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A novel miniaturized frequency reconfigurable microstrip patch antenna for modern wireless applications

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Abstract: In this paper a novel miniaturized frequency reconfigurable microstrip patch antenna for wireless communication is presented. The antenna consists of a square patch and for achieving miniaturization the ground plane of the antenna is modified. The antenna incorporates two switches for achieving frequency reconfigurability. By controlling the states of the switches, the antenna exhibits three distinct operating modes, two single band (i.e. 2.42 GHz and 5.55 GHz) and a dual band (i.e. 3.77 GHz, 6.21 GHz). For the proposed antenna the reflection coefficient (S_{11}) is well below -10 dB. The proposed antenna having geometric configuration of 16 × 17 × 0.8 mm^3 is designed and simulated using CST Microwave studio. A prototype of the antenna is fabricated using low cost FR-4 glass epoxy substrate and the reflection coefficient is measured using Vector Network Analyzer. The simulated reflection coefficient for all the modes are presented and compared with the experimental data validating its usefulness for modern wireless system applications.

Keywords: Wireless, reconfigurable, microstrip, miniature, patch antenna.

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1. Introduction

The popularity of wireless technology has grown quickly, and more gadgets are adopting this revolutionary method of communication. We are surrounded by the revolution of wireless technology in everything from tablets, laptops, wearable devices, internet of things (IoT), and many more. The size of these gadgets is reducing day by day with the addition of more functionality in smaller packages, and the desire for energy-efficient solutions. With the increasing demand for compact and portable devices, antenna design engineers are challenged for designing miniaturized antennas those are capable to provide more functionality in single structure. The miniaturized reconfigurable antenna is a prominent contender in this wireless revolution.

A reconfigurable antenna has the ability of changing any of its parameters such as frequency, polarization, radiation pattern or their combination (Bharathi et al., 2017; Nazir et al., 2016). A frequency reconfigurable antenna replaces multiple antennas operating at various frequencies by a single antenna. To achieve frequency reconfigurability, the surface current distribution of antenna is modified electrically by using switches such as PIN diodes, varactors, field effect transistors and micro-electromechanical systems (MEMS) (Han et al., 2016; Hassan et al., 2017; Sharma & Tripathi, 2015; Musa et al., 2022). In Da Costa et al. (2017), Tawk et al. (2010) optically controlled frequency reconfigurable antenna using photoconductive switch is presented. The concept of ideal switch, i.e., by using perfect electric conductor (PEC) when the switch is ON and the absence for an OFF switch state is used in the literature available (Hamid et al., 2010; Liu et al., 2015; Li et al., 2013; Li & Li, 2014; Li et al., 2014a; Li et al., 2014b; Madi et al., 2012; Osman et al., 2014; Osman et al., 2015; Ojaroudi et al., 2014).

Over the past few years large number of frequency reconfigurable antennas have been reported with slots on the patch or ground plane and by using switches placed at appropriate locations to alter the surface current distribution and change the operating frequency of the antenna. These slots can have different shapes to change the physical dimensions and thereby variation in the frequency (Nazir et al., 2016). Frequency reconfigurable antenna that has fractal geometry in the form of cedar-shape is proposed (Madi et al., 2012). E-shape patch antenna with switches to reach two single and two dual band modes for military and C-band communication is discussed (Ullah et al., 2018). Circular monopole antenna with modifications able to switch between ultra-wideband (UWB) and various frequency bands is presented (Aboufoul et al., 2012; Boudaghi et al., 2012). In Shah et al. (2019), a novel shaped frequency-reconfigurable antenna is presented for six different frequency bands.

A reconfigurable slot antenna with cross polarization reduction is demonstrated in (Han et al., 2016) for two single band and two dual band modes. In (Majid et al., 2012) a compact frequency reconfigurable microstrip slot antenna with 33% reduction in size and operating from 2.2 GHz to 4.75 GHz switching at six different frequencies is proposed. Microstrip patch-slot antenna using five PIN diodes positioned in the slot to reconfigure nine different frequency bands is presented (Majid et al., 2013), while in (Majid et al., 2014) three PIN diodes used in the slot antenna operates in six different frequency bands and using back reflector the bidirectional radiation pattern at each frequency band is converted to unidirectional one. A slot dipole antenna operating in three single band, three double band and one single band states is reported (Idris et al., 2014). Khidre et al. (2015) presented a varactor loaded slot antenna where frequency ratio is tuned from 1.45 to 1.93. The antenna proposed in (Ghaffar et al., 2021) having a compact size and able to operate in four dual band modes with eight different frequencies.

Inset fed microstrip patch antenna proposed in (Nazir et al., 2016) consists of a rectangular and U-shaped patch. The antenna incorporates three PIN diodes to vary effective length, therefore, the antenna will operate at four frequency bands of wireless fidelity (Wi-Fi), worldwide interoperability for microwave access (WiMAX) and global positioning system (GPS). Liu et al. (2015) presented coplanar waveguide (CPW) fed monopole reconfigurable antenna operating in single, dual and triple band modes. A center fed frequency reconfigurable antenna with shorting rods at the edges is reported (Nguyen-Trong et al., 2017).

Monopole antenna with modifications in the ground plane and feed line is designed (Borhani et al., 2015) for Bluetooth, WiMAX and WLAN (Wireless Local Area Network) applications. Rectangular patch antenna with two meandered slots is discussed (Baruah & Bhattacharyya, 2017). To use spectrum efficiently for cognitive radio applications author (Sharma & Tripathi, 2016) proposes hybrid antenna combination of both spectrum sensing and frequency reconfigurability. In the literature available antennas for UWB communication with reconfigurable band notch function have also been proposed (Nasrabadi & Rezaei, 2016; Badamchi et al., 2014; Badamchi et al., 2014). For 4G LTE (Long Term Evolution) applications Chattha et al. (2018) presented frequency reconfigurable antenna with pattern reconfigurability. By changing the switching states of diodes placed in the rectangular ring slot at bottom plane of an antenna frequency reconfigurability is achieved (Bharadwaj et al., 2020). For handheld wireless devices a microstrip patch antenna with symmetric armed U and reversed L slots is presented (Saikia & Borah, 2023). A compact frequency reconfigurable antenna operating in single, dual and wideband operating modes for wireless applications is realized (Awan et al., 2021). For sub-6 GHz applications a frequency reconfigurable antenna incorporating two switches has been investigated (Abdulhussein et al., 2023; Gençoğlan et al., 2023).

Several designs of flexible and conformal frequency reconfigurable antennas have been reported in literature (Awan et al., 2022; Ghaffar et al., 2021; Ibrahim et al., 2023; Kumar & Mathur, 2024; Reddy et al., 2021). By integration of inbuilt filters for harmonic suppression a flexible frequency reconfigurable filtenna for global system for mobile communication (GSM), 4G long-term evolution (LTE), industrial, medical, and scientific (ISM), and 5G Sub-6 GHz band is presented (Awan et al., 2022). In Ibrahim et al. (2023) frequency selective surface is designed to improve the gain of the frequency reconfigurable antenna with flexible characteristics. A flexible antenna having small dimensions where frequency and pattern reconfiguration to cover 1.9 and 2.4 GHz bands was realized (Ghaffar et al., 2021).

In this paper we propose a miniaturized rectangular microstrip patch antenna with modifications in the ground plane for achieving frequency reconfigurability to operate at two single band modes (i.e., 2.42 GHz and 5.55 GHz) and a dual band mode (i.e. 3.77 GHz, 6.21 GHz). The overall size of the antenna is 0.129 $\lambda_0 \times 0.137\ \lambda_0 \times 0.0064\ \lambda_0$, where λ_0 is calculated at 2.42 GHz. Frequency reconfiguration is achieved by using PIN diodes working as ideal switches and placed at precise location in order to change the surface current distribution under different switching conditions. In place of switching devices copper strips of size 0.35 mm × 1 mm are used, presence of copper strips means the switch is ON and their absence indicates the switch is OFF. In order to validate the proposed design an antenna prototype has been fabricated and tested. Good agreement has been obtained between measured and simulated results. In comparison to the antennas reported in the literature, this work proposes a low profile miniaturized reconfigurable microstrip patch antenna with minimum number of PIN diodes. The proposed antenna offers size miniaturization by a factor of (λ_0/7.8).

The paper is organized as follows: Section 2 describes the design of the antenna. Section 3 presents the simulation and measured results of the proposed antenna. Finally, section 4 concludes the paper.

2. Antenna design

The geometry of the proposed reconfigurable antenna along with its structural dimensions is shown in Figure 1. The antenna is printed on FR-4 (Flame Retardant-4) substrate, which is glass-reinforced epoxy resin laminate having thickness of 0.8 mm and relative permeability of 4.4. The main reason for preferring FR-4 substrate for antenna fabrication is due to its low cost, easy availability and ease of fabrication for designing miniaturized antennas precisely. The overall size of the antenna is 16 × 17 mm^2. The antenna structure consists of a square patch of size 8 × 8 mm^2, 50 Ω microstrip feed line and modified ground plane with ideal switches for changing the resonance frequency. In the proposed structure PIN diodes are used as ideal switches; in the ON state the diode is modelled by zero impedance, i.e., continuous metal strip while in the OFF state it is modelled by infinite impedance, i.e., without metal strip. Parametric study is done in order to understand the influence of the design parameters on antenna performance. The optimized design parameters of the antenna are mentioned in Table 1.

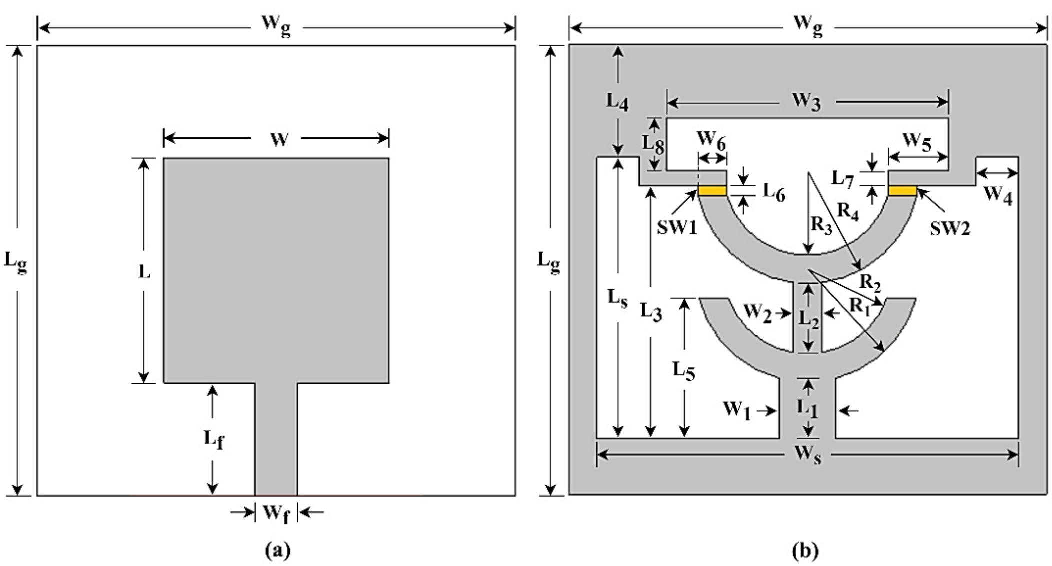


Figure 1. Proposed frequency reconfigurable microstrip patch slot antenna (a) front view and (b) back view.

Table 1. Dimensions of the proposed antenna (all values are in mm).

Parameter	Values	Parameter	Values	Parameter	Values	Parameter	Values
L	8	L_1	2	L_8	1.9	W_6	1
W	8	L_2	2.5	W_f	1.5	R_1	4
L_g	16	L_3	9	W_1	2	R_2	3
W_g	17	L_4	4	W_2	1	R_3	3
L_f	4	L_5	5	W_3	10	R_4	4
L_s	10	L_6	0.35	W_4	1.5		
W_s	15	L_7	0.5	W_5	2.13		

The design evolution steps of the proposed antenna are shown in Figure 2. At first a rectangular slot of size 15 mm x 10 mm is cut in the ground plane (Figure 2(a)). To this design a pair of U-shaped structures that has specific dimensions is printed inside the ground slot as shown in Figure 2(b) resulting in antenna operating at 2.39 GHz with S_{11} = -16.58 dB. A rectangular slot in addition with two L-shaped structures are added as depicted in Figure 2(c), which results in the antenna operating at 2.42 GHz with S_{11} = -26.98 dB. By using copper strips of size ($L_6 \times W_6$) as ideal switch results in a frequency shift at 5.55 GHz as seen in Figure 2(d). Hence, without PEC the antenna resonates at 2.42 GHz and with PEC it resonates at 5.55 GHz. As can be seen in Figure 2(e), with switch SW2 is ON the antenna exhibits dual band characteristic at 3.77 GHz and 6.21 GHz. Figure 3 shows the variation in the frequency as the proposed antenna evolves from the initial to final state.

For reconfiguration of the antenna two ideal switches are used, different states of the switches result in 4 different modes of operation. Two modes have similar results (i.e., when one of the switches is ON and the other one is OFF); therefore, three modes have been considered. Table 2 summarizes the different operating modes and the switching states of the PIN diode at each mode. In mode 1 switch SW1 and SW2 are ON, the antenna resonates at 5.55 GHz (5.07-6.0 GHz, BW = 16.8%) covering the 5150-5350 MHz, 5470-5725 MHz and 5725-5875 MHz frequency bands included by Indian government for Wi-Fi services in the 5 GHz band. In mode 2 both the switches are OFF, the antenna resonates at 2.42 GHz (2.39-2.44 GHz, BW=2.07%) Wi-Fi band. When the SW1 switch is OFF and SW2 is ON (Mode 3), the antenna has dual band operation with resonance at 3.77 GHz (3.72-3.83 GHz, BW=2.91%) n78 band and 6.21 GHz (5.85-6.54 GHz, BW=11.14%) n96 band.

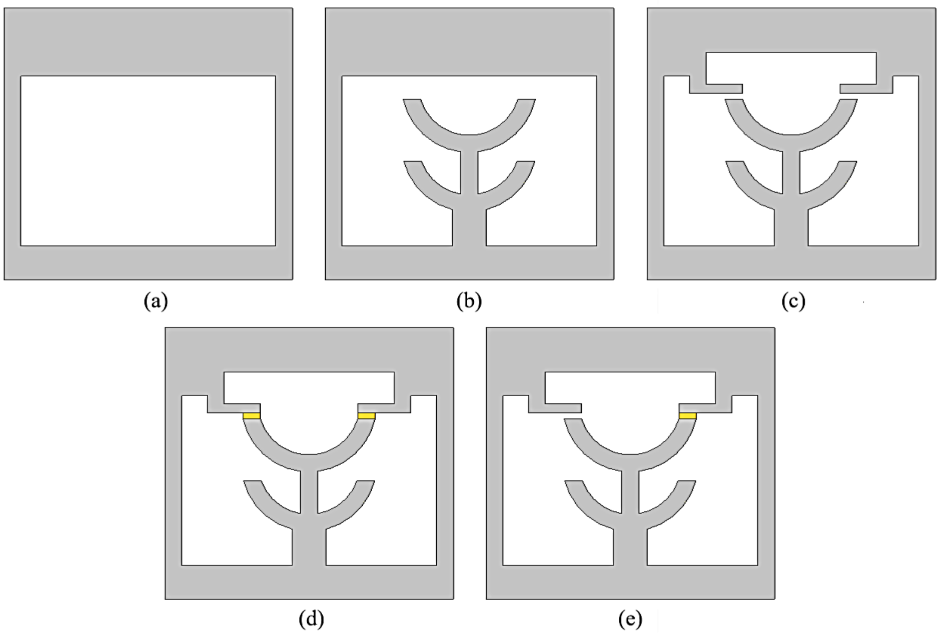


Figure 2. (a) Ordinary microstrip slot antenna, (b) with double U-shaped structures, (c) proposed antenna structure without PEC, (d) proposed antenna structure with PEC and (e) proposed antenna structure with single PEC.

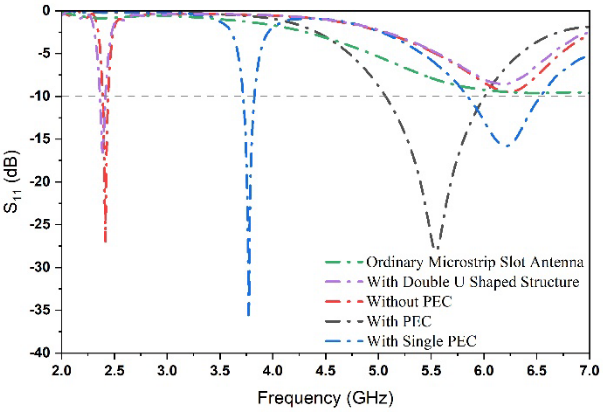


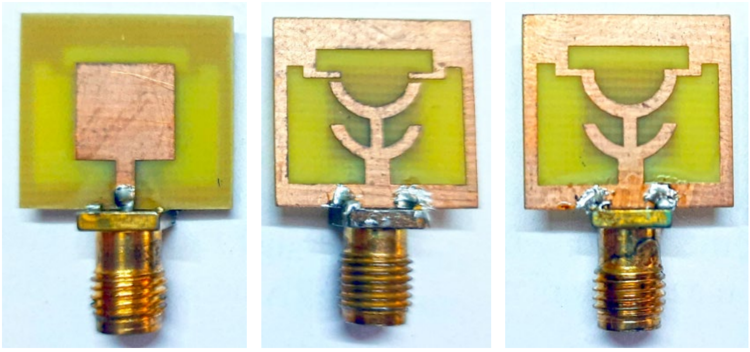
Figure 3. Simulated Reflection coefficient of antenna for various structures shown in Figure 2.

Table 2. Operating modes of switches and resonance frequency.

Operating Mode	Switch Status		Resonance Frequency (GHz)
	SW1	SW2	
Mode 1	ON	ON	5.55
Mode 2	OFF	OFF	2.42
Mode 3	OFF	ON	3.77 and 6.21

3. Results and discussions

CST microwave studio software is used to analyze and evaluate the performance of the proposed prototype. To demonstrate the functionality of the proposed frequency reconfigurable antenna, a prototype was fabricated on FR-4 substrate that has dielectric constant, ε_r of 4.4 and height of 0.8 mm same as the simulations. The photographs of the fabricated antenna are depicted in Figure 4. For practical applications, an antenna must have S_{11} values less than -10 dB, which shows the antenna is properly matched to the transmission line. The reflection coefficient (S_{11}) measurements are done using Rohde & Schwarz ZVL13 Vector Network analyzer. The measured and simulated S_{11} parameters of the proposed antenna are shown in Figure 5. As can be seen, good correlation between the measured and simulated results is obtained. The comparison between the simulated and measured reflection coefficient (S_{11}) in dB is tabulated in Table 3. The small variation may be due to the tolerances of the fabricated antenna. Thus, the proposed antenna is capable to operate at two single band modes (i.e., 2.42 GHz and 5.55 GHz) and a dual band mode (i.e., 3.77 GHz, 6.21 GHz), with S_{11} less than -10 dB.



(a) (b) (c

Figure 4. Fabricated prototype (a) top view, (b) bottom view (without PEC) and (c) bottom view (with PEC).

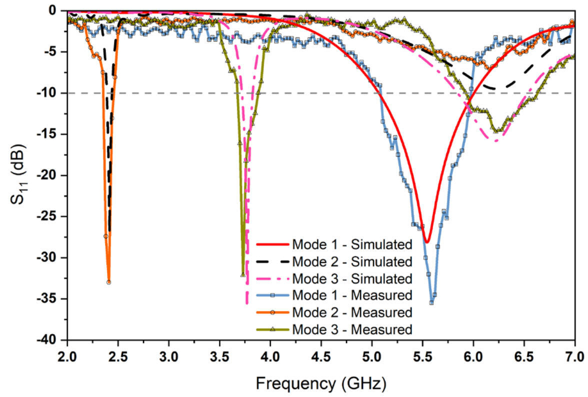


Figure 5. Simulated and measured reflection coefficient (S_{11}) of the antenna for various operating modes.

Table 3. Comparison of simulated and measured parameters of the proposed antenna.

Operating Mode	Simulated			Measured		
	Resonance Frequency (GHz)	S_{11} (dB)	Frequency Range (GHz)	Resonance Frequency (GHz)	S_{11} (dB)	Frequency Range (GHz)
Mode 1	5.55	-28.14	5.07 to 6.01	5.59	-35.48	5.08 to 5.98
Mode 2	2.42	-26.98	2.39 to 2.44	2.41	-22.99	2.36 to 2.47
Mode 3	3.77	-35.56	3.72 to 3.83	3.73	-32.12	3.67 to 3.88
	6.21	-15.81	5.84 to 6.54	6.33	-14.70	5.92 to 6.64

An antenna's VSWR (Voltage Standing Wave Ratio) is an important parameter used to assess its performance. It is a measure of how well a particular antenna matches the feed line that connects to it. For most antenna applications a VSWR value below 1.5 is considered as ideal. Figure 6 illustrates the simulated VSWR curves for various operating modes of the antenna. In the simulation, the VSWR values at 2.42, 3.77, 5.55 and 6.21 GHz is 1.09, 1.03, 1.08 and 1.39 respectively. As the corresponding values of VSWR are less than 1.5 which ensure optimal performance of the antenna for all the operating modes.

The surface current distributions of the antenna at four resonant frequencies is illustrated in Figure 7. It can be seen from Figure 7 that the surface current distribution on the patch and ground plane both affects the resonance frequency of the antenna in different ways. At 2.42 and 3.77 GHz the surface current distribution on the patch is very strong while at 5.55 and 6.21 GHz there is a negligible current density on the patch.

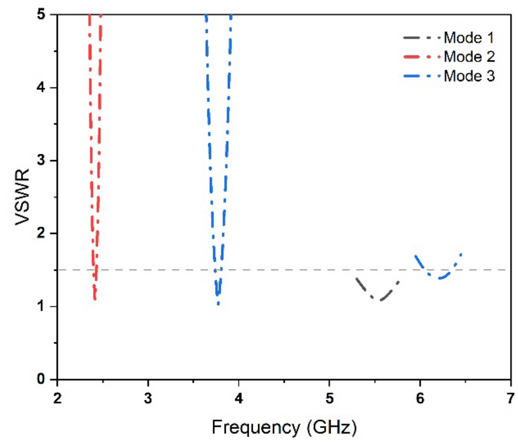


Figure 6. Simulated VSWR of the antenna for various operating modes.

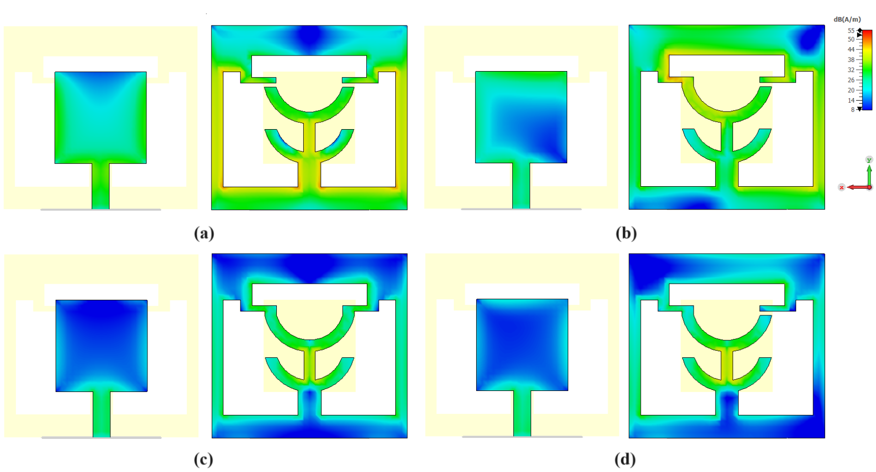
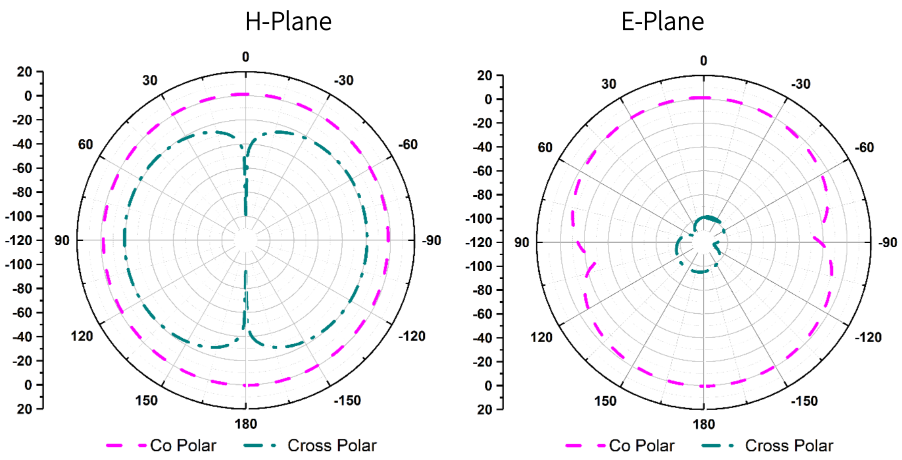


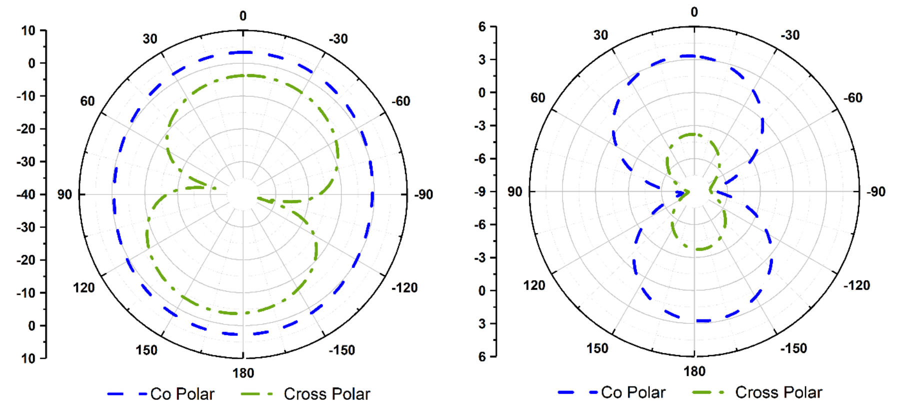
Figure 7. Surface current distribution on the patch and ground layer at (a) 2.42 GHz, (b) 3.77 GHz, (c) 5.55 GHz and (d) 6.21 GHz.

The simulated results of the normalized radiation patterns of the proposed antenna including the co-polarization and cross-polarization in the H-plane and E-plane at the various operating frequencies is shown in Figure 8. As observed in Figure 8 the proposed antenna has nearly omni-directional radiation patterns in the H-plane and in E-plane the radiation pattern is bidirectional.

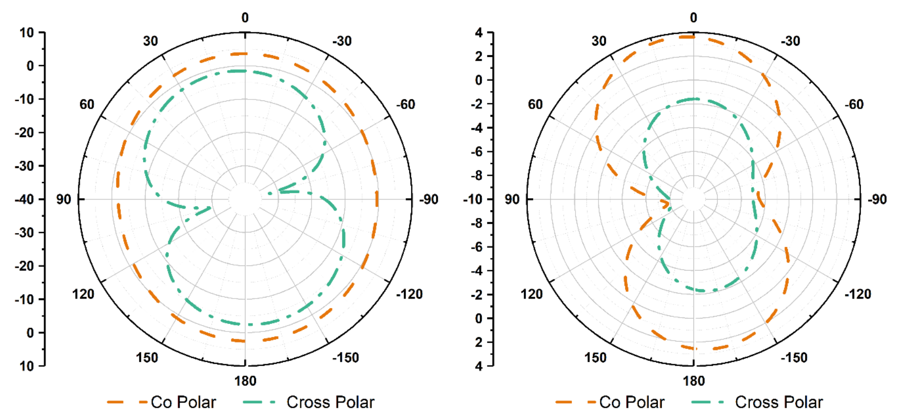
Figure 9 illustrate the simulated gain for the three operating modes of the antenna. The gain values of the proposed antenna at 2.42 GHz, 3.77 GHz, 5.55 GHz and 6.21 GHz are -5.42 dBi, 1.45 dBi, 2.58 dBi and 2.66 dBi, respectively.



(a)



(b)



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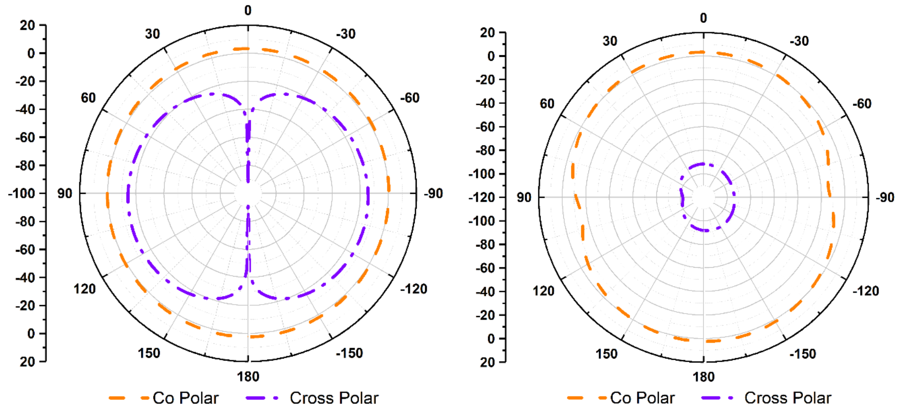

(d)

Figure 8. Simulation results of normalized radiation patterns for H-plane and E-plane at (a) 2.42 GHz, (b) 3.77 GHz, (c) 5.55 GHz and (d) 6.21 GHz.

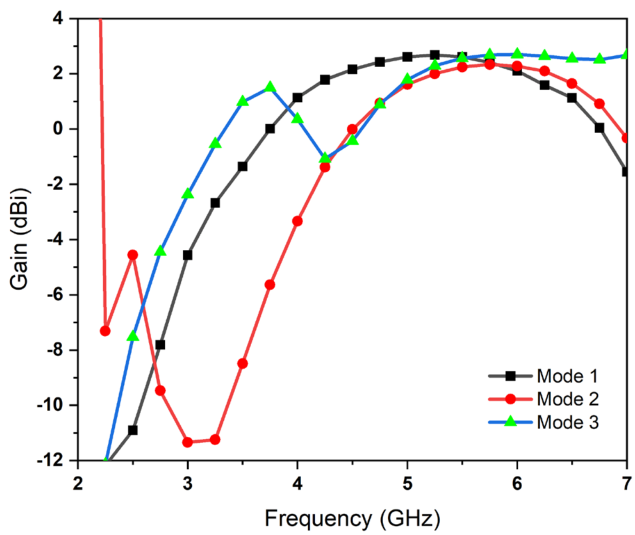

Figure 9. Simulated gain of the antenna for various operating modes.

Table 4 compares the fundamental properties of the proposed antenna with other related works. In addition to its innovative ground plane design for antenna miniaturization, the antenna offers frequency reconfigurability, which is a major advantage when it comes to wireless applications. As can be seen the proposed antenna offers size miniaturization by a factor of (λ_0/7.8), and by using 2 switches, it operates in three different operating modes (two single-band and one double-band) with sufficient bandwidth and peak gain of 2.66 dBi.

4. Conclusions

A novel miniaturized frequency reconfigurable microstrip patch antenna with modified ground plane is proposed. For achieving frequency reconfigurability two PIN diodes are used as switch and are placed at proper locations to modify the surface distribution of the antenna. Antenna prototype has been designed and simulated by considering PIN diode working as an ideal switch and represented by PEC. The antenna is fabricated, and the results are compared and validated. The results show that by changing the operating modes of the PIN diodes, the antenna provides frequency reconfigurability at two single band modes (i.e., 2.42 GHz and 5.55 GHz) and a dual band mode (i.e. 3.77 GHz, 6.21 GHz) with a peak gain of 2.66 dBi. Future research will focus on replacing the ideal PIN diodes with practical ones. The antenna is small, has a simple structure and is low cost, which lends itself well to wireless applications.

Table 4. Performance comparison of the proposed work with previous work.

Ref.	Dimension (mm^3)	Number of Switches	Operating modes	Resonance frequencies (GHz)	Operational bandwidth (MHz)	Gain (dBi)
(Hassan et al., 2017)	30×28.4×0.508	2	4	4.2/ 4.3/ 5.1/ 5.5/ 7.5	630/ 600/ 700/ 1000/ 700	2.96/ 2.98/ 4.04/ 4.27/ 2.57 (Gains are in dB)
(Liu et al., 2015)	43×40×1.6	4	3	2.6/ 2.7/ 4/ 5.27/ 6/ 8.5	540/ 580/ 900/ 440/ 670/ 1100	3.38/ 3.61/ 4.95/ 3.69/ 4.2/ 4.32
(Ullah et al., 2018)	40×35×1.6	2	4	2.45/ 3.59/ 4.5/ 5.2/ 6.22/ 6.27	430/ 1090/ 1045/ 2210/ 1125/ 847	2.02/ 2.65/ 2.84/ 2.05/ 4.31/ 4.25
(Aboufoul et al., 2012)	50×50×1.52	3	3	2.4/ 3.3/ 4.2/ 5.4	500/ 600/ 1000/ 900	2.2/ 2.3/ 2.7/ 3.9
(Shah et al., 2018)	33×16×1.6	3	4	2.1/ 2.4/ 3.5/ 4.1/ 4.8/ 5.2	196/ 321/ 752/ 485/ 2003/ 698	1.85/ 2.21/ 2.38/ 2.75/ 3.26/ 3.46
(Majid et al., 2012)	50×46×1.52	5	6	3.12/ 3.42/ 3.75/ 4.06/ 4.42/ 4.77	370/ 360/ 360/ 360/ 370/ 380	Average simulated gain is 4.1 dBi
(Borhani et al., 2015)	20×20×0.8	3	3	2.4/ 3.5/ 5.2	210/ 400/ 580	Not reported
(Bharadwaj et al., 2020)	30×30×0.762	2	3	3.8 / 4.5/ 5/ 5.9/	330/ 790/ 620/ 100	3.31/ 3.9/ 3.8/ 4.64
(Saikia et al., 2023)	35×40×1.6	3	6	4.36/ 4.47/ 4.96/ 5.66/ 5.81/ 6.01	370/ 610/ 410/ 390/ 410/ 540	6.92/ 6.95/ 6.58/ 8.09/ 7.53/ 8.17 (Gains are in dB)
(Abdulhussein et al., 20231)	30×20×1.6	2	3	2.7/ 3.67/ 4.55/ 4.8	187/ 866/ 1202/ 952	Not reported
(Gençoğlan et al., 2023)	22×16×1.6	2	3	2.09/ 2.15/ 3.16/ 4.3/ 4.8/ 5.2/ 5.3	30/ 30/ 70/ 450/ 710/ 120/ 380	Not reported
This Work	16×17×0.8	2	3	2.42/ 3.77/ 5.55/ 6.21	50/ 110/ 940/ 700	-5.42/ 1.45/ 2.58/ 2.66

Conflict of interest

The authors have no conflict of interest to declare.

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