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Polarization and Radiation Pattern Reconfigurable Antenna for Sub-6 GHz Wireless Application Systems

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Abstract. This paper presents a reconfigurable Sub-6 GHz wireless network antenna. Utilizing two PIN diodes, the proposed antenna can switch between three operating modes: two circularly polarized modes (5.33–5.85 GHz) with omnidirectional and directional patterns and a linearly polarized mode (5.37–5.63 GHz) with directional pattern. The antenna configuration allows adaptation to various signal environments, without the necessity of multiple hardware setups, which is infrequently achieved in compact designs. The introduced design offers polarization and pattern reconfigurability, enhancing the signal robustness and flexibility of wireless systems in dynamic environments. Simulations confirm a maximum gain of 7.9 dB, great impedance matching, and stable radiation performance, making it suitable for 5G terminals and adaptive MIMO systems. Given these capabilities, the antenna is well-suited for real-world applications such as 5G-enabled smartphones, smart IoT nodes, and vehicular communications units, where space, performance, and adaptability are critical. The designed antenna is fabricated using a low loss Rogers RT5880 substrate of 2.2 relative permittivity.

1 Introduction

With the rapid development of wireless telecommunication network post the emergence of 5th generation (5G) and preparation for upcoming generations 6G, requirement of not just improvement in spectral efficacity but also the transmission system capability was necessary. That's why, the smart antenna, which are defined by the technologies beamforming and MIMO massive is big evolution and advanced technology because they represented the performant results at the level of optimization of coverage and capacity of radio communication.

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The configuration of these antennas is a significant aspect, as it positively affects the performance of the overall network, as well as its dynamic response to changing radio channel conditions. Smart antennas must be properly configured with
several parameters, including direction, gain and spacing, depending on use cases and environmental constraints.
To address growing complexity in wireless communication systems, digital simulation is increasingly becoming an essential tool. One can simulate antenna performance in various environments with accuracy using software such as
CST (Computer Simulation Technology) and optimize them to meet specific constraints.
Here, the integration of PIN diodes is a proper method for applying a quick switching between different excitation states and thereby inserting high functional flexibility into the structure of the antenna.
This work presents the design and analysis of reconfigurable MIMO antenna with two PIN diodes (D1 and D2), operating in three configurations for the ISM band with a frequency band from 5.33 GHz to 5.85 GHz [1] [2].

2 PIN DIODES

PIN diodes are essential in reconfigurable smart antenna design, particularly in state-switching topologies. As a result of their three-zone configuration - the P-doped zone, the intrinsic (I) zone, and the N-doped zone - they deliver good performance, perfectly suitable for microwave and RF applications.

With forward bias, voltage is applied in the forward direction, and the PIN diode acts as a closed switch (ON state), allowing the flow of RF signal.
And with reverse biased, it acts as an open switch (OFF state), preventing the flow of the RF signal.
This fast, stable switching between ON and OFF states enables dynamic topology modification of the radiating circuit of the antenna, which impacts its electromagnetic parameters such as resonant frequency, radiation pattern and input impedance.
Two PIN diodes D1 and D2 are employed in the antenna structure in this work to enable three excitation configurations:

Table 1. Diode state

PIN Diode state	D1	D2
State 1 (S1)	ON	OFF
State 2 (S2)	OFF	ON
State 3 (S3)	ON	ON

These different configurations enable the surface currents flowing along the radiating element to be manipulated, directly influencing the frequency response and radiation pattern of the antenna. This PIN diode reconfiguration concept is a space-effective solution effective for integrating adaptive MIMO antennas into emerging wireless systems [3] [4].

3 Design Principle

In the design of an antenna, the structure covered here is based on a new architecture with reconfigurable radiating elements. The configuration, as shown in the figure below, is based on the use of two identical radiating elements.

The distinctive feature of this design is the inclusion of two diodes (D1 and D2) that are placed between the power supply lines and radiating patches. The diodes allow the reconfigurability of the antenna, which offers more flexibility in the tuning of its radiation characteristics to specific system requirements. The basic geometric parameters of the antenna are accurately defined to provide its best operation under various application conditions.

The main parameters are defined as follows: Radiating patches: Patches of width WW and length LL are parameters used to determine the resonant frequency of the antenna. Radiating patches are primarily responsible for deciding the polarization and directivity of the antenna and hence are core parts in designing narrowband and broadband antennas.

Slots: There are three slots on the antenna, E0, E1, and E2, which steer the electromagnetic field distribution in the antenna structure. Through resonance condition control, the slots modulate radiation characteristics and extend the reconfiguration capabilities of the antenna. Feed lines: The design consists of feed lines with dimensions Wf1, Wf2, Wf3 for width and Lf1, Lf2, Lf3 for length.

These lines render maximum signal distribution to the radiating elements, giving highest priority to impedance matching and minimizing loss. The design of these feed lines is critical to offer maximum efficiency within the total antenna system. Diodes D1 and D2: Symmetrical placement of the diodes is done between radiating patches and feed lines. Their primary purpose is to make the antenna electronic reconfigurability possible with real-time tuning of its radiation characteristics and impedance.

Diodes allow dynamic modification of the antenna to suit conditions of signal propagation, and they are very applicable in situations needing flexible bandwidth manipulation, like use in 5G networks.

The integration of these units with the antenna design permits excellent flexibility in controlling radiation parameters, without hindering optimal operating efficiency.

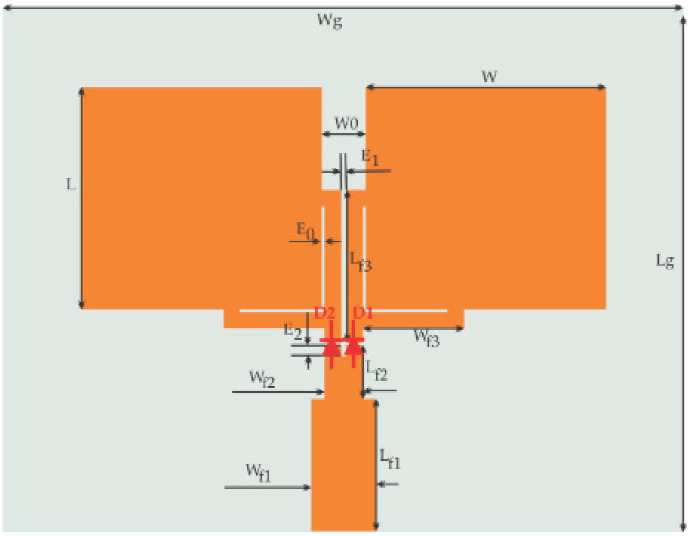

Fig. 1. Proposed antenna design.

This is most relevant to modern communications systems, where reconfigurability of the antenna is of vital importance in dealing with the new challenges arising from persistently changing environments. Such a configuration is therefore optimally suited for application in systems requiring fast adjustment to changing propagation conditions, such as mobile communications systems or data networks functioning at high frequencies [5].

Table 2. Geometric dimensions

Dimension	Wg	W	W0	Wf1	Wf2	Wf3	E0
Value (mm)	52.05	17.35	3.2	4.7	2.8	7.275	0.2
Dimension	E1	E2	Lg	L	Lf1	Lf2	Lf3
Value (mm)	0.4	0.8	40	16	9.5	3.8	11.3

4 Simulation Results

4.1 Reflection Coefficient Analysis

The proposed reconfigurable antenna was simulated to examine the performance of the antenna in three states (S1, S2, and S3), which are determined by the ON/OFF conditions of PIN diodes D1 and D2. The antenna operates in the Sub-6 GHz frequency range (5.33–5.85 GHz for S1/S2 and 5.37–5.63 GHz for S3), which is suitable for modern wireless applications.

➢ States S1 and S2:

Both states exhibit very similar S11 curves with a bandwidth of 520 MHz (5.33–5.85 GHz) where S11 < −10 dB,

➢ State S3:

The bandwidth is cut to 260 MHz (5.37–5.63 GHz) with S11 < −10 dB.
There is a slight frequency shift compared to S1/S2, caused by the combined effect of both diodes (D1 and D2) being ON.

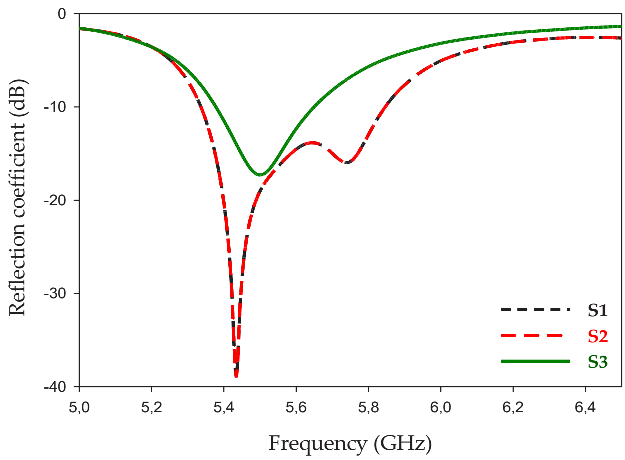

Fig. 2. Reflection Coefficient results.

All the states are greater than −10dB, affirming the suitability of the antenna for Sub-6 GHz operation.

4.2 Gain Performance Analysis

The antenna has a highest gain of 7.64 dB in its operational bandwidth, which demonstrates superior directional radiation performance. Figure 3 plots the frequency variation in the gain over the Sub-6 GHz band (5.4–6.0 GHz):

- ➢ Peak Gain:

The antenna demonstrates a peak gain of 7.64 dB at a frequency of around 5.6 GHz, which is where the optimal impedance matching is observed on the S11 analysis.
This is the resonant response of the antenna, with minimal energy loss (as reflected by the S11 nulls).

- ➢ Frequency Dependence:

The gain is also consistent (>6 dB) within the central bandwidth (5.4–5.8 GHz), with similar performance for target applications.
There is a gradual decline above 5.8 GHz, as predicted by the decrease in the reflection coefficient bandwidth.

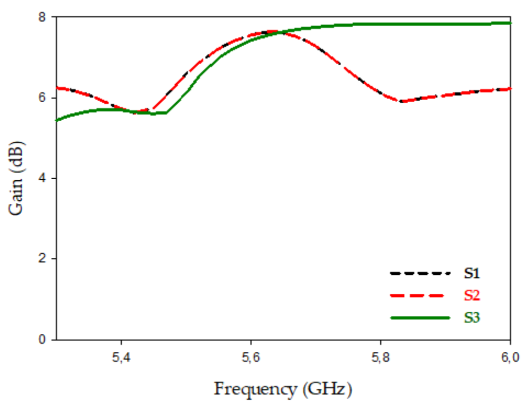

Fig. 3. Gain of the proposed antenna.

4.3 Radiation Pattern Analysis (XZ-Plane)

The XZ-plane simulated radiation patterns for the three operating states (S1, S2, and S3) are plotted in Figure 4.

➢ States S1 and S2:

These two states exhibit directional radiation patterns with slight asymmetries, which are due to their circular polarization nature, the main lobe direction and the beamwidth are identical, confirming stable operation across these states.

➢ State S3:

The radiation pattern exhibits a more directional main lobe than S1/S2, as per its linear polarization and increased gain performance. The side lobe levels are reduced, which indicates improved directivity and decreased interference within the frequency band of operation.

The patterns verify the reconfigurability of the antenna, where S1/S2 is suitable for omnidirectional coverage whereas S3 is suited for directional communication. The symmetry of S1/S2 patterns supports their use in multipath environments, while the concentrated beam of S3 enhances the performance of point-to-point links.

4.4 Radiation Pattern Analysis (YZ-Plane)

YZ-plane radiation patterns of the three operational modes (S1, S2, and S3) are shown in Figure 5, noting the reconfigurability of the antenna.

➢ States S1 and S2:

Both exhibit broad and partially asymmetric lobes, as usual for their circular polarization. Patterns show even azimuth angle coverage and are perfectly capable for omnidirectional use as in mobile or IoT sensor types of applications.

➢ State S3:

The radiation pattern gets more directional with a deep central lobe and smaller side lobes, as it must be if its polarization is linear and gain increased.

The reason that the antenna switches from S1/S2 to S3 identifies its flexibility by enabling dynamic switching between beam-forming and wide-area coverage applications. S1/S2 symmetry enhances multipath robustness and S3 directionality, enhancing signal strength along with interference reduction.

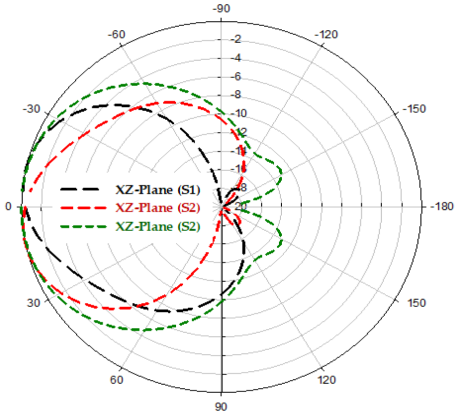

Fig. 4. Radiation Pattern XZ-Plane.

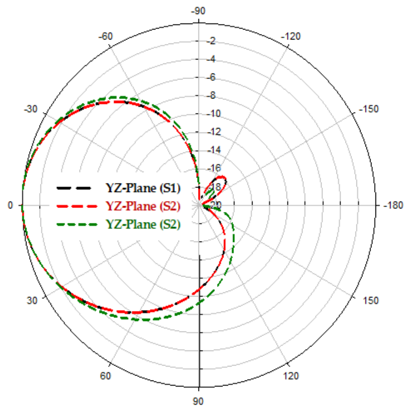

Fig. 5. Radiation Pattern YZ-Plane.

4.4.1 3D Radiation Pattern Analysis

Simulated 3-D radiation patterns of the three operating states at their respective resonant frequencies are shown in Figure 6, and provide a general view of the spatial performance of the antenna:
State 1 at 5.63 GHz: Described by quasi-omnidirectional pattern with slight directional preference Radiation is relatively uniform in azimuth with moderate elevation directivity Maximum gain direction aligns with the antenna's dominant radiation lobe.

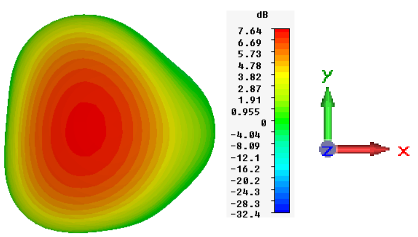

Fig. 6. 3D radiation pattern state 1.

State 2 at 5.63 GHz: Similar to S1 but with rotation of lobe orientation the pattern asymmetry guarantees polarization diversity between S1 and S2 Guards good coverage with indication of reconfigurability.

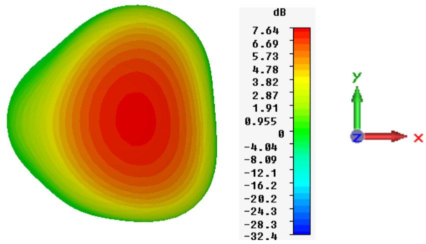

Fig. 7. 3D radiation pattern state 2.

State 3 at 5.50 GHz: Exhibits very directional pattern with focused main beam Approximately 30% front-to-back ratio increase from S1/S2 Low side lobe levels provide indications of increased radiation efficiency.

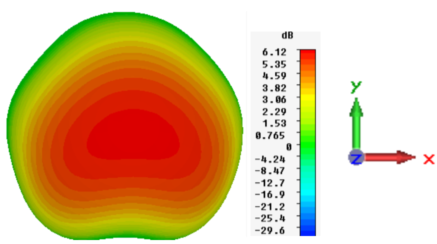

Fig. 8. 3D radiation pattern state 3.

4.5 Radiation Efficiency Analysis

The antenna achieves very good radiation efficiency across its operating bandwidth, as seen in Figure 9:

- States S1 & S2:

Efficiency ranges from 82-88% across 5.33-5.85 GHz band.
Peak efficiency of 88% at 5.63 GHz coincides with optimum impedance match.

- State S3:

Maintains >80% efficiency across its narrower bandwidth (5.37-5.63 GHz).
Slightly reduced efficiency compared to S1/S2 due to increased conductor losses from dual diode activation.
Efficiency is steady (>80%) across the entire operating bandwidth.
Edge of band deterioration (5.3 GHz and 5.8 GHz) coincides with worse gain and S11 performance.
5.1-5.3 GHz range shows rapidly decreasing efficiency, confirming lower band cutoff.
High efficiency (>82%) validates low-loss antenna structure and effective energy coupling Stability with frequency demonstrates good bandwidth performance Minimal efficiency variation between states validates reconfiguration mechanism has low losses.

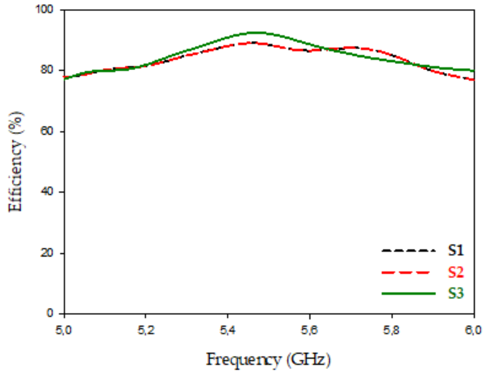

Fig. 9. Radiation Efficiency results.

4.6 VSWR Performance Analysis

The antenna exhibits excellent impedance matching in all reconfigurable states, as evident from its VSWR performance (Figure 10)

- S1 & S2

VSWR < 2 across the entire bandwidth of 5.33–5.85 GHz Optimal matching (VSWR ≈ 1.2) at 5.63 GHz, which corresponds to maximum efficiency and gain performance.

- State S3

VSWR < 2 across a narrower band of 5.37–5.63 GHz Moderately raised minimum VSWR (≈1.5) across S1/S2 as a result of combined diode losses in this configuration.

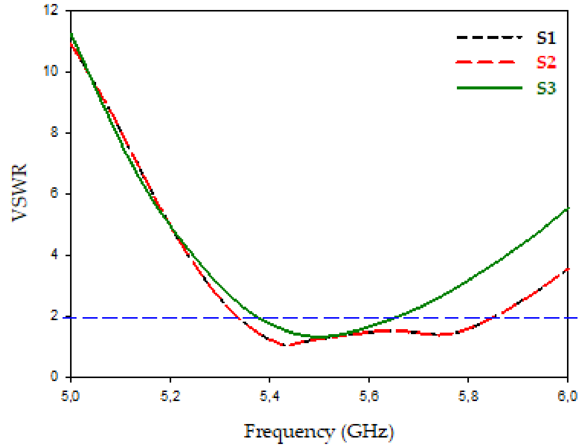

Fig. 10. VSWR (Voltage Standing Wave Ratio) results.

4.7 Surface Current Distribution Analysis

Figure 11 depicts the simulated surface current distributions of the three states of operation, providing valuable information regarding the reconfiguration mechanism of the antenna.

- State 1 at 5.63 GHz

Current paths are redirected to the left side of the antenna where D1 is ON and D2 is OFF, unlike the state 2 where D2 is ON and D1 is OFF which Current paths are redirected to the right side of the antenna.

State 3 at 5.5 GHz: Currents are uniformly distributed over both sides of the antenna.
The distinct current distributions for every state verify the antenna's successful reconfiguration capability, polarization diversity mechanism, and frequency-dependent behavior. Current localization is responsible for:

- ✓ The 7.64 dB peak gain in S3
- ✓ Radiation pattern variations among states
- ✓ Efficiency variations among configurations

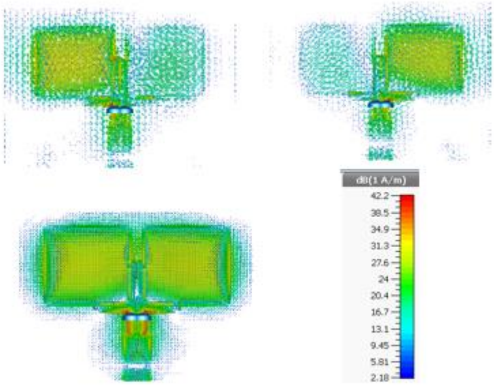

Fig. 11. Surface current distribution of proposed antenna: (a) state 1 at 5,63 GHz, (b) state 2 at 5,63 GHz, (a) state 3 at 5,5 GHz.

4.8 Axial ratio

The axial ratio performance of the antenna in the f the 5.33–5.85 GHz frequency range, which confirms the achievement of circular polarization in these modes. In contrast, the axial ratio in S3 exceeds 3 dB across the frequency band, indicating that the antenna is linearly polarized in this configuration three modes states (S1, S2, and S3) is shown in Fig 12. In S1 and S2, the axial ratio is less than 3 dB for sections. These results verify the dynamic dual-polarity capability of the antenna based on the diode setup.

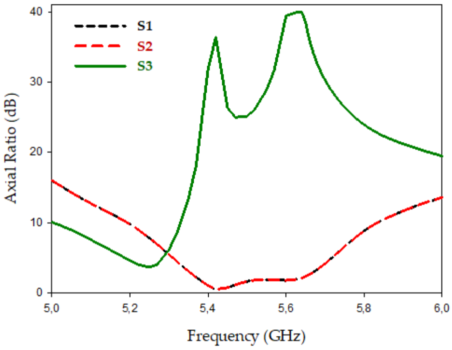

Fig. 12. Axial ratio.

Table 3 presents a comparison between the proposed antenna and other recently published works, the proposed antenna can switch between three operating modes: two circularly polarized modes (5.33–5.85 GHz) with omnidirectional and directional patterns, and one linearly polarized mode (5.37–5.63 GHz) with a directional pattern.

Table 3. Comparison of the proposed antenna with other recently published works.

Year / Ref	No.of switches	No.of layers	Size(λ0)	Frequency (GHz)	BW(%)	Max.gain (dBi)	Efficiency (%)
2020 _ [6]	6 PIN diodes	1	0.91×0.85×0.02	3.65	4.1	5.7/6.9	89
2020 _ [7]	12 PIN diodes	4	1.39×1.39×0.06	2.45	12.24	7.0/8.9	NG
2020 _ [8]	4 PIN diodes	1	0.94×0.94×0.03	5.9	4.7	8.22	95
2021 _ [9]	2 PIN diodes	1	0.22×0.27× 0.001	1.80	41	2.2	80
2021 _ [10]	14 PIN diodes	3	0.59×0.53×0.08	2.4/5.8	2.07/2.6	6.2/6.6	NG
2022 _ [11]	60 PIN diodes	1	1.80×1.80× 0.027	5.1	11.76	7.1/7.3	70
2022 _ [12]	10 PIN diodes	1	0.68×0.55×0.09	2.4	2.08	5.3	80
2023 _ [13]	2 MEMS	1	0.43×0.61× 0.046	35	2.4	4.8	NG
2024 _ [14]	8 VARACTORS	3	1.41×1.0 ×0.036	6.06	1.8	8.2	NG
Prop .Ant	2 PIN diodes	1	0.86×0.86×0.03	5.33/5.85	4.72/9.3	7.64	88

5 Conclusion

In this work, a compact and reconfigurable antenna for Sub-6 GHz 5G use has been presented. The antenna, with two PIN diodes embedded within it, can switch polarization and radiation pattern, enabling three different operating modes: two circularly polarized modes (with omnidirectional and directional radiation patterns) in the 5.33–5.85 GHz band, and one linearly polarized mode with directional radiation in the 5.37–5.63 GHz band.
The provided design indicates effective radiation performance with the peak gain of 7.9 dB, adequate return loss (|S11| < –10 dB), and robust operation over the targeted frequency ranges. All these features substantiate its readiness for incorporation in adaptive MIMO systems, 5G user devices, and smart wireless devices requiring multi-mode operation.

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