-reconfigurable antenna optimized for sub-6 GHz 5G applications. Utilizing a PIN diode as a switching element, the antenna achieves dynamic frequency reconfiguration, allowing it to switch between multiple frequency bands with minimal power loss. The proposed antenna is fabricated on an FR4 substrate, with a total size of 34×34 mm², offering a practical solution for modern wireless communication systems that demand compact and efficient designs. Simulation results show that the antenna operates effectively at two primary frequency bands, 2.05 GHz and 5.25 GHz in the "PIN_ON" state, and 2.3 GHz and 5.5 GHz in the "PIN_OFF" state. The antenna achieves excellent impedance matching and low reflection coefficients at these resonant frequencies, making it ideal for various sub-6 GHz 5G applications. Additionally, the gain, directivity, and voltage standing wave ratio (VSWR) characteristics are thoroughly analyzed, demonstrating the antenna's adaptability and suitability for 5G networks..

Keywords:
5G, Reconfigurable antenna, PIN diode, Patch antenna, Sub-6GHz

1. INTRODUCTION

The advent of fifth-generation (5G) wireless technology represents a significant leap forward in cellular communication, offering enhanced data transmission speeds, reduced latency, and improved overall responsiveness of wireless networks. With capabilities that support data rates in the range of tens of gigabits per second, 5G is designed to meet the growing demands of modern communication systems, providing not only better service quality but also higher reliability and efficiency. As mobile devices continue to shrink in size, optimizing the design of their components, particularly antennas, has become essential. Reconfigurable antennas have emerged as a key solution, enabling dynamic adjustment of key parameters such as polarization, radiation pattern, and operating frequency to suit different requirements [1]. This adaptability makes them highly advantageous in 5G applications, where efficiency, bandwidth, and space constraints are critical factors. Recent advances in the design of reconfigurable antennas have been driven by the use of tunable components such as PIN diodes [2,3], RF MEMS [4], varactor diodes [5], and field-effect transistors (FETs) [6], which allow for flexible and efficient antenna reconfiguration. These technologies have made reconfigurable antennas a central focus in contemporary research, as they provide a pathway to achieving the performance standards set by the 5G era.

Over the past few decades, significant advancements have been made in the design and development of reconfigurable antennas, which are crucial for their ability to dynamically adjust operational parameters, such as frequency, polarization, and radiation patterns. These antennas can be implemented using devices like PIN diodes, varactor diodes, RF MEMS, liquid metals, and Field Effect Transistors (FETs). The early work on reconfigurable antennas dates back to the 1970s, with recent designs focusing on enhancing their performance for modern communication systems like 5G. For instance, a hexagonal reconfigurable antenna using four PIN diodes was developed for low- and mid-band 5G, Wi-Fi, and X-band satellite applications, achieving frequency and pattern reconfigurability with compact dimensions of 30×20×1.6 mm^3 [7]. Another design used a triangular monopole antenna with PIN diodes for dual and tri-band reconfigurability in the mid-band 5G spectrum [8], although this range does not provide high speeds for real-time surveillance. In the millimeter-wave range, a microstrip patch antenna with variable resistors achieved frequency reconfiguration for 5G WLAN, though it suffered from high power consumption [9]. Additionally, a polarization-reconfigurable antenna using PIN diodes was developed for 5G, enabling circular polarization modes with operating bands around 3.4 GHz [10], though the design was relatively bulky. Larger designs, such as a U-shaped antenna and another for frequency and pattern reconfiguration at millimeter-wave frequencies, also demonstrated improved performance but at the cost of increased power dissipation and larger physical dimensions [11,12]. A more compact design was proposed to operate on both Wi-Fi (2.45 GHz) and 5G (28 GHz) frequencies, though practical challenges remain in its implementation [13].

This paper focuses on designing a sub-6 GHz frequency reconfigurable antenna utilizing a PIN diode. The primary objective is to create a compact, efficient antenna that can operate at different frequency bands by switching the PIN diode between its "ON" and "OFF" states.

2. Design Equations

Before proceeding with the antenna design, it is essential to determine key parameters such as the length (L), width (W), and substrate thickness (h). These parameters are crucial for ensuring the antenna operates efficiently at the desired frequency. A fundamental equation is typically used to calculate these dimensions, serving as a guideline to achieve optimal return loss at the target frequency. For rectangular antennas, the width (W) is calculated using the following equation [14]:

$$W = \frac{c}{f_o\sqrt{(\varepsilon_r+1)/2}} \qquad (1)$$

where (c) is the speed of light in a vacuum $(3 \times 10^8 m/s)$, (f_o) is the resonance frequency in Hz, and (ε_r) is the relative permittivity of the dielectric substrate (F/m). This equation helps establish the appropriate width to ensure efficient radiation and impedance matching at the desired frequency.

To determine the length of the radiating element, it is necessary to compute the effective permittivity (ε_{eff}) of the substrate, which is determined through the following relationship:

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2\sqrt{1+12\frac{h}{w}}} \qquad (2)$$

For a given resonance frequency f_r, the length is given by,

$$L = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}} \qquad (3)$$

2.1 PROPOSED ANTENNA DESIGN

The proposed design in Fig. 1 illustrates a frequency-reconfigurable antenna utilizing a PIN diode for dynamic frequency adjustment. The key design parameters for this antenna, listed in Table 1, include the dimensions of various components. The substrate width (W_S) and length (L_S) are both set at 34 mm, providing the foundational size of the antenna. The patch, which forms the radiating element, consists of two lengths, L_{T1} and L_{T2}, each measuring 15 mm, and the width of the patch W_T is set at 4 mm. The slot dimensions, crucial for frequency reconfiguration, are given as 3 mm in length (L_{sl}) and 1 mm in width (W_{sl}), allowing the antenna to adjust its resonance. The PIN diode itself, which plays a central role in switching between frequencies, has a length (L_p) and width (W_p) of 4 mm each.

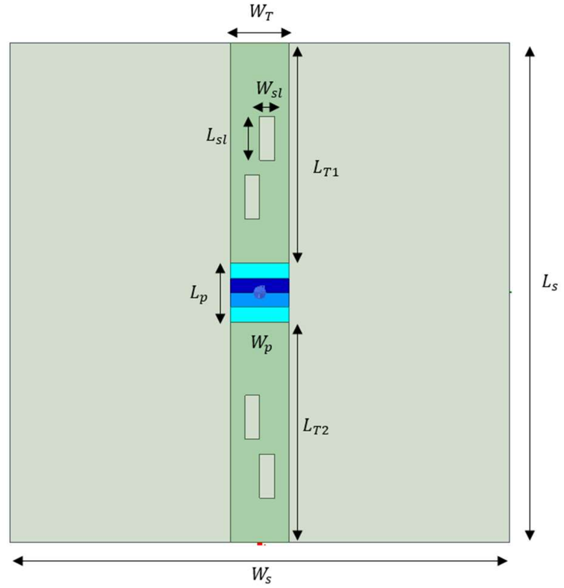


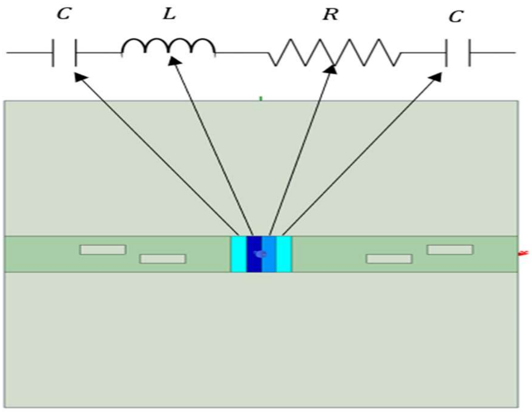
Fig. 1 Proposed Reconfigurable Antenna Design using PIN Diode

The PIN diode functions in two modes—ON and OFF—each affecting the antenna's equivalent circuit differently as shown in Fig. 2(a) and (b). When the diode is ON, the equivalent capacitance (C) is 0.5 µF, inductance (L) remains at 0.4 nH, and resistance (R) is 2 Ω. In the OFF state, the capacitance drops to 32 pF, while the resistance significantly increases to 15 kΩ, with the inductance remaining unchanged. These variations in electrical parameters (listed in Table 2) alter the antenna's frequency response, allowing it to shift between different operating bands. This design enables the antenna to achieve dynamic reconfigurability in its frequency range, supported by the ON/OFF states of the PIN diode, making it suitable for 5G and sub-6 GHz applications.

This design enables the antenna to achieve dynamic reconfigurability in its frequency range, supported by the ON/OFF states of the PIN diode, making it suitable for 5G and sub-6 GHz applications. The relatively compact dimensions and efficient switching mechanism offer a practical solution for modern wireless communication systems.

Table 1: Design Parameters

Labels	Type	Dimension
W_s	Substrate Width	34mm
L_s	Substrate Length	34mm
L_{T1}	Patch Length 1	15mm
L_{T2}	Patch Length 2	15mm
W_T	Width of Patch	4mm
L_{sl}	Slot Length	3mm
W_{sl}	Slot Width	1mm
L_p	Pin Diode Length	4mm
W_p	Pin Diode Width	4mm



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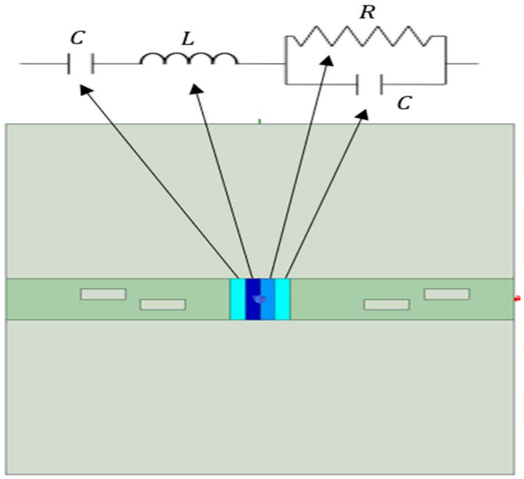


(b)

Fig. 2 Equivalent Circuit Diagram of PIN Diode (a) ON Mode (b) OFF Mode

Table 2: PIN Diode Equivalent Circuit Values

Parameters	**PIN Diode ON**	**PIN Diode OFF**
C	$0.5\mu F$	$32pF$
L	$0.4nH$	$0.4nH$
R	2Ω	$15K\Omega$
C	$0.5\mu F$	$32pF$

3. RESULTS AND DISCUSSION

The proposed design has been designed and simulated using a full-wave electromagnetic (EM) simulator, specifically Ansys High Frequency Structure Simulator (HFSS), as depicted in Fig. 3. The substrate employed is FR4, with a relative permittivity (ϵ_r) of 4.4 and a loss tangent (δ) of 0.02. The patch is excited through a 50Ω microstrip line, which is fed symmetrically from both sides. A PIN diode is utilized to establish an electrical connection between the two rectangular patches. As illustrated earlier in Fig. 2, the PIN diode is represented in HFSS using a lumped RLC model, with the corresponding R, L, and C values for both ON and OFF states, as detailed in Table 2.

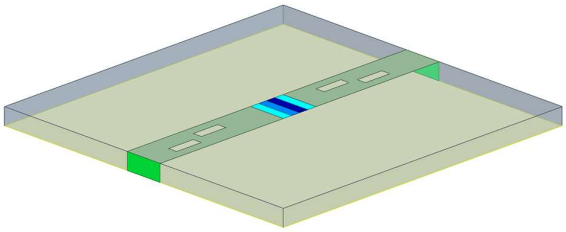


Fig. 3 HFSS model of the proposed Antenna

When the antenna is excited at an optimal impedance point, the reflection coefficient should be below -10 dB, and the voltage standing wave ratio (VSWR) is expected to fall within the range of 1 to 2. The reflection coefficient is a measure of impedance matching within the system and can be calculated using Eq. (3):

$$\text{Reflection Coefficient } |\Gamma| = \frac{Z_a - Z_f}{Z_a + Z_f} \quad (3)$$

where (Z_a) represents the antenna impedance and (Z_f) is the characteristic impedance of the feedline, with (Γ) being the reflection coefficient.

Additionally, the VSWR is connected to the reflection coefficient and can be determined using Eq. (4):

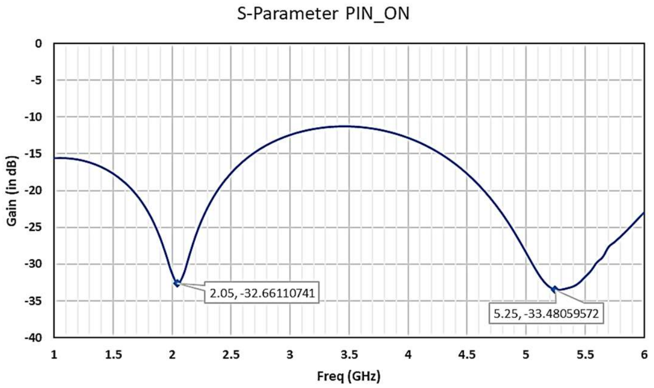
$$\text{VSWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|} \quad (4)$$

Both parameters are critical for assessing the performance and impedance matching of the antenna system.

3.1 REFLECTION COEFFICIENT

The reflection coefficient analysis shown in fig. 4(a) of the proposed sub-6GHz reconfigurable frequency antenna, with the PIN diode in ON condition, shows two primary resonant frequencies at 2.05GHz and 5.25GHz, where the reflection coefficient reaches deep nulls of approximately -32.66dB and -33.48dB, respectively. These low values indicate that the antenna is well-matched at these frequencies, allowing efficient signal radiation with minimal reflection.

Outside these resonant points, particularly between 1–2 GHz and 3–4.5 GHz, the reflection coefficient rises, indicating less efficient performance. Thus, in the "PIN_ON" state, the antenna is optimized for operation at around 2.05 GHz and 5.25 GHz, making it effective in sub-6 GHz applications at these specific bands.



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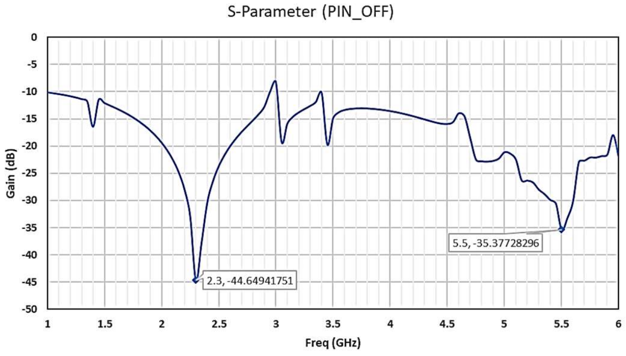


(b)

Fig. 4 Reflection Coefficient of the proposed antenna when (a) PIN diode is in ON state (b) PIN diode is in OFF state

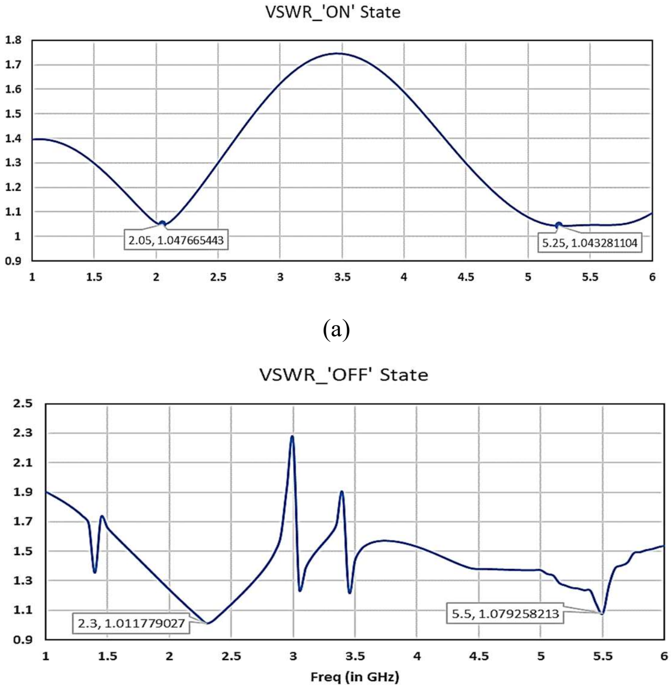
The reflection coefficient analysis of the reconfigurable antenna with the PIN diode in the OFF state shows two primary resonant frequencies at 2.3 GHz and 5.5 GHz, where the reflection coefficients drop to -44.65dB and -35.38 dB, respectively. These deep nulls indicate that the antenna is very well-matched at these frequencies, allowing minimal signal reflection and maximum radiation efficiency. The performance at these resonant frequencies is ideal for sub-6 GHz applications, making the antenna highly effective for communication within these bands when the PIN diode is off.

Outside of these resonance points, particularly between 2.5 GHz and 4.5 GHz, the reflection coefficient is less consistent, with varying peaks and dips indicating reduced efficiency and higher signal reflection. While the antenna still performs moderately in other parts of the spectrum, its optimal performance is clearly centered around 2.3 GHz and 5.5 GHz when the PIN diode is off. This demonstrates the antenna's ability to selectively reconfigure its frequency response based on the state of the PIN diode.

3.2 VOLTAGE STANDING WAVE RATIO

The VSWR plot as shown in fig. 5(a) for the proposed design with the PIN diode in the ON state indicates the antenna's impedance matching performance. The VSWR values range between 1.0 and 1.7, with lower values indicating better matching. There are two key points at 2.05 and 5.25 along the x-axis, where the VSWR values are around 1.05 and 1.04, respectively, representing frequencies where the antenna is well-matched. These minima suggest that the antenna performs optimally at these frequencies with minimal power reflection.

In contrast, the VSWR reaches a peak around 3.5, with a value of 1.7, indicating poorer matching and higher power reflection at this frequency. While the antenna is efficient at 2.05 and 5.25, it is less efficient at around 3.5, leading to some power loss. The analysis suggests the antenna is tuned for optimal performance at the frequencies corresponding to the minima, while it is less efficient near the peak.



(a)

(b)

Fig. 5 VSWR plot for the proposed design when (a) PIN diode is in 'ON' State (b) PIN diode is in 'OFF' State

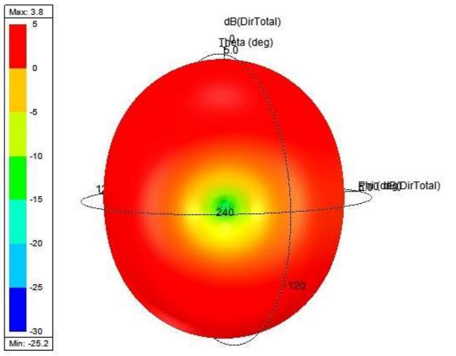
The VSWR plot as shown in fig. 5(b) for the proposed antenna with the PIN diode in the OFF state shows efficient performance at specific frequencies. At 2.3 GHz and 5.5 GHz, the VSWR values are 1.01 and 1.08, respectively, indicating excellent impedance matching and minimal signal reflection. These frequencies represent optimal operating points where the antenna performs efficiently in the OFF state.

However, there are notable inefficiencies around 2.8 GHz and 3.2 GHz, where the VSWR rises above 2.0, indicating significant power reflection and reduced performance. The peaks at these frequencies suggest poor impedance matching, which could lead to reduced transmission efficiency. While the antenna performs well at certain frequencies, the higher VSWR values at others suggest some limitations in its operational bandwidth when the diode is turned off.

3.3 Gain and Directivity

3.3.1 When PIN diode is in 'ON' state

In analyzing the three plots—3D gain plot, directivity plot, and gain plot as shown in fig. 6 for the proposed reconfigurable antenna design with the PIN diode in the "ON" state—several key observations can be made. The 3D gain plot provides a spatial visualization of how the antenna radiates energy, showing a generally spherical radiation pattern with a peak gain of approximately 3.8dB. This pattern indicates a relatively omnidirectional radiation characteristic with stronger energy directed in the central region, as depicted by the red zone in the center of the sphere. In contrast, the directivity plot illustrates a more specific radiation pattern in two dimensions, showing a characteristic figure-eight shape. The peak directivity is around 2dB in the main lobe, which corresponds to enhanced radiation along certain angles (primarily around 90° and -90°), with deep nulls along others, reflecting the antenna's ability to focus energy in specific directions, which is essential for improving the efficiency of the reconfigurable design. Finally, the gain plot further supports these findings by showing that the antenna achieves a gain between -14dB and -20dB at different azimuth angles, with the strongest gain aligned with the main lobes of the directivity pattern. This low gain at specific angles may indicate a trade-off between omnidirectionality and focused radiation. Together, these plots suggest that the antenna has a reasonably balanced performance between directivity and gain when the PIN diode is activated, making it suitable for scenarios where directional control is prioritized.



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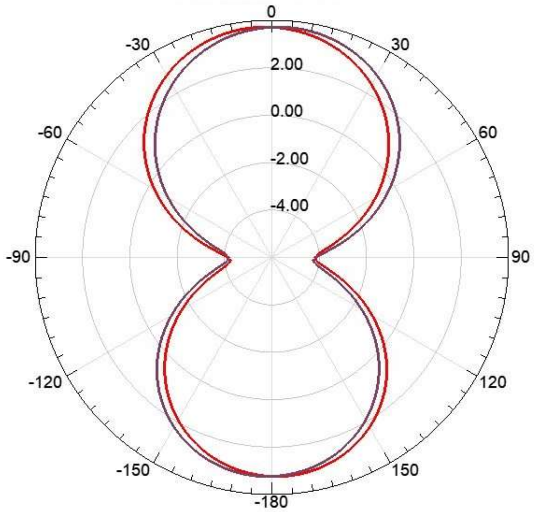

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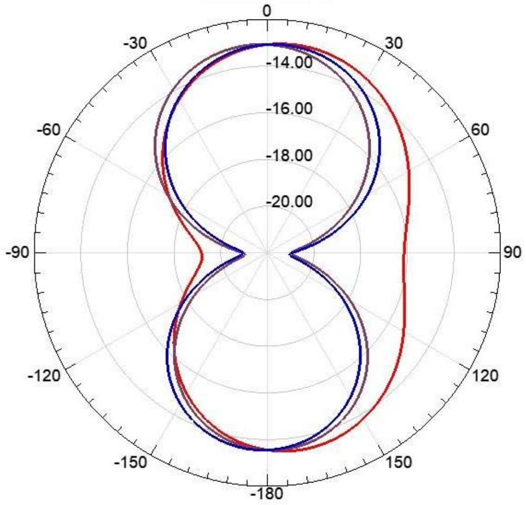


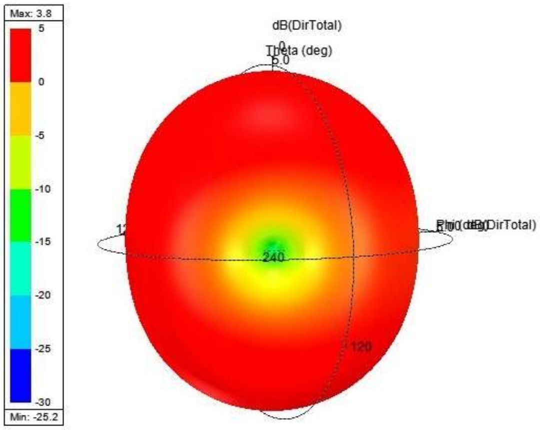
(c)

Fig. 6 (a) 3D Gain Plot (b) Directivity plot and (c) Gain Plot when PIN diode is in 'ON' state for the proposed design

3.3.2 When PIN diode is in 'OFF' state

The analysis of the plots as shown in fig. 7 for the proposed reconfigurable antenna with the PIN diode in the OFF state reveals that the antenna exhibits a predominantly omnidirectional radiation pattern with specific directional enhancements, as shown in the 3D gain plot. The maximum gain observed is 4.3 dB, with some nulls present at certain angles, suggesting that the OFF state of the PIN diode affects the current distribution across the antenna elements, leading to variations in radiation intensity. The directivity plot highlights a figure-eight pattern typical of dipole-like antennas, with a peak directivity of 3.6 dB at ±90 degrees. This indicates that the antenna effectively radiates energy in two opposite directions, which is beneficial for applications requiring bidirectional communication.

However, the gain plot reveals a notable reduction in gain, with a maximum of approximately -10.4 dB, indicating potential losses when the PIN diode is in the OFF state. Despite maintaining its directional radiation characteristics, the antenna's efficiency is compromised, as evidenced by the lower gain values. The comparison between the gain and directivity plots suggests that while the antenna retains its focus in certain directions, the overall power radiated is reduced, potentially due to impedance mismatches or the inherent effects of the diode's OFF state. These findings emphasize the trade-offs involved in the antenna's reconfigurability, particularly in scenarios where higher gain is crucial.



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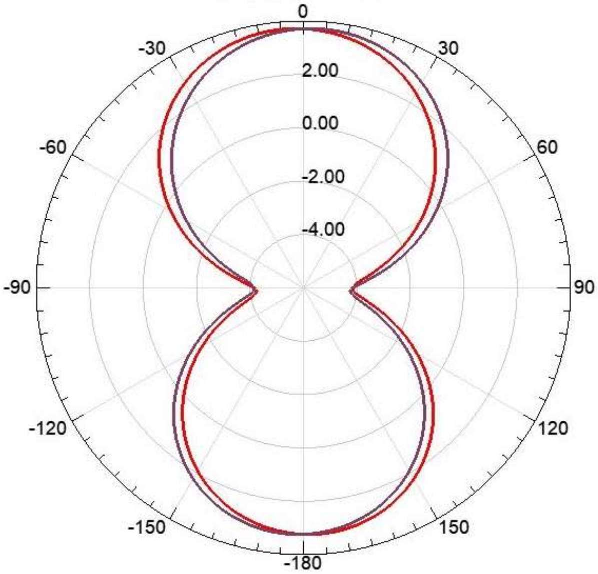

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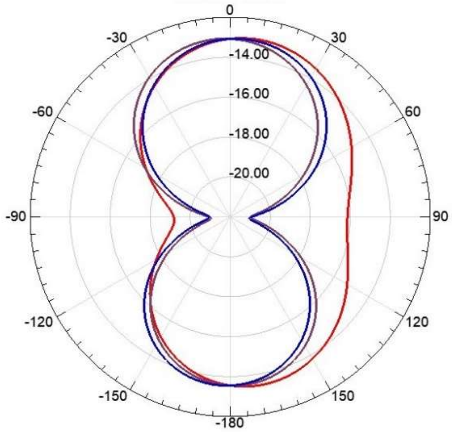


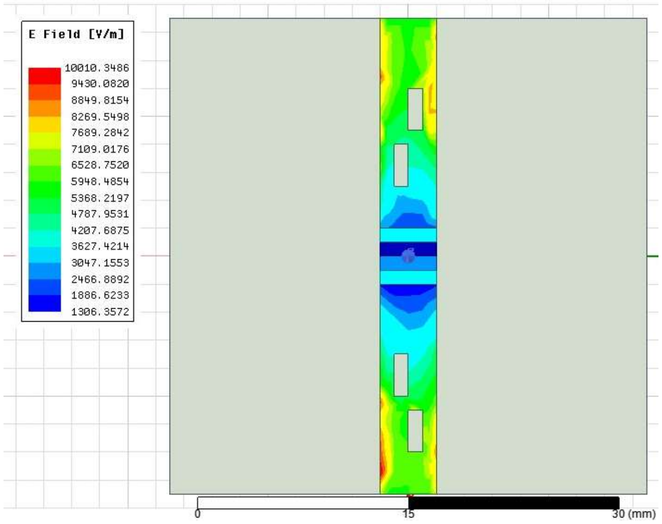
(c)

Fig. 7 (a) 3D Gain plot (b) Directivity plot and (c) Gain plot when PIN diode is in 'OFF' state

3.4 Surface Current and Electric field

The analysis of the surface current density (Jsurf) and electric field intensity (E field) plots shown in fig. 8 for the reconfigurable antenna when the PIN diode is in the 'ON' state reveals important insights into the antenna's performance. When the diode is turned on, the antenna's configuration is altered, directly influencing the distribution of the electric field and surface current. In the electric field intensity plot, the central region of the antenna exhibits a strong concentration of the electric field, with peak values exceeding 10,000 V/m, particularly around the edges and the areas closest to the diode's location. This indicates that the 'ON' state allows the antenna to radiate more efficiently, focusing the field at specific locations, which could improve the antenna's directive gain and operational frequency.

On the other hand, the surface current density plot shows the distribution of currents across the antenna's surface. The highest concentration of surface currents, marked by red and yellow regions, appears around the same central regions, particularly near the diode's connection points. This alignment between strong electric fields and high surface current densities signifies that the antenna is operating efficiently in this state. Additionally, the central high-current density suggests that the PIN diode is successfully reconfiguring the current pathways, allowing the antenna to adapt to different operational modes. This configuration likely enhances the antenna's bandwidth and tunability, making it suitable for applications that require dynamic frequency adjustments.



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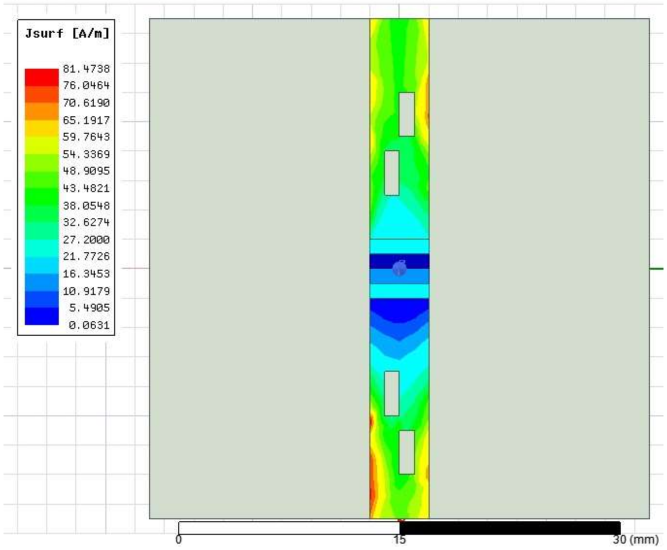
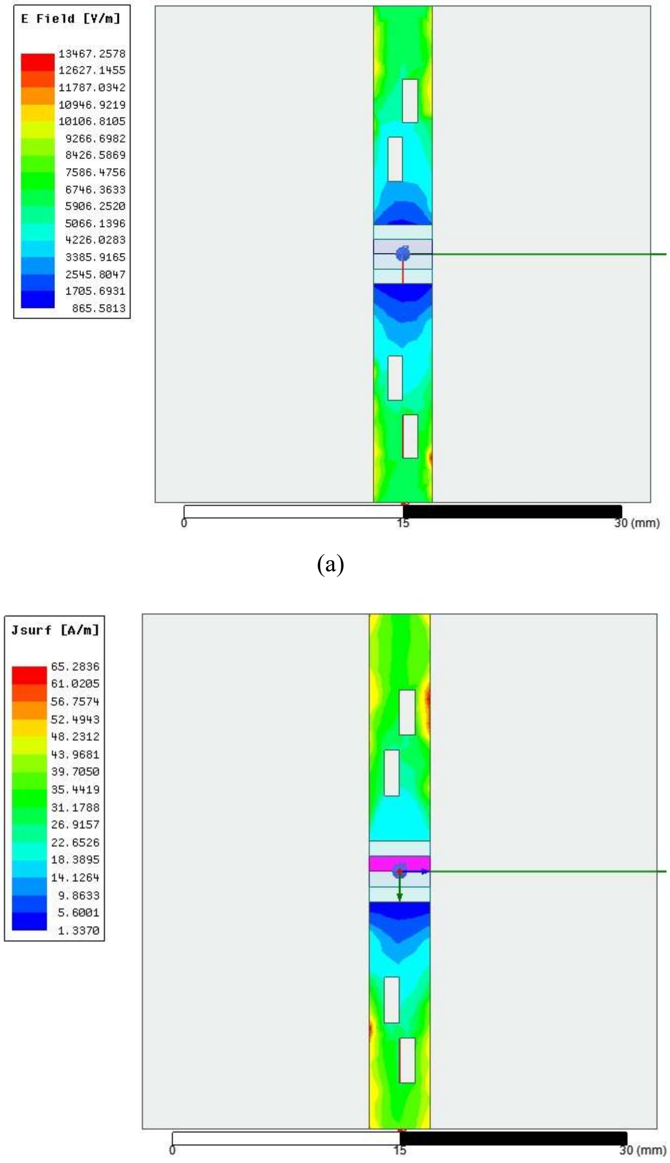


(b)

Fig. 8 (a) Electric field intensity and (b) Surface Current density when PIN diode is in ‘ON’ state

The surface current density (Jsurf) and electric field intensity (E field) plots for the reconfigurable antenna when the PIN diode is in the 'OFF' state exhibit distinct characteristics compared to the 'ON' state. In the electric field intensity plot, the peak field strength is notably higher, reaching values over 13,000 V/m. This high concentration of electric field intensity around the central region of the antenna suggests that in the 'OFF' state, the antenna experiences more localized field effects, potentially limiting its radiation efficiency and altering its resonant frequency. The strong fields at the central section could indicate the diode's isolation effect, which confines the energy rather than allowing it to propagate more freely as seen in the 'ON' state.

In the surface current density plot, the distribution shows a clear reduction in current flow compared to the 'ON' state, with the maximum surface current density peaking at around 65 A/m. The current is primarily concentrated near the central region, specifically around the location of the PIN diode, which is characteristic of a reconfigurable antenna where the diode's state dictates the current pathways. The limited spread of the surface current in this configuration suggests that the antenna is not fully optimized for radiation and may be operating at a different mode, emphasizing more localized reactive power rather than radiated power. This behavior highlights the reconfigurable nature of the antenna, where the 'OFF' state restricts current flow and electric field propagation, thereby tuning the antenna's operational parameters for specific frequencies or radiation patterns.



(a)

(b)

Fig. 9 (a) Electric field intensity and (b) Surface Current density when PIN diode is in ‘OFF’ state

3.5 Frequency Bands, Uses and Comparative analysis

Table 3 provides an overview of the frequency bands used in communication systems, particularly focusing on the operating frequencies of the proposed antennas. It highlights which frequency ranges are employed for 5G and other wireless technologies. While some frequencies, such as the 2.3 GHz band (n40), are deployed for 5G in certain countries (e.g., India and Australia), others, like the 5 GHz range, are predominantly allocated for Wi-Fi and not typically used for 5G.

Table 3: Frequency Bands and Their Uses

Frequency	**Band**	**Typical Uses**	**Countries Using for 5G**
2.05 GHz	Sub-6 GHz	Specialized communication systems, research	Not commonly used for 5G
2.3 GHz	n40	4G LTE, potential for 5G in some regions	India, Australia, other regions
5.25 GHz	5 GHz band	Wi-Fi (5.25–5.35 GHz), wireless communications	Not used for 5G; used for Wi-Fi
5.5 GHz	5 GHz band	Wi-Fi (5.47–5.725 GHz), wireless communications	Not used for 5G; used for Wi-Fi

The below table presents the compares the proposed reconfigurable antenna with previously reported work.

Table 4: Comparative analysis

Ref	**Size (mm^2)**	**Substrate**	**Band 1(in GHz)**	**Band 2(in GHz)**
15	50X43	FR4	3.8 GHz	6.4 GHz
16	45X38	FR4	2.1 GHz	2.1 GHz
17	26X30	FR4	3.1GHz-10.4 GHz	22 GHz-29 GHz
This work	34X34	FR4	2.05 GHz, 5.25 GHz	2.3 GHz, 5.5 GHz

4. CONCLUSION

The proposed frequency-reconfigurable antenna successfully meets the design objectives of compactness, efficiency, and reconfigurability for sub-6 GHz 5G applications. By integrating a PIN diode, the antenna demonstrates flexible frequency switching with optimized impedance matching at different operational bands. The simulation results confirm the antenna's strong performance, especially in terms of low reflection coefficients, high gain, and favorable VSWR values at key frequency bands. The proposed frequency-reconfigurable antenna, operating in the sub-6 GHz spectrum, demonstrates strong potential for applications in modern communication systems, particularly 5G and Wi-Fi. By efficiently switching between 2.05 GHz, 2.3 GHz, 5.25 GHz, and 5.5 GHz bands, the antenna is well-suited for mobile broadband, public safety, and high-speed wireless networks. The compact design and frequency agility make it a valuable solution for sub-6 GHz 5G deployments, where both coverage and capacity are crucial. Future optimization could enhance its performance in additional bands and reduce power consumption, making it even more versatile for next-generation communication technologies.

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