

Design and Simulation of Frequency Reconfigurable Microstrip Patch Antenna For 5G and Iot Applications

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ABSTRACT

Recently, the idea of reconfigurable antennas has made it feasible to design a single antenna that can support multiple wireless standards while maintaining the same performance as multiple antennas. The integration of a single antenna that can operate at multiple frequencies is required to enable multiple applications in a single device. This paper presents a compact frequency-reconfigurable microstrip antenna designed to support multiple wireless standards in modern communication devices. The proposed antenna, with dimensions of $30 \times 15 \times 1.52$ mm³, is simulated using CST Studio Suite and achieves reconfigurability through the integration of PIN diodes as switches within strategically placed slots on the radiating structure. By controlling the bias states of the two PIN diodes (Sw1 and Sw2), the antenna can dynamically switch between four distinct operating modes: All switches ON: dual-band operation at 2.4 GHz (lower WLAN) and 5.6 GHz (higher WLAN), All switches OFF: single-band resonance at 4.2 GHz (radio altimeter applications), Sw1 ON and Sw2 OFF: single-band operation at 2.9 GHz (military and meteorological radars), Sw1 OFF and Sw2 ON: dual-band coverage at 3.5 GHz (5G sub-6 GHz) and 5.6 GHz (higher WLAN/5G). The design maintains consistent performance across these configurations while offering a low-profile, single-antenna solution that eliminates the need for multiple dedicated radiators. This makes it highly suitable for integration into space-constrained devices such as smartphones, laptops, tablets, IoT systems, and next-generation wireless networks. The proposed antenna demonstrates versatile multiband/frequency agility compatible with WLAN, 5G, radio altimeters, military radars, and weather radar applications, highlighting its potential to address the growing demand for efficient, multifunctional antennas in emerging wireless ecosystems.

Keywords — Frequency Reconfigurable Antenna, PIN Diode, Microstrip Patch Antenna, IoT, 5G Application.

INTRODUCTION

Reconfigurable antenna polarisations, radiation patterns, and operating frequencies are greatly desired due to the explosive growth of wireless communications and the increasing need to integrate numerous wireless standards onto a single platform [1]. Depending on the host system's operating needs, reconfigurable antennas alter their radiation pattern, polarisation, impedance bandwidth, and operating frequency. At various frequencies and polarisations, they are able to emit a variety of patterns. It can be difficult for antenna designers to get the needed reconfigurable antenna functionality and integrate it into a whole system to provide an effective and economical solution. It has proven difficult to convert an antenna into a reconfigurable device by altering the internal structure of the antenna in several ways. Several things must be taken into account, including stability, efficiency, and generating a good gain [1].

[4] discusses various reconfigurable components that can be used on the antenna to change its structure and function. Different possible mechanisms can be used for every possible reconfigurable process. Reconfigurable antennas are utilized in various applications, including space and ground systems, for satellite communication and mobile phone technologies, cognitive radio, and multiple-input-multiple-output (MIMO) systems. The re-

configurability can be obtained by a change in surface current distribution, feeding network, physical structure, or radiating edges of the antenna, so a change in one parameter of the antenna can affect the other. Such antennas are a solution to requirements like MIMO Applications, Direction finding, Cognitive Radio, Beam steering, Radar command and Control. Therefore, more than one wireless standard can be accessed by using the reconfigurable antennas.

A low-profile ($0.21\lambda_g \times 0.35\lambda_g \times 0.02\lambda_g$) and a simply-structured frequency-switchable antenna with eight frequency choices were presented in the work. The radiating structure (monopole) is printed on a 1.6-mm-thick, commercially available substrate of FR-4 ($\epsilon_r = 4.4$, $\tan\delta = 0.020$). Specifically, it uses three PIN diodes in the designated places to shift the resonant bands of the antenna. The antenna operates at four different modes depending on the ON and OFF states of the PIN diodes. While in each mode, the antenna covers two unique frequencies (Mode 1 = 1.8 and 3.29 GHz, Mode 2 = 2.23 and 3.9 GHz, Mode 3 = 2.4 and 4.55 GHz, and Mode 4 = 2.78 and 5.54 GHz). The performance results show that the proposed antenna scheme explores significant gain (>1.5 dBi in all modes) and reasonable efficiency ($>82\%$ in all modes) for each mode. Using a high-frequency structure simulator (HFSS), the switchable antenna is designed and optimized. The fabricated model, along with the PIN diode and biasing network, is tested experimentally to validate the simulation results. The proposed antenna may also be combined in compact and heterogeneous radio frequency (RF) front-ends because of its small geometry and efficient utilization of the frequency spectrum [15]

[17] A frequency reconfigurable Libra shape antenna has been presented to provide frequency reconfigurability. Two PIN diodes are integrated into the designed antenna structure; thus, the antenna is operated in four different modes. Each mode is characterised by specific resonant frequencies, reflection coefficients (S_{11}), and bandwidths, demonstrating the reconfigurability of the antenna. Between 26 and 40 GHz, the S_{11} values for the different modes of the antenna are below -10 dB, indicating the usability of the antenna in this frequency range. The proposed structure has been fabricated with a printed circuit device and tested with a vector network analyser in the microwave laboratory. The experimental results support the simulation results and confirm that the antenna can maintain optimum performance in the specified frequency ranges. The developed multimode antenna structure is a good candidate for various applications such as telecommunications (5G), satellite communication systems, scientific research, Radio Astronomy, Industrial and Medical Applications, and radar systems.

[18] presents a compact multifrequency reconfigurable patch antenna in terms of design and fabrication for operating in the S and C bands of the RF spectrum, which are overwhelmed by wireless applications. Reconfiguration is achieved by using a single PIN diode on the ground plane. By varying the voltage applied to the diode, three modes can emerge, exhibiting main resonant frequencies at 2.07, 4.63, and 6.22 GHz. Resonance switching requires a voltage of less than 0.9 V. The antenna fabricated on an FR-4 substrate, with a volume of $70 \times 60 \times 1.5$ mm³, has a radiating patch element of a rectangular ring shape. The proposed low-cost antenna is easily implemented in a typical university lab-based environment. The total bandwidth for the three modes is close to 1 GHz, while the voltage standing wave ratio (VSWR) of the fabricated version of the antenna does not exceed 1.02, and the return loss is well below -40 dB for the three primary resonant frequencies.

[19] presents the design and evaluation of a compact-sized antenna targeting heterogeneous applications working in the C-band, 5G-sub-6GHz, and the ISM band. The antenna offers frequency reconfigurability along with multi-operational modes ranging from wideband to dual-band and tri-band. A compact-sized antenna is designed initially to cover a broad bandwidth that ranges from 4 GHz to 7 GHz. Afterwards, various multiband antennas are formed by loading various stubs. Finally, the wideband antenna, along with multi-stub loaded antennas are combined to form a single antenna. Furthermore, PIN diodes are loaded between the main radiator and stubs to activate the stubs on demand, which consequently generates various operational modes. The last stage of the design is optimisation, which helps in achieving the desired bandwidths. The optimised antenna works in the wideband mode covering the C-band, Wi-Fi 6E, and the ISM band. Meanwhile, the multiband modes offer the additional coverage of the LTE, LTE 4G, ISM lower band, and GSM band. The various performance parameters are studied and compared with measured results to show the performance stability of the proposed reconfigurable antenna. In addition, an in-depth literature review along with a comparison with the proposed antenna is performed to show its potential for targeted applications. The utilisation of FR4 as a substrate of the antenna,

along with its compact size of 15 mm × 20 mm, while having multiband and multi-mode frequency reconfigurability, makes it a strong candidate for present as well as for future smart devices and electronics.

[20] presents a frequency reconfigurable monopole antenna developed for UWB/Ku band applications. The design employs a microstrip-fed Reuleaux-triangle-shaped patch with a defected ground structure. The antenna exhibits a wide operating bandwidth achieved due to rectangular slits integrated into the Reuleaux-triangle patch. Meanwhile, adding rectangular slots in the ground plane improves the return loss level. Frequency reconfigurability is obtained by utilising PIN diodes to adjust the current distribution, altering the antenna's electrical length via the capacitive and inductive effects induced by the rings near the feed line. The antenna operates in two distinct frequency bands, 2.68–8.55 GHz and 12.7–15.65 GHz, contingent upon the PIN-diodes' ON/OFF states. In the OFF state, the antenna covers the UWB region, in particular, the ISM band (5.8 GHz), WLAN band (5.2 GHz), and lower X-band (8 GHz), exhibiting a 10 dB impedance bandwidth from 2.68 to 8.55 GHz with a maximum gain of 2.36 dBi. In the ON state, the antenna functions in the Ku band (12.7–15.65 GHz) with gains from 2.63 to 3.85 dBi. The antenna's dynamic switching between UWB and Ku band operations makes it suitable for applications such as satellite communications, health monitoring, 5G, aerospace, and remote sensing.

METHODOLOGY

ANTENNA DESIGN PROCESS

The basic shape and switching methods of the suggested frequency reconfigurable antenna are presented in this section. Using the PIN diode switches in the modelling environment, the antenna is rearranged to produce two single-band and two dual-band modes. Additionally, the measuring setup uses PIN diodes to accomplish reconfigurability.

In Fig. 1, a microstrip patch antenna is designed using the Rogers RO3003 Duroid (lossy) material as a substrate, while the patch and the ground plane are all designed using copper annealed. Table 1 lists all the antenna parameters. The proposed antenna is fed using a coaxial feeding line method; it has a partial ground plane. The antenna resonates at dual bands, 2.4 GHz and 6.3 GHz. The purpose of this design is to achieve dual band, to operate on two distinct frequency bands simultaneously or selectively. This can be useful for improving network performance, reducing interference, or expanding compatibility with different wireless standards.

Fig. 2 presents the same microstrip patch antenna which is designed in fig. 1, two slots with 1 x 2 mm width are created in the radiating structure. The reason for creating the slot is to determine the position to put the PIN diode switch. The proposed antenna is fed using a coaxial feeding line method and has a partial ground plane. Figure 1 presents the front and back view antenna. The purpose of this design is to identify the ideal position for placing the slot in order achieve reconfigurability.

Fig. 3 presents the same microstrip patch antenna, which is designed using the same materials as in Figure 1, but on the patch, there are two slots with 1 x 2 mm width on the radiating structure, a copper strip, and a vacuum was used as a switch in the ON and OFF states. In order to test for frequency reconfiguration, the first slot serves as switch 1 (S1) while the second slot serves as switch 2 (S2), copper is used as the ON state while vacuum as OFF state. The purpose of this design is to evaluate the ability to reconfigure frequency settings, specifically to ascertain whether frequencies can be adjusted as intended.

Fig. 4 present same microstrip patch antenna, which is designed using the same materials as in Figure 1, but the slot in the patch of the antenna is replaced with a PIN diode switch in order to achieve frequency reconfiguration. The purpose of this design is to facilitate frequency reconfiguration, allowing for the adjustment or modification of frequencies as required. Figures below present the front and back view antenna.

Geometry Of the Proposed Antenna

Due to the commercial availability of the Rogers RO3003 substrate, the antenna design is now more viable and

inexpensive. Obtaining optimal gain, efficiency, and directivity is the antenna's advantage. For the antenna excitation, a 50Ω microstrip line with a width of 5.5 mm is utilized. The antenna is excited via the waveguide port that is designated for the feed line. As illustrated in Fig. 2, the radiating structure has two slots set aside for the integration of vacuum switches, each measuring 1 mm in width. The suggested monopole antenna is $30 \times 15 \times 1.52 \text{ mm}^2$. The detailed dimensions of the suggested building are compiled in Table 1.

Table 1: Dimensions of the proposed Antenna			
Parameters	Values (mm)	Parameters	Values (mm)
l	30	w	15
l_1	10	w_1	6
l_2	2	w_2	6
l_3	8.1	w_f	3.5
l_g	5.5	t	0.035
h	1.52	Substrate	R03003 (lossy)

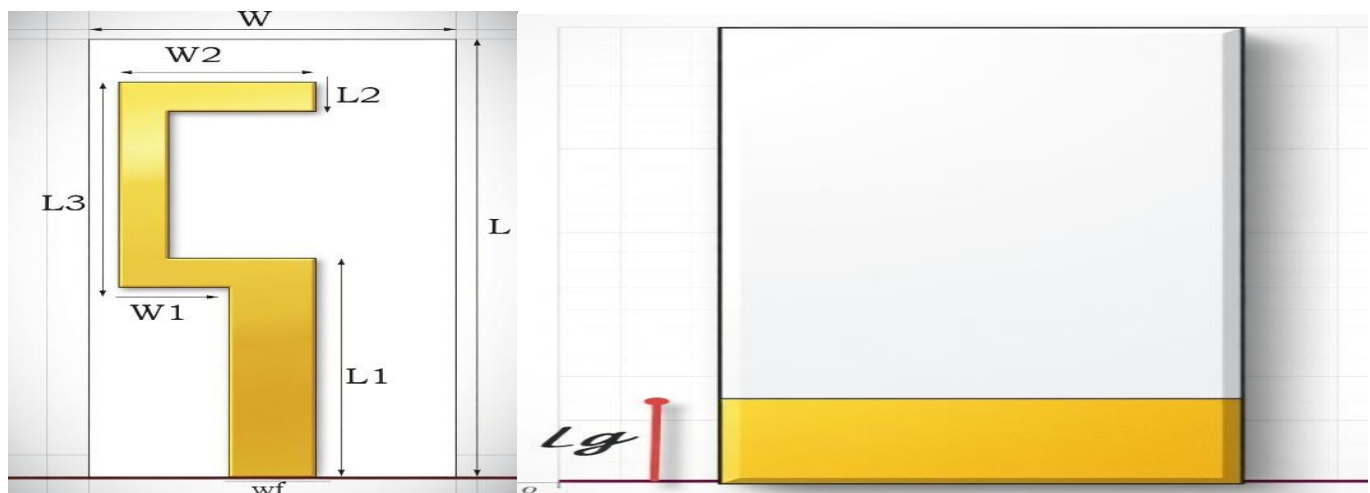


Fig 1: (a) Front view of the antenna, (b) Back view of the Antenna

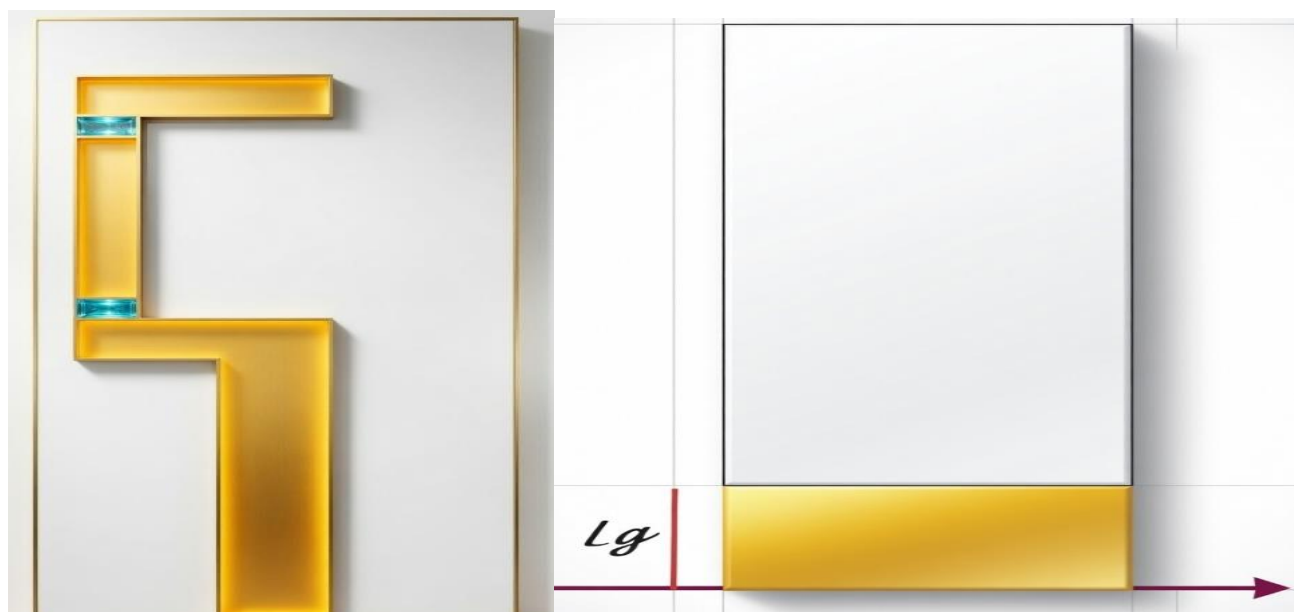


Fig 2: (a) Front view of the antenna with slot, (b) Back view of the Antenna



Fig 3: (a) Front view of the antenna with slot replaced with copper annealed (b) Back view

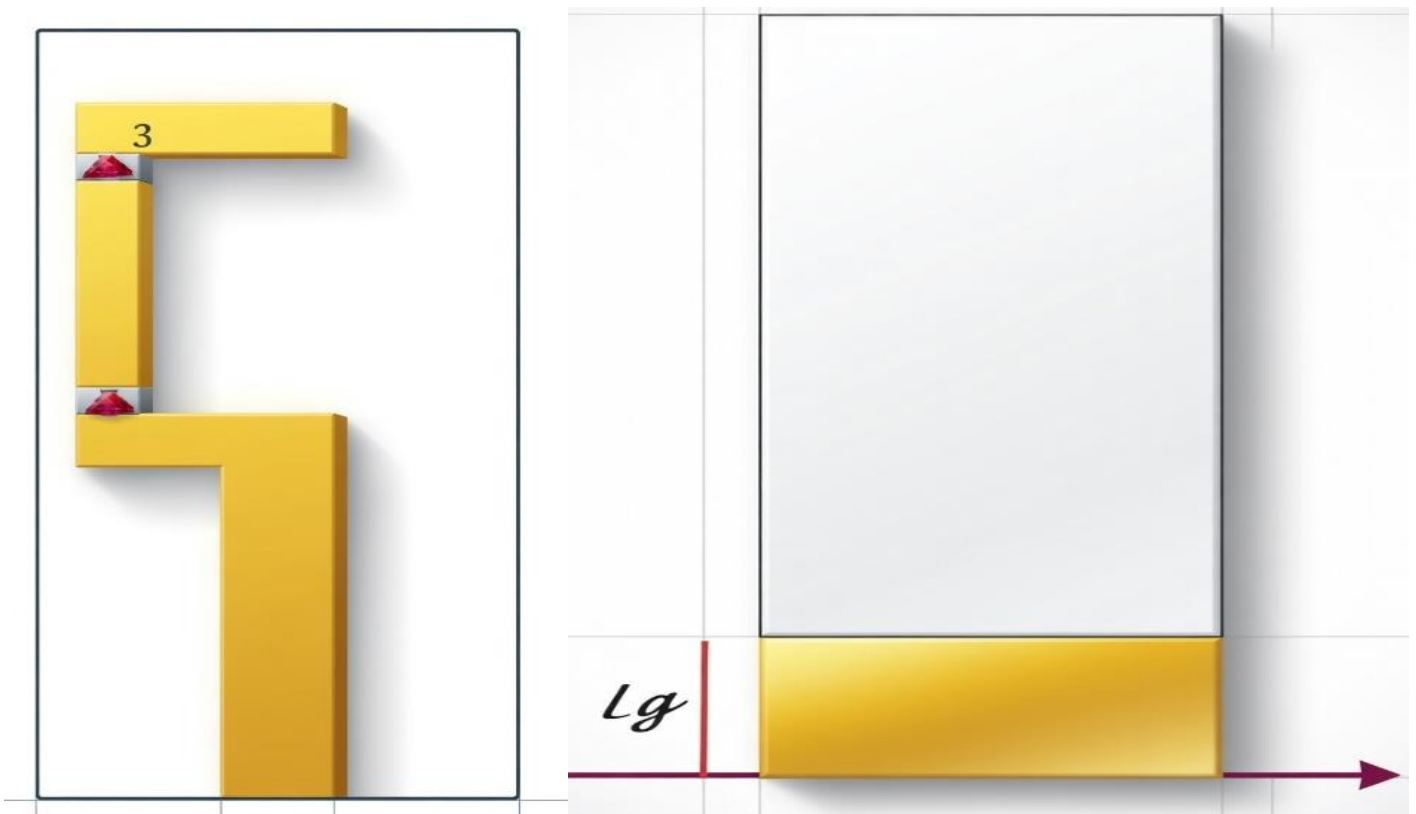


Fig 4: (a) Front view of the antenna with PIN diode switches (b) Back view of the Antenna

Switching Techniques

Figure 5 illustrates the schematic diagram of the switching configurations implemented in the CST Studio Suite simulation environment. It clearly depicts the integration of the two PIN diodes within the antenna structure, along with their respective bias connections to the DC power source. In the diagram, the terminals labeled with normal numbers (1, 2, and 3) represent the positive (anode) connections, while those marked with primes (1', 2', and 3') denote the negative (cathode) connections. This labeling facilitates a clear understanding of the forward and reverse bias states employed to achieve the desired frequency reconfigurability.

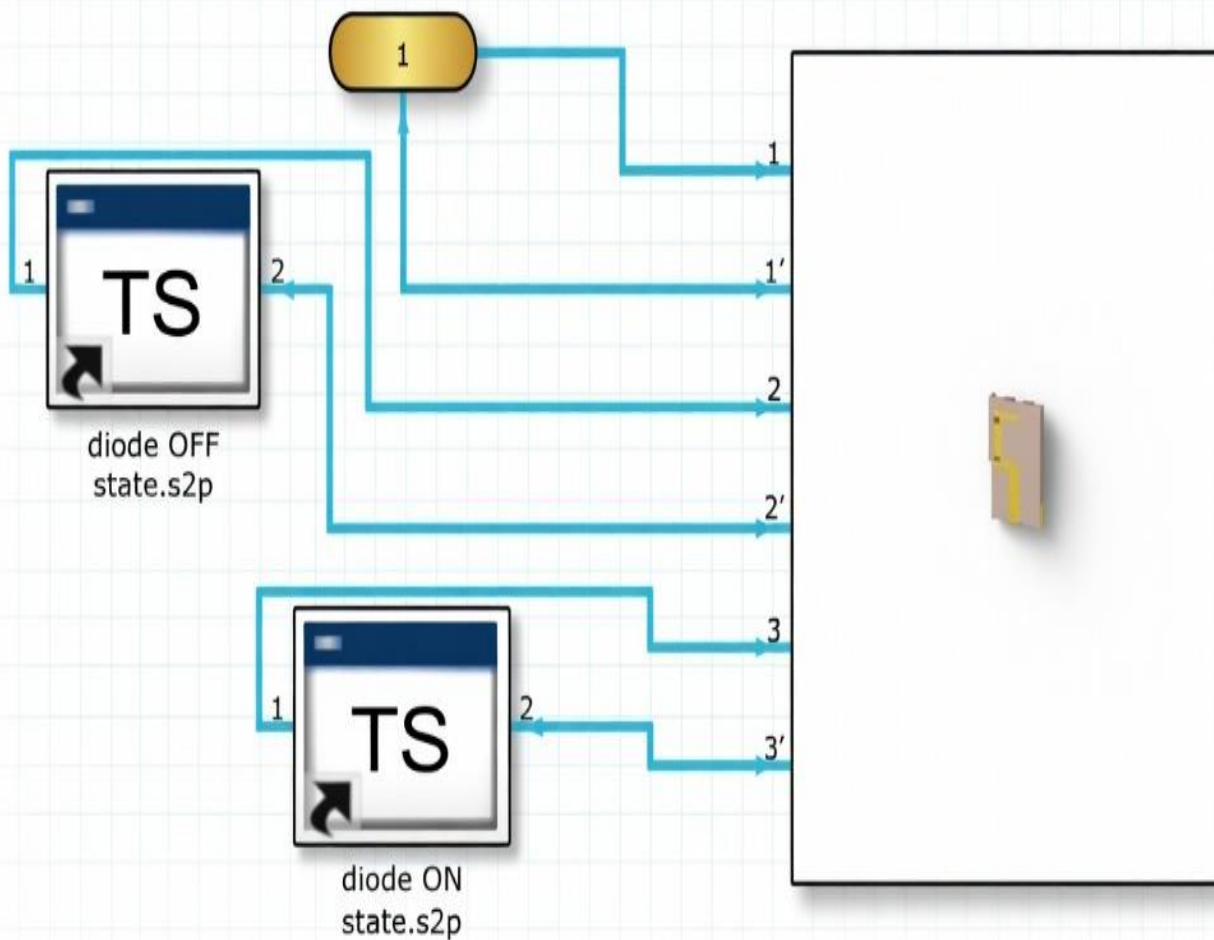


Figure 5: Schematic diagram of the switching states

RESULTS AND DISCUSSION

This section presents the simulation results and detailed performance analysis conducted to achieve effective frequency reconfigurability in the proposed microstrip patch antenna.

The obtained results are summarized and compared in Table 2, including a benchmark against the ideal switching case (modeled using perfect copper strips), as well as realistic implementations using PIN diodes both in the baseline configuration (without reflector) and with an added reflector plane. Key performance metrics, including return loss (S_{11}), realized gain, radiation efficiency, surface current distributions, E-plane and H-plane radiation patterns, are systematically evaluated and discussed.

Figure 6 illustrates the simulated reflection coefficient (S_{11}) for the reference antenna design (as originally shown in Figure 1), which features a partial ground plane, no slots, and no switches, thus exhibiting fixed dual-band resonance without reconfigurability. The antenna achieves strong resonance at 2.4 GHz and 6.3 GHz, with $|S_{11}|$ values well below -10 dB across both operating bands, indicating excellent impedance matching and broadband behavior within each resonance.

These characteristics confirm that the baseline (non-reconfigurable) design serves as a highly suitable candidate for conventional WLAN (2.4 GHz) and certain sub-6 GHz wireless applications. The subsequent sections build upon this reference performance to demonstrate how the introduction of strategically placed slots and PIN-diode-

based switching enables dynamic frequency agility while preserving acceptable impedance matching and radiation characteristics across the targeted reconfigurable modes.

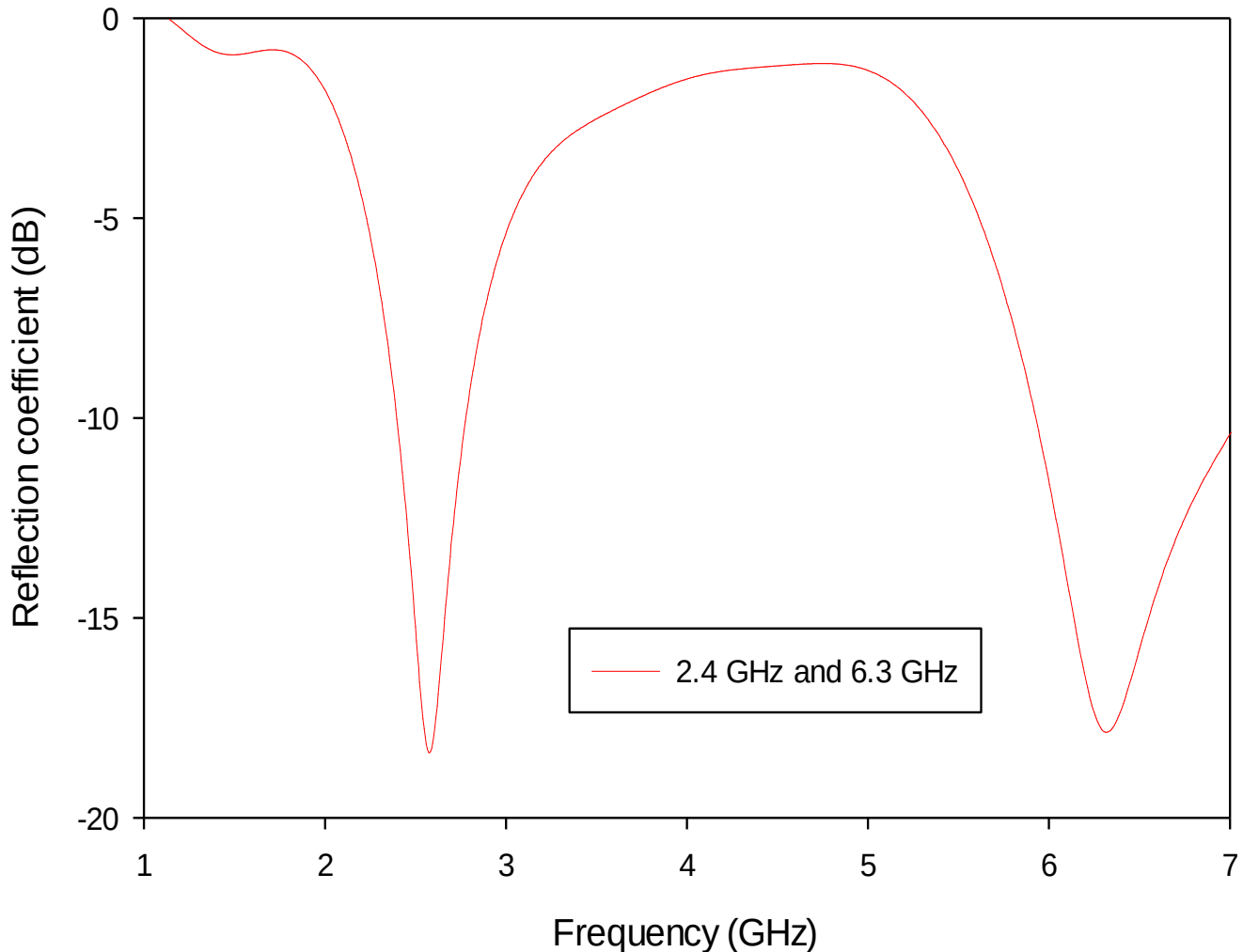


Figure 6: Return loss/Reflection Coefficient (S_{11}) of the antenna without switch

Figure 7 presents the simulated realized gain of the reference (non-reconfigurable) antenna across its operating bandwidth. The results demonstrate stable and respectable gain performance suitable for practical WLAN and sub-6 GHz applications.

The antenna achieves a peak gain of 4.2 dBi at 4.78 GHz, which lies within the upper resonant band and reflects strong radiation efficiency in that region. At the primary design frequencies, the realized gain reaches 1.98 dBi at 2.4 GHz (lower WLAN band) and 2.24 dBi at 6.3 GHz (upper band), indicating good directional performance consistent with typical compact microstrip patch antennas operating without additional gain-enhancement techniques such as reflectors or parasitic elements.

These gain values, combined with the previously discussed excellent impedance matching ($|S_{11}| < -10$ dB across both bands), confirm the suitability of the baseline design as a reliable radiator for conventional dual-band wireless applications, while also providing a solid reference point for evaluating the impact of subsequent modifications (slot introduction, switching elements, and optional reflector integration) on gain characteristics in the reconfigurable configurations.

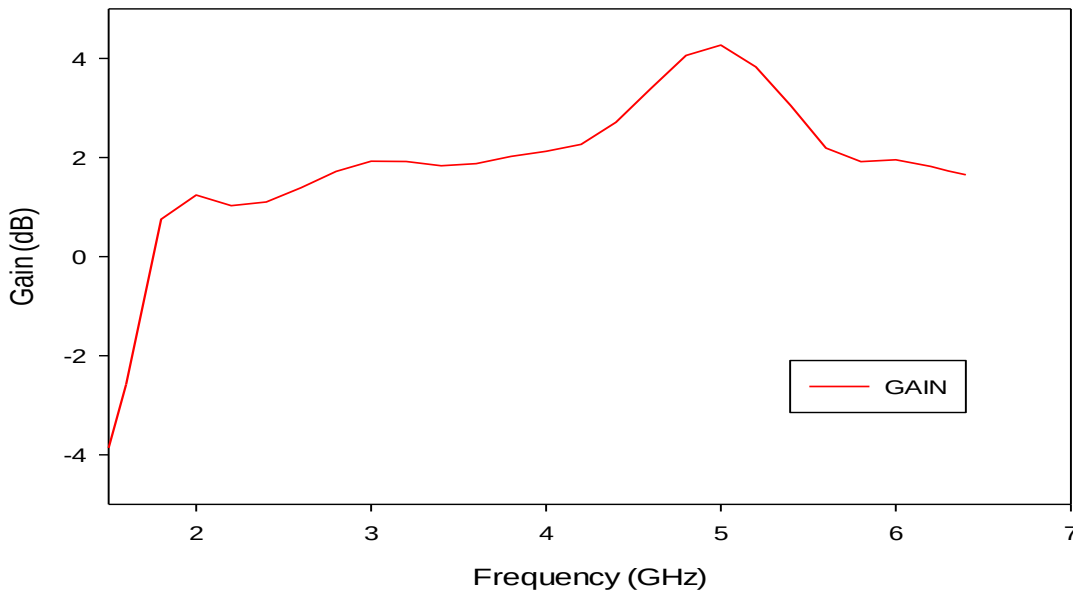


Figure 7: Gain of the antenna without a switch

Figure 8 depicts the simulated radiation efficiency of the reference (non-reconfigurable) microstrip patch antenna across its operating frequency range. The results reveal a peak radiation efficiency of 94%, achieved within the upper resonant band, indicating excellent energy conversion from input power to radiated power in that region. At the primary target frequencies, the antenna exhibits radiation efficiencies of 56% at 2.4 GHz (lower WLAN band) and 58% at 6.3 GHz (upper band). These values are respectable for a compact, single-layer microstrip design without additional efficiency-enhancement structures (such as artificial magnetic conductors or reflectors) and remain consistent with typical performance expectations for low-profile antennas intended for WLAN and sub-6 GHz wireless applications.

Combined with the previously reported excellent impedance matching ($|S_{11}| < -10$ dB) and moderate gain values in both bands, the obtained efficiency characteristics further validate the baseline antenna as a solid foundation for subsequent reconfigurable modifications. The introduction of slots, PIN diodes, and optional reflector integration in later configurations will be evaluated against these reference efficiency levels to assess any trade-offs or improvements introduced by the frequency-agility mechanism.

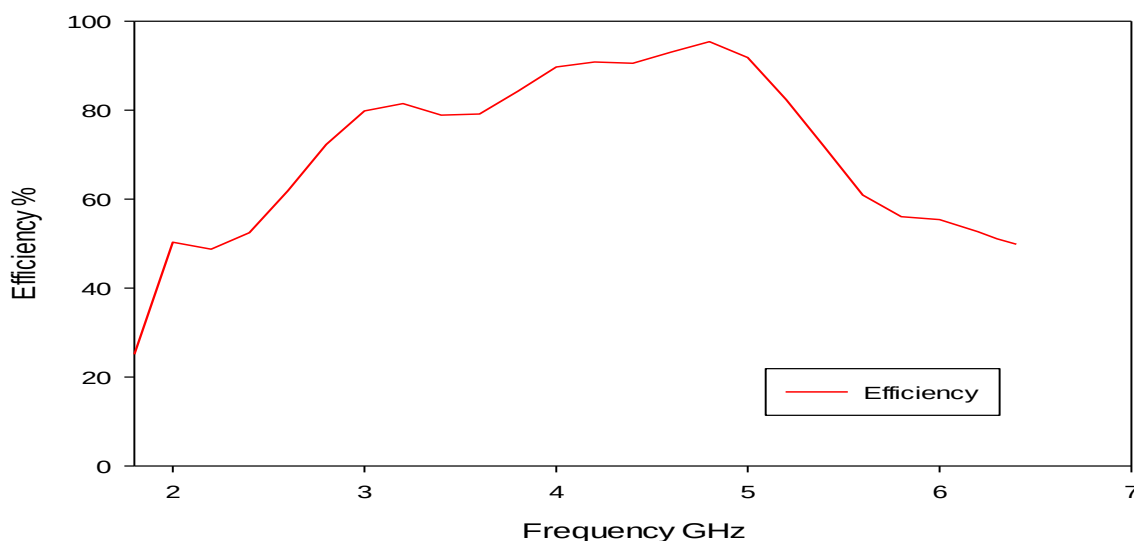


Figure 8: Efficiency of the antenna without a switch

Figure 9 illustrates the simulated far-field radiation patterns of the reference (non-reconfigurable) microstrip patch antenna in its principal planes at the resonant frequencies of interest.

In the H-plane (typically the azimuthal plane, $\phi = 0^\circ$ or 90° depending on orientation), the proposed antenna exhibits a nearly omnidirectional radiation pattern. This characteristic indicates relatively uniform radiation intensity in all in-plane directions, making the antenna well-suited for applications requiring broad azimuthal coverage, such as indoor WLAN access points, mobile devices, or IoT nodes where signals may arrive from arbitrary horizontal angles.

Conversely, the E-plane (typically the elevation plane, θ variation) displays a bidirectional radiation pattern, with the main lobes directed primarily forward and backward (or upward and downward, depending on the coordinate system and ground-plane orientation). This pattern is characteristic of conventional microstrip patch antennas and results in concentrated radiation along the broadside directions, which is advantageous for point-to-point or directed communication links while still providing acceptable coverage in the principal elevation angles.

These complementary radiation behaviors, omnidirectional in the H-plane and bidirectional in the E-plane confirming the antenna's balanced performance for typical dual-band WLAN and sub-6 GHz applications, where both wide angular coverage in the horizontal plane and reasonable directivity in the vertical plane are desirable. The patterns observed in Figure 9 serve as the baseline reference for assessing any modifications to the radiation characteristics introduced by the slot perturbations, PIN-diode switching, and optional reflector in the reconfigurable configurations discussed in subsequent sections.

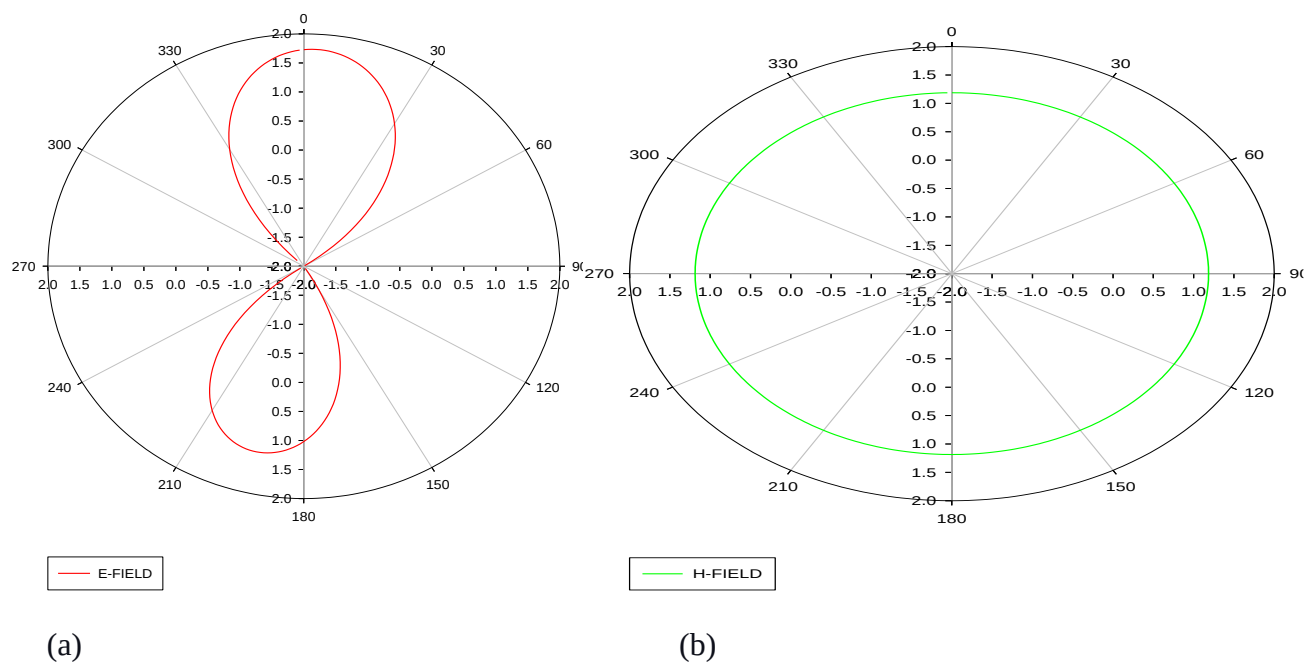


Figure 9: Radiation Pattern of the antenna (a) E-Plane (b) H-Plane

Table 2: Summary of results for the antenna in Fig. 1			
S/N	Frequency (GHz)	Gain (dBi)	Efficiency (%)
1	2.4	1.5	54
2	6.3	1.8	58

Table 2 summarizes the key performance metrics extracted from Figures 6, 7, and 8 for the reference (non-reconfigurable) antenna at its resonant frequencies, reporting reflection coefficient values ensuring $|S_{11}| < -10$

dB, along with realized gains of 1.5 dBi and 1.8 dBi, and radiation efficiencies of 54% and 58% at 2.4 GHz and 6.3 GHz, respectively.

Figure 10 presents the simulated reflection coefficient for the reconfigurable configuration (as originally shown in Figure 2), featuring a partial ground plane, strategically introduced slot, and ideal switching modeled via copper strips (ON state) and vacuum gaps (OFF state); the design achieves excellent impedance matching ($|S_{11}| < -10$ dB) across multiple resonant modes.

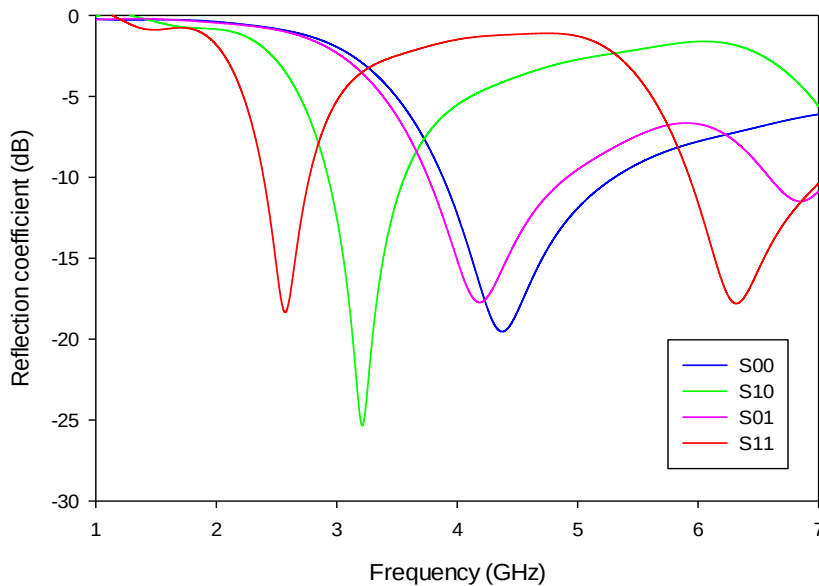


Figure 10: Return loss/Reflection Coefficient (S_{11}) of the antenna with copper annealed as a switch

The antenna gain is shown in fig. 11. The graph shows a peak gain value of 4.52 dB. The optimal gains of (2.1 dB, 1.96 dB, 1.46 dB, 1.82 dB, 1.4 dB, and 1.8 dB) at (4.37 GHz, 4.17 GHz, 6.3 GHz, 3.2 GHz, 2.4 GHz, and 6.3 GHz) resonance frequency were obtained, respectively.

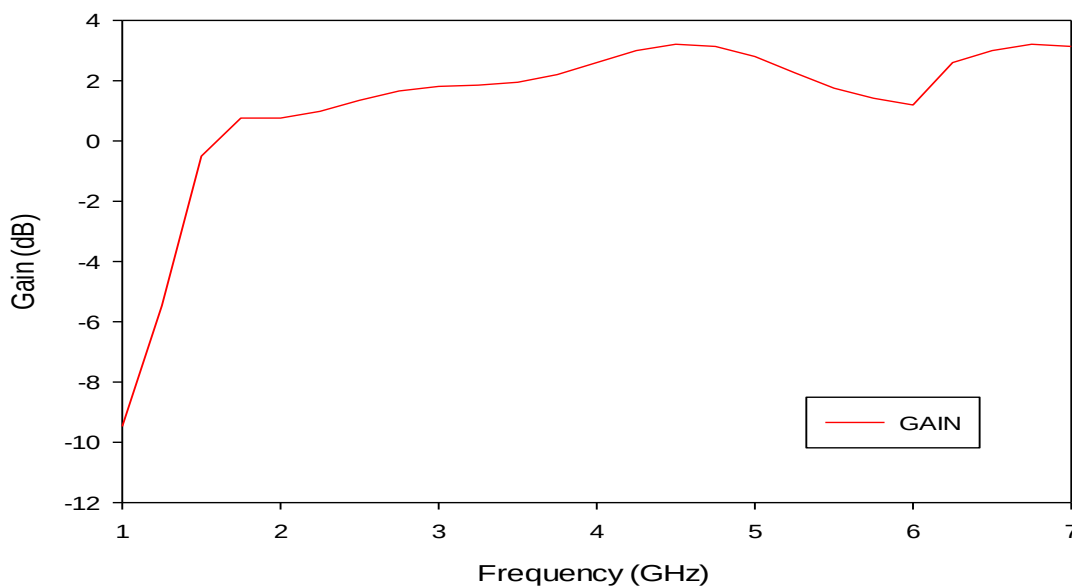


Figure: 11

Figure 11: Gain of the antenna with copper annealed as a switch

The antenna Efficiency is shown in Fig. 12. The graph below shows a peak efficiency value of 79%. The optimal efficiency of (74%, 76%, and 67%, 78% and 79%, and 67%) at (4.37 GHz, 4.17 GHz, and 6.3 GHz, 3.2 GHz, and 2.4 GHz and 6.3 GHz) resonance frequency was obtained.

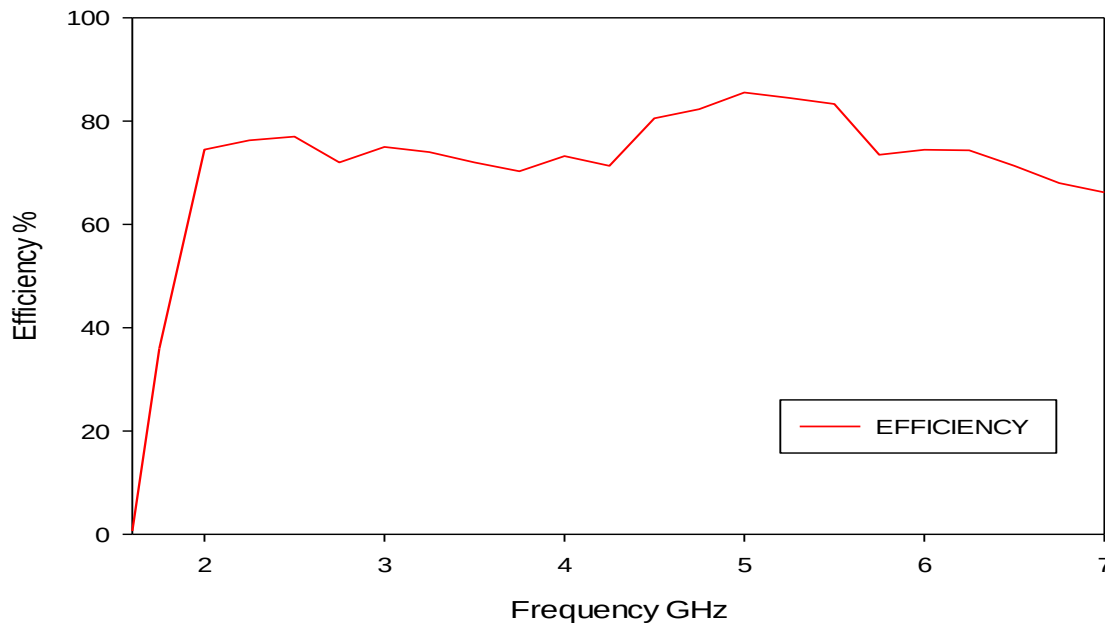
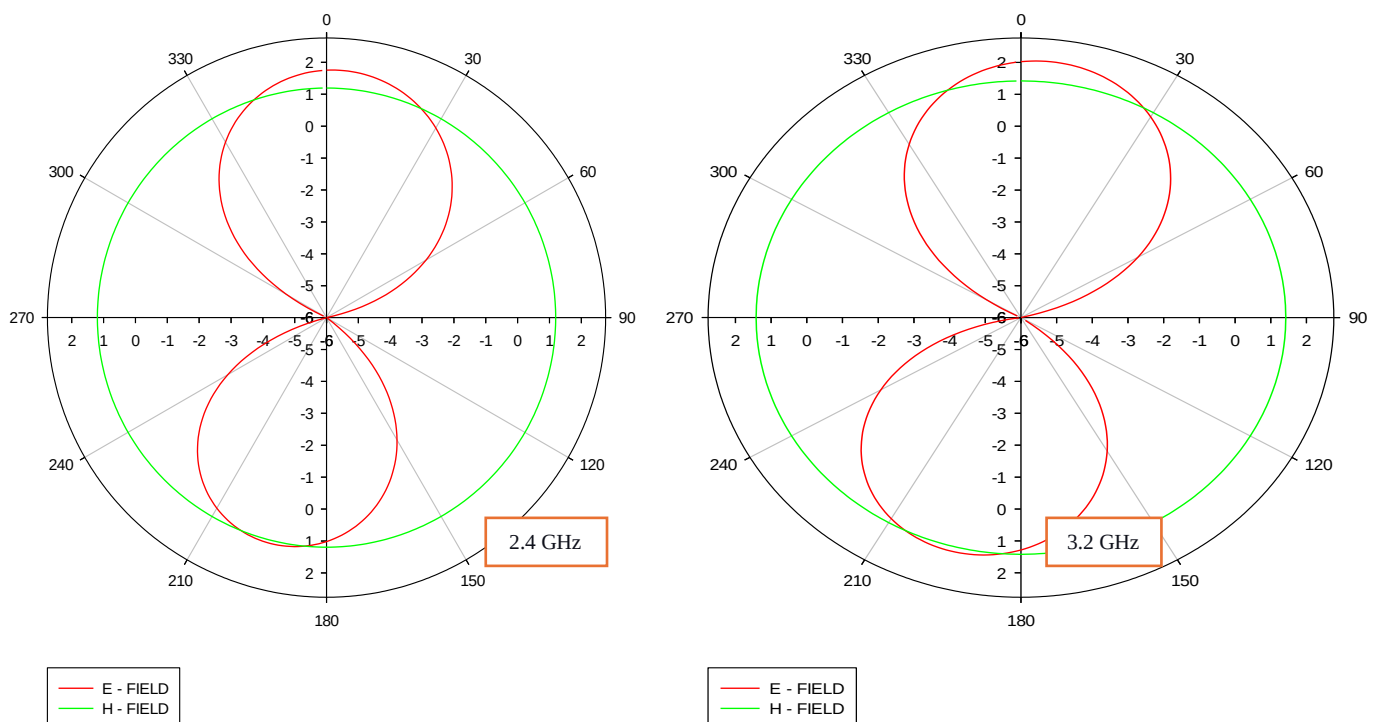


Figure 12: Efficiency of the antenna with copper annealed as a switch

From Fig.13 below, the simulated H-plane of the proposed antenna has an omnidirectional radiation pattern, which means it can radiate energy equally in all directions, whereas the E-plane has unidirectional and bidirectional radiation, which can radiate energy in only

one direction and in two directions (left and right or front and back), respectively.



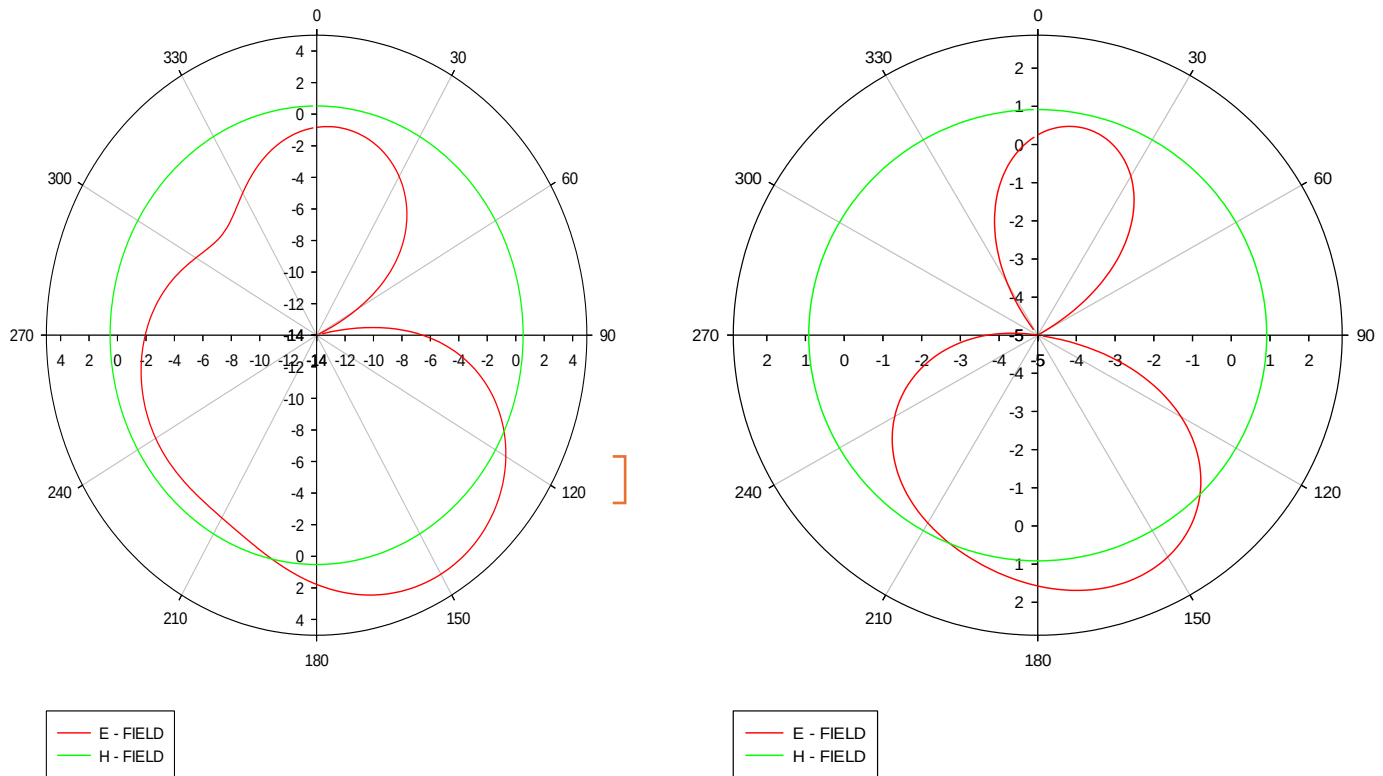


Figure 13 Radiation pattern of the antenna with copper annealed as switch **E-Plane** (b) **H-Plane**.

Table 3: Summary of results for the antenna in Fig. 3

Diode State		Resonance Frequency (GHz)	Gain (dBi)	Efficiency (%)
S1	S2			
0	0	4.37	2.6	75
0	1	4.17 and 6.8	3.2 and 3.3	79 and 66
1	0	3.23	1.9	78
1	1	2.4 and 6.3	1.6 and 3.3	80 and 78

Table 3 summarizes the simulated performance metrics, including reflection coefficient (S_{11}), realized gain, and radiation efficiency, for all resonant bands achieved in the ideal switching configurations, as extracted from Figures 10, 11, and 12. The two switches, S1 and S2, are modeled using copper strips for the ON state (1) and vacuum gaps for the OFF state (0), resulting in four distinct configurations: 00 (both OFF), 11 (both ON), 10 (S1 ON, S2 OFF), and 01 (S1 OFF, S2 ON). These combinations enable the antenna to achieve multiple resonant modes with $|S_{11}| \leq -10$ dB across the bands, demonstrating excellent impedance matching and providing a reliable benchmark for evaluating the transition to realistic PIN-diode implementations.

Figure 14 illustrates the reflection coefficient (S_{11}) of the proposed frequency-reconfigurable microstrip patch antenna when employing actual PIN diodes as switching elements (detailed in Section 3). The simulation results reveal successful reconfiguration across six resonant frequencies, comprising two single-band modes at 4.2 GHz (radio altimeter) and 2.9 GHz (military/meteorological radars), as well as two dual-band modes at 2.4 GHz, 5.6 GHz (lower and higher WLAN), and 3.5 GHz, 5.6 GHz (sub-6 GHz 5G, higher WLAN/5G). With all resonant bands maintaining $|S_{11}| \leq -10$ dB, the design confirms effective frequency agility and strong impedance matching, positioning the antenna as a promising candidate for multifunctional wireless applications, including WLAN, sub-6 GHz 5G, radio altimeters, and radar systems.

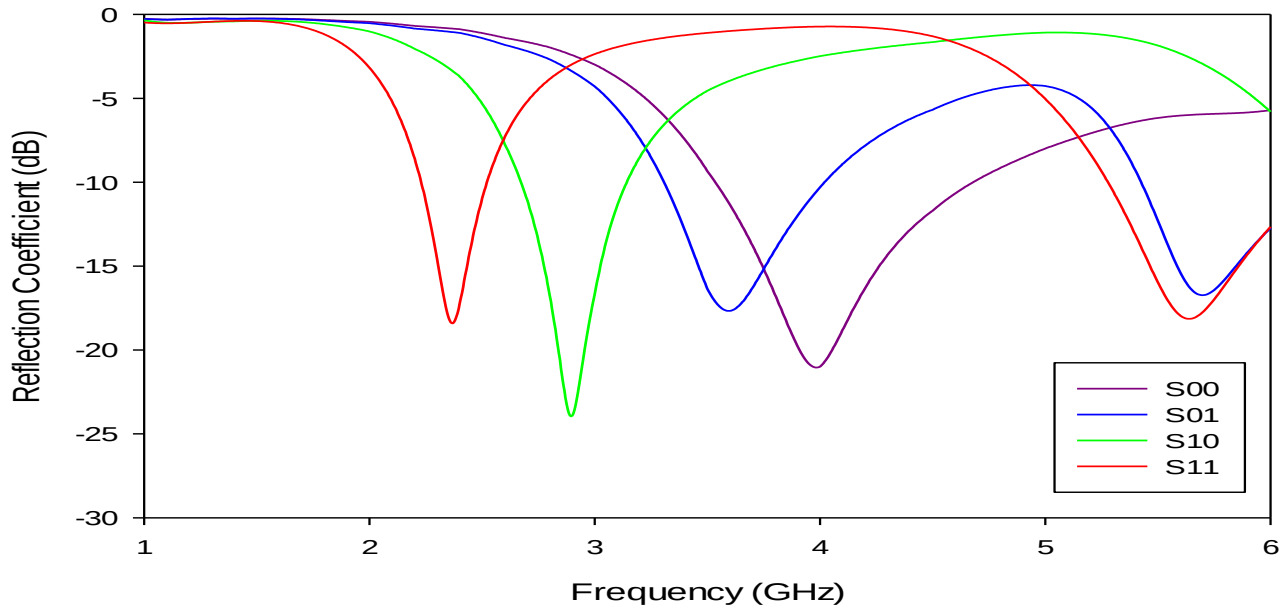


Figure 14: Reflection coefficient of the antenna with PIN diode switch

Figure 15 below shows the graph of the gain for a frequency reconfigurable microstrip patch antenna using a PIN diode as a switch, at all the resonant bands. The highest gain of 5.8 dB was recorded.

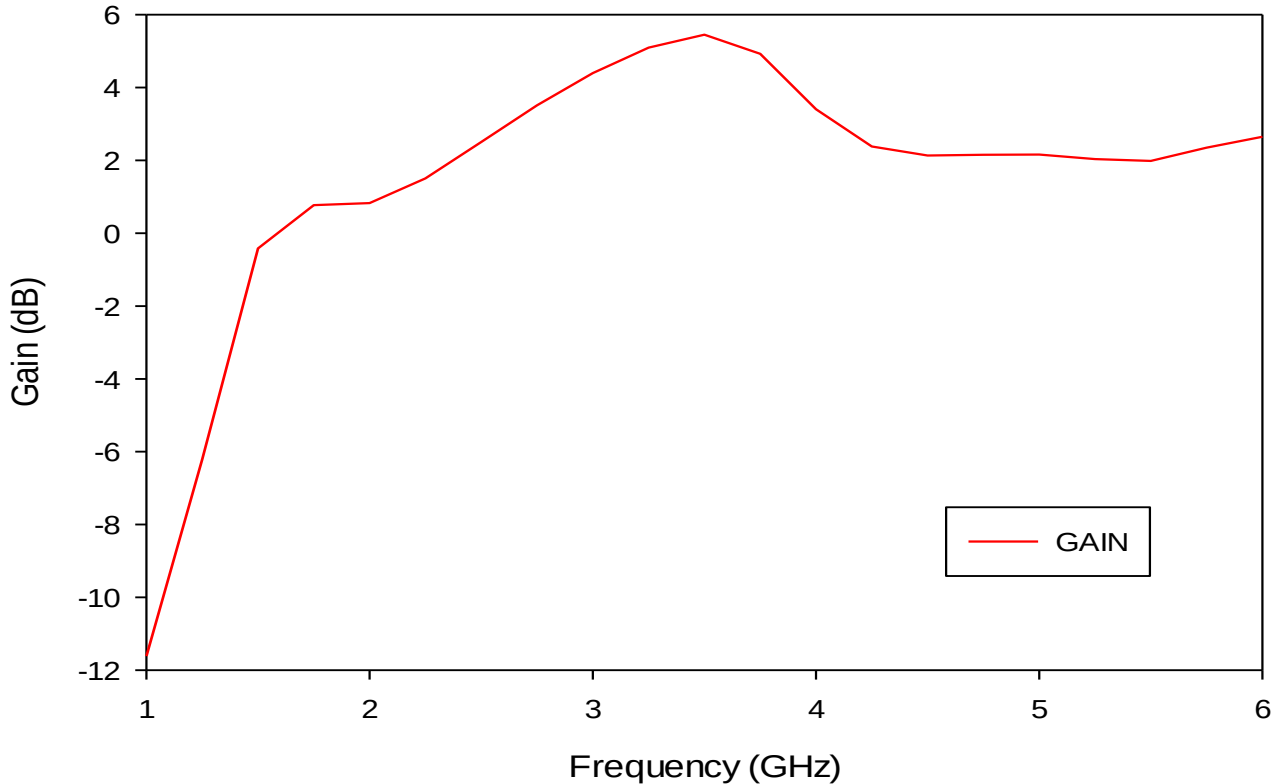


Figure 15: Gain of the antenna with PIN diode switch

Figure 17 below shows the graph of Efficiency for a frequency reconfigurable microstrip patch antenna using a PIN diode as a switch, at all the resonant bands. The highest efficiency of 85% was recorded.

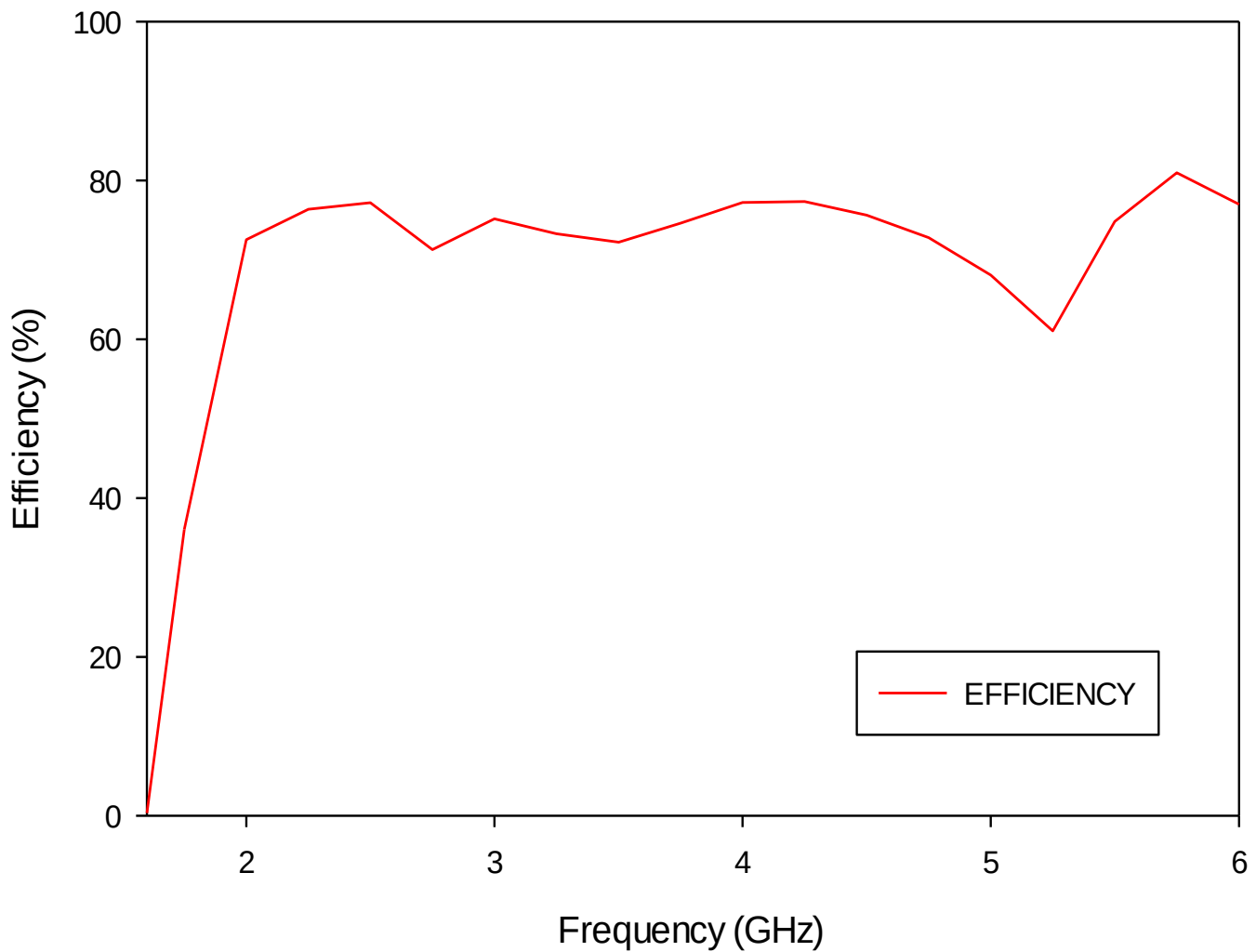
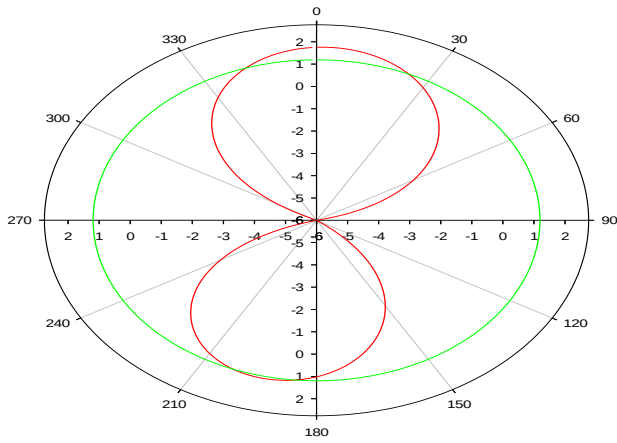


Figure 16: Efficiency of the antenna with PIN diode switch

Figure 17 presents the simulated far-field radiation patterns of the proposed frequency-reconfigurable microstrip patch antenna (with PIN diodes and optional reflector) in the principal planes across the achieved resonant frequencies.

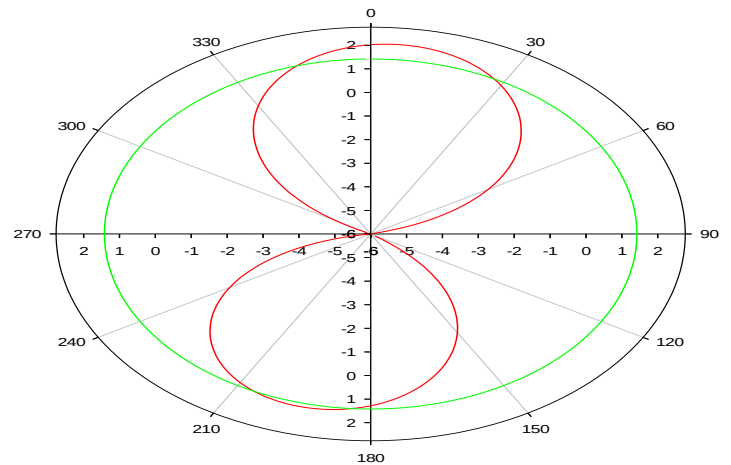
In the H-plane (azimuthal plane), the antenna maintains a nearly omnidirectional radiation pattern, characterized by a relatively uniform gain distribution in all horizontal directions. This feature ensures broad angular coverage and makes the design particularly suitable for applications requiring isotropic-like performance in the azimuthal plane, such as mobile devices, WLAN access points, IoT nodes, or indoor wireless environments where signals may arrive from arbitrary horizontal angles.

In contrast, the E-plane (elevation plane) exhibits a bidirectional radiation pattern, with the primary lobes directed forward and backward (or upward and downward, depending on the antenna orientation and ground/reflector configuration). This bidirectional behavior is typical of microstrip patch antennas and results in enhanced directivity along the broadside directions while suppressing radiation toward the back (especially when a reflector is incorporated), thereby improving front-to-back ratio and overall radiation efficiency in targeted elevation angles.



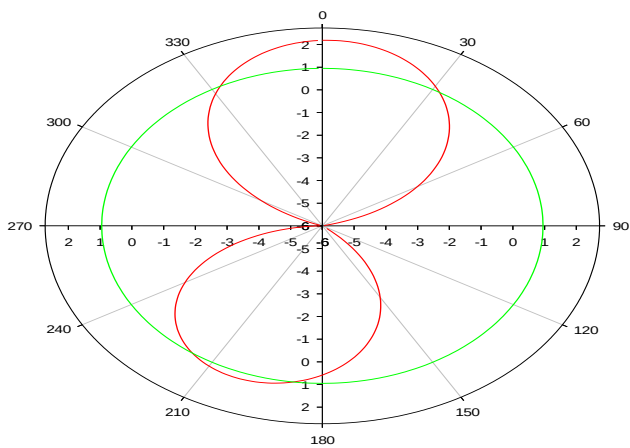
— E - FIELD
— H - FIELD

2.4 GHz



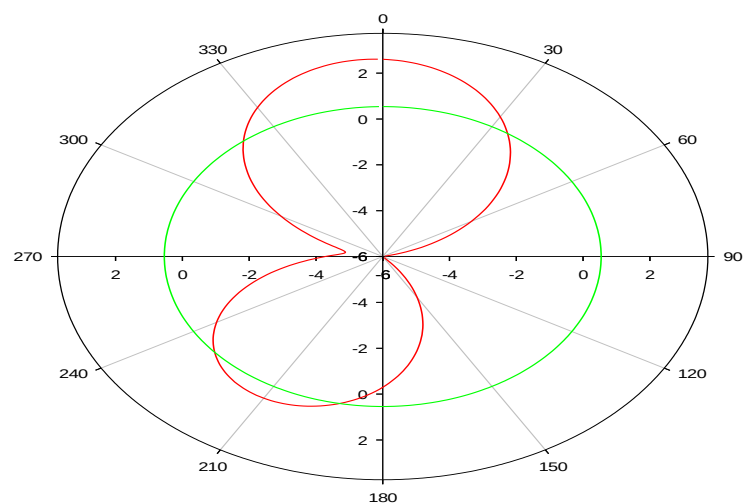
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2.9 GHz



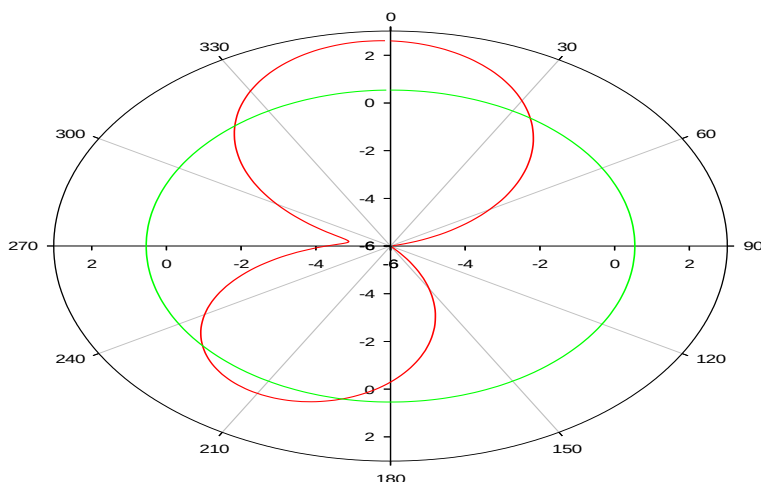
— E - FIELD
— H - FIELD

3.5 GHz



— E - FIELD
— H - FIELD

4.2 GHz



— E - FIELD
— H - FIELD

5.6 GHz

Figure17: Radiation pattern of the antenna with PIN diode switches E-Plane (b) H-Plane.

Table 4: Summary of results for the antenna in Fig. 4

Diode State		Resonance Frequency (GHz)	Gain (dBi) With reflector	Efficiency (%)
S1	S2			
0	0	4.2 GHz	2.45	78
0	1	3.5 GHz and 5.6 GHz	5.8 and 2.1	79 and 80
1	0	2.9 GHz	3.9	78
1	1	2.4 GHz and 5.6 GHz	2.3 and 2.2	78 and 80

Table 4 presents a comprehensive summary of the key performance metrics, reflection coefficient (S_{11}), realized gain, and radiation efficiency extracted from the simulation results shown in Figures 14, 15, and 16 for the proposed frequency-reconfigurable microstrip patch antenna employing PIN diodes as switching elements. The binary notation is adopted to describe the four switching configurations: 1 denotes the ON state (PIN diode forward-biased, low impedance), 0 denotes the OFF state (PIN diode reverse-biased, high impedance), yielding the combinations 00 (both OFF), 11 (both ON), 10 (first switch ON, second OFF), and 01 (first switch OFF, second ON). A notable improvement is observed when a reflector plane is introduced beneath the antenna structure: both the realized gain and radiation efficiency exhibit significant enhancements across all resonant bands compared to the baseline configuration without the reflector, while maintaining $|S_{11}| \leq -10$ dB, thereby confirming the effectiveness of the reflector in directing radiation and reducing back-lobe losses without compromising impedance matching.

The proposed frequency-reconfigurable microstrip patch antenna demonstrates several key advantages over existing works listed in Table 5. With a compact dimension of 30×15 mm² on Rogers RO3003 substrate ($\epsilon_r \approx 3.0$, low loss tangent ≈ 0.0010), it is significantly smaller than most prior designs (e.g., 50×33 mm² in [15], 100×100 mm² in [21], and 59.8×59.8 mm² in [23]), enabling better integration into space-constrained devices such as smartphones, tablets, and IoT systems. Using only a single antenna element (compared to 2–4 elements in several references like [16], [17], and [20]), it achieves six operating bands (supporting frequencies from 2.4 GHz to 6.3 GHz across multiple single- and dual-band modes for WLAN, sub-6 GHz 5G, radio altimeters, and radars), matching or exceeding the band count of most competitors (e.g., seven in [22] but over a narrower 1–5 GHz range, and six in [23] but limited to 2.3–2.68 GHz). Additionally, the realized gain range of 2.1–5.8 dBi is competitive or superior to many reported values (e.g., 3.2 dBi in [15], 1.7–3.4 dBi in [16], and 2.6 dBi in [23]), benefiting from the low-loss Rogers RO3003 substrate (which offers better efficiency, signal integrity, and thermal stability compared to higher-loss FR-4 or PDMS substrates used in most references).

Overall, the proposed work provides an excellent size-bandwidth-gain trade-off through optimized slot-based PIN-diode reconfigurability (only two switches) and strategic reflector integration, delivering greater operational versatility and compactness while maintaining strong performance metrics suitable for multifunctional modern wireless applications.

Table 5: Comparison between the proposed work and the existing work for validation

Ref	Antenna Dimension (mm)	Substrate used	Number of antennas used	Number of operating bands	Frequency Range (GHz)	Gain (dBi)
[15]	50 x 33	PTEP	1	Two	2.4-3.4	3.2
[16]	53 x 35	FR-4	2	Three	2.45-5.2	1.7-3.4
[17]	35 x 25	FR-4	4	Three	2.1-8	-
[20]	40 x 28	FR-4	3	Three	2.3-9.2	-
[21]	100 x 100	FR-4	1	Three	2.45-3.5	5.5

[22]	60 x 50	FR-4	1	Seven	1-5	-
[23]	59.8 x 59.8	PDMS	1	six	2.3-2.68	2.6
Proposed work	30 x 15	Rogers RO3003	1	six	2.4-6.3	2.1-5.8

CONCLUSION, RECOMMENDATION, AND LIMITATIONS

This study successfully demonstrates the design and simulation of a compact frequency-reconfigurable microstrip patch antenna capable of dynamically adapting its operating frequencies through controlled switching states using two PIN diodes. The proposed antenna, simulated in CST Studio Suite, achieves multiple resonant modes tailored to diverse wireless applications while maintaining a low-profile structure suitable for integration into modern portable devices.

In the all-ON switch configuration, the antenna exhibits dual-band operation at 2.4 GHz (lower WLAN) and 5.6 GHz (higher WLAN). When both switches are OFF, it resonates in a single band at 4.2 GHz, supporting radio altimeter systems. Selective switching Sw1 ON with Sw2 OFF enables single-band performance at 2.9 GHz for military and meteorological radar applications, while Sw1 OFF with Sw2 ON provides dual-band coverage at 3.5 GHz (sub-6 GHz 5G) and 5.6 GHz (higher WLAN/5G). These configurations collectively enable compatibility with WLAN standards, 5G communications, radio altimeters, military radars, and weather radar systems, offering a versatile single-antenna solution for multifunctional wireless devices such as smartphones, tablets, laptops, and IoT platforms.

A key advantage of the proposed design lies in its use of only two switches, which minimizes insertion losses and circuit complexity compared to prior works that relied on three or more switches. Furthermore, the optimized antenna geometry results in a more compact form factor while expanding the number of accessible resonant bands and supported applications relative to earlier multi-switch designs with larger footprints and limited operational flexibility.

Although this work is presently limited to full-wave electromagnetic simulations, the results highlight promising performance metrics and confirm the efficacy of the slot-based switching approach for frequency agility. Future efforts will focus on prototype fabrication, experimental validation through laboratory measurements, and potential enhancements such as further miniaturization, incorporation of additional reconfigurability mechanisms (e.g., pattern or polarization tuning), and real-world integration testing to bridge the gap toward practical deployment in next-generation wireless systems.

In conclusion, the presented frequency-reconfigurable microstrip patch antenna represents an efficient, low-complexity approach to addressing the increasing demand for multifunctional, compact radiators in emerging wireless ecosystems, paving the way for more adaptive and integrated communication solutions.

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