

Frequency Reconfigurable Antenna for Multi Standard Wireless and Mobile Communication Systems

Ikhlas Ahmad¹, Haris Dildar¹, Wasi Ur Rehman Khan¹, Sadiq Ullah¹, Shakir Ullah¹,
Mahmoud A. Albreem², Mohammed H. Alsharif³ and Peerapong Uthansakul^{4,*}

¹Department of Telecommunication Engineering, University of Engineering & Technology, Mardan, 23200, Pakistan

²Department of Electronics and Communications Engineering, A'Sharqiyah University, Ibra 400, Oman

³Department of Electrical Engineering, College of Electronics and Information Engineering,
Sejong University, Seoul, 05006, Korea

⁴School of Telecommunication Engineering, Suranaree University of Technology, Nakhon Ratchasima, Thailand

*Corresponding Author: Peerapong Uthansakul. Email: uthansakul@sut.ac.th

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Abstract: In this paper, low profile frequency reconfigurable monopole antenna is designed on FR-4 substrate with a compact size of $30 \text{ mm}^3 \times 20 \text{ mm}^3 \times 1.6 \text{ mm}^3$. The antenna is tuned to four different modes through three pin diode switches. In Mode 1 (SW1 to SW3 = OFF), antenna covers a wideband of 3.15–8.51 GHz. For Mode 2 (SW1 = ON, SW2 to SW3 = OFF), the proposed antenna resonates at 3.5 GHz. The antenna shows dual band behavior and covers 2.6 and 6.4 GHz in Mode 3 (SW1 and SW2 = ON, SW3 = OFF). The same antenna covers three different bands of 2.1, 5 and 6.4 GHz when operating in Mode 4 (SW1 to SW3 = ON). The proposed antenna has good radiation efficiency ranges from 70%~84%, providing adequate average gain of 2.05 dBi in mode 1, 1.87 dBi in mode 2, 1.4–1.75 dBi in mode 3 and 1.05–1.56 dBi in mode 4. The achieved impedance bandwidths at respective frequencies ranges from 240 to 5000 MHz. The Voltage Standing Waves Ratio (VSWR) of less than 1.5 is achieved for all operating bands. To validate the simulation results, the proposed antenna is fabricated and experimentally tested in antenna measurement laboratory. Due to its reasonably small size and support of multiple bands operation, the proposed antenna can be used in modern communication systems for supporting various applications such as fifth generation (5G) mobile and wireless local area networks (WLAN).

Keywords: Reconfigurable antenna; pin diode; communication systems; 5G; WLAN

1 Introduction

The fifth generation (5G) of mobile communication operating in the sub-6 GHz frequency band is aimed for faster and reliable communication services with an enhanced network capacity. With the advancement of wireless communication technology requirement of multiple wireless services in a single device has increased significantly, so conventional antenna fails to meet



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this new requirement of wireless communication systems. To meet the demands, an antenna is designed which has an ability to switch its characteristics according to the requirements. Such antenna is called a reconfigurable antenna [1]. Reconfigurable antennas are used for different wireless applications that operate in a wide range of frequency as they have proved to be very useful in completing new requirements of the system. Reconfigurable antennas can alter their behavior according to the requirements. They have ability to deliver the same performance as that of multiple antennas without increasing the size which would have occurred in case of using multiple antennas [2]. There are three basic types of reconfigurable antennas which include Frequency, Pattern, and polarization reconfigurable antennas. Frequency reconfigurable antennas provide frequency tuning over desired frequency bands and efficient utilization of spectrum [3]. Pattern reconfigurable antennas direct their radiation pattern towards a desired direction and are a fundamental concept for beam steering in the future mobile networks. Pattern reconfigurable antennas with beam reconfigurability can also be employed in Multiple-Input Multiple-Output (MIMO) services [4]. Polarization reconfigurable antennas reduce multipath fading, improve the effectiveness in receiving communication signal and reduce co-channel interference.

The antenna can be made reconfigurable by using different types of switching techniques [5]. In [6], a liquid metal is used to obtain reconfigurability in a frequency-reconfigurable patch antenna for Industrial, Scientific and Medical (ISM)/Global Positioning System (GPS) band. RF pin diodes are used in [7] to obtain reconfigurability for nine different frequency bands. Eight Varactor diodes are used for reconfigurability, which operates in the range of 1.64 to 2.12 GHz in [8]. In [9], Radio Frequency Microelectromechanical Systems (RF-MEMS) switches are used for switching purposes at a faster rate with dual frequency reconfigurable bands (4.57 and 4.88 GHz) by integrating the antenna with a bias network. Electrically tuned plasma is used to achieve reconfigurability in low profile broad band plasma antenna for VHF and UHF applications [10]. In [11], a set of optical (photo conductive) switches are used for frequency and radiation reconfiguration with application of millimeter-wave (mmW) 28 and 38 GHz frequency range. For beam steerable planer antenna, four PIN diodes is used as a switching device [12] to achieve reconfigurability for Worldwide Interoperability for Microwave Access (WiMAX) and Wireless Local Area Network (WLAN) applications. A reconfigurable MIMO antenna for cognitive radio applications is made with PIN and Varactor diodes reconfiguration mechanism in [13].

A coplanar waveguide (CPW) fed Sub 6 GHz Frequency Reconfigurable Antenna for 5G and Ultra-wideband (UWB) Applications is presented in [14] where a single pin diode is used for reconfigurability. In [15] a Differentially-Fed Frequency Reconfigurable antenna is presented for WLAN and Sub-6 GHz 5G Applications. These antennas can operate in either single or dual band modes depending on the state of switch. Lumped element switch is used to attain reconfiguration. In [16], author has presented the defected ground structure with its effects on different parameters of the antenna. A monopole frequency reconfigurable antenna is introduced in [17]. Three pin diodes are used for reconfigurability. There are four modes of operation. Each mode has different applications. Mode 1 for The Global System for Mobile Communications (GSM). Mode 2 for 3G advanced/ Long Term Evolution (LTE). Mode 3 for Wi-Fi/WLAN/ISM and Mode 4 is for Airport Surveillance Radar band/WLAN applications. In [18], a compact hexa-band frequency-reconfigurable antenna is presented. The proposed antenna operates at six different bands such as Wireless Fidelity (Wi-Fi), WiMAX, Universal Mobile Telecommunications System (UMTS) and WLAN.

In [19] Multiband frequency reconfigurable antenna is presented for 5G and Ultra-wideband (UWB) applications. A PIN Diode is employed to achieve frequency reconfiguration in the

proposed antenna. A multi-band frequency reconfigurable Inverted F antenna for wireless applications is presented in [20]. An F-shaped frequency reconfigurable antenna is presented in [21] which covers different bands which include the WLAN, WiMAX, Wi-Fi, and GSM band. In [22] a tri-band frequency reconfigurable antenna is presented for LTE/Wi-Fi/ITS applications. Switching is done by two PIN diodes loaded on the ground plane. A multi band reconfigurable antenna for future wireless applications is presented in [23] in which total eight frequency bands between 1.46 and 6.15 GHz have been achieved using two pin diodes. A compact multiband frequency reconfigurable planar inverted-F antenna (PIFA) is presented in [24]. Seven different bands have been achieved by using a single RF switch for switching mechanism. The antenna is designed for GPS, LTE, UWB and satellite applications. In [25] a multi-band frequency reconfigurable antenna for 5G communication is reported. Two pin diodes have been inserted in the triangular-shaped radiator for switching the modes. Antenna has two operational modes covering five resonant bands. In [26], a dipole-based frequency reconfigurable antenna is presented, having four pin diodes for switching. Depending upon switching states of pin diodes antenna has two resonant modes, covering three different bands for sub-6 GHz and WLAN applications. In [27], a composite right/left-handed (CRLH) unit cell loaded frequency reconfigurable antenna is reported. Antenna has two varactor diodes with varying the capacitance providing ten different LTE bands. In [28] a compact CPW fed frequency reconfigurable antenna is presented. Two pin diodes have been used for switching, providing dual and tri-band operational modes. Similarly, a CPW fed multi-mode frequency reconfigurable antenna for Sub-6 GHz and other wireless applications is reported in [29]. Three pin diodes have been loaded between stubs to achieve reconfigurability. Antenna has a wide band and four reconfigurable bands.

A high-performance frequency reconfigurable multi band antenna designed on an FR-4 substrate, is presented in this paper. The proposed antenna is reconfigured by using pin-diode switches and it radiates in seven different bands with good gain, radiation efficiency and compact size. The rest of the paper is organized as follows: Section 2 explains the design methodology and geometry of the proposed switchable multiband antenna. The analysis of simulation and measured results is discussed in Sections 3 and 4 concludes this research work.

2 Methodology

This section presents basic geometry and design theory of the proposed multi band frequency reconfigurable antenna. Frequency reconfigurability is achieved in simulation through the lumped element RLC equivalent circuit of the pin diodes. The designed antenna can be operated in different frequencies by using the ON/OFF condition of the diodes. Better efficiency and satisfactory far field results have been obtained using a partial ground plane.

2.1 Design Theory and Structural Geometry

The geometrical structure of the proposed antenna is depicted in Fig. 1. The presented antenna having dimension $30 \text{ mm}^3 \times 20 \text{ mm}^3 \times 1.6 \text{ mm}^3$ is designed on a 1.6 mm thick FR-4 substrate. The substrate has relative permittivity ϵ_r of 4.3 and loss tangent δ of 0.025, backed by truncated metallic ground plane to obtain better gain, good efficiency, and directivity. For insertion of the pin diode switches, a gap of 1 mm was kept between the patches. A microstrip line of width 3 mm having 50Ω impedance is used to excite the antenna. The summary of the dimensions of the proposed antenna is presented in Tab. 1.

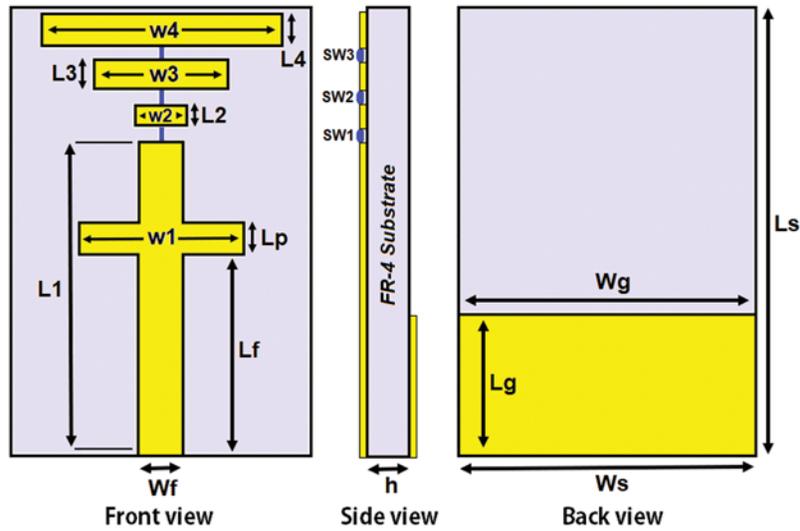


Figure 1: The geometry of proposed antenna

Table 1: Dimensions of proposed antenna

Parameters	Values (mm)	Parameters	Values (mm)
Ws	30	L2	1.5
Ls	20	L3	2
Wg	30	L4	2
Lg	9.5	W1	11
Wf	3	W2	3.4
Lp	2	W3	9
Lf	13.5	W4	16
L1	21	h	1.6

The effective resonant lengths for intended frequencies are calculated using transmission line model theory [30]. The effective length of the antenna corresponding to the respective resonant bands are one quarter of the guided wavelength (i.e., $L_f \approx \lambda_f/4$).

2.2 Resonant Modes

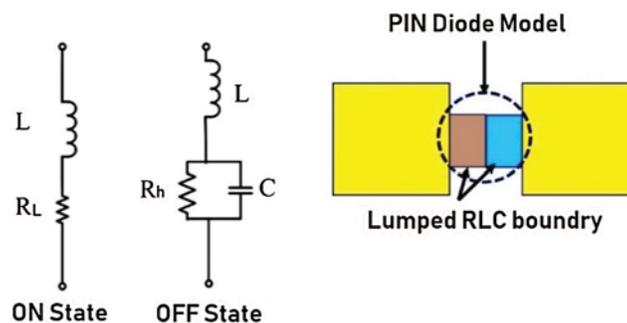
In proposed antenna frequency reconfigurability is achieved by changing the ON and OFF states of each pin diode that offers an open and short circuit behavior between radiating patches. The presented antenna has four operating modes, each have unique scheme of resonant frequencies. In Mode 1 (SW1 to SW3 = OFF), antenna covers a wideband of at 3.15–8.51 GHz. For Mode 2 (SW1 = ON, SW2 to SW3 = OFF), the proposed antenna resonates at 3.5 GHz. The antenna shows dual band behavior and covers 2.6 and 6.2 GHz at Mode 3 (SW1 and SW2 = ON, SW3 = OFF). The same antenna covers three different bands of 2.1, 5 and 6.4 GHz when operating at Mode 4 (SW1 to SW3 = ON). The conditions of the pin diodes at each mode and respective resonant bands are detailed in Tab. 2.

Table 2: Conditions of the pin diodes for various resonant bands

MODES	SW1	SW2	SW3	Operating bands (GHz)
1	OFF	OFF	OFF	3.51–8.51
2	ON	OFF	OFF	3.10–4.11
3	ON	ON	OFF	2.41–2.81 and 5.47–7.18
4	ON	ON	ON	2.03–2.27, 4.61–5.35 and 5.87–7.22

2.3 Switching Technique

For switching purpose four pin diodes (SMP1345-079LF) are used, as they behave like a variable resistor in the radio frequency (RF) range. These pin diodes provide open and the short circuit behavior at their respective insertion positions, thus vary the effective resonant length of the antenna and hence result in reconfiguration of antenna's operating frequency. The equivalent circuits for both ON and OFF states of a pin diode switches are shown in the Fig. 2. For ON state it is simply an RL series circuit, having a low value resistor " R_L " and an inductor " L ". In OFF state it is equivalent to an RLC circuit, having inductor " L " in parallel with a high value resistor " R_h " and a capacitor " C ". Pin diode of model Skyworks SMP1345-079LF are used in this work. According to its datasheet it has been modeled in CST as $R_L = 1.5 \Omega$, $L = 0.7 \text{ nH}$ and $C = 0.15 \text{ pF}$.

**Figure 2:** Pin diode model and its equivalent circuits for ON and OFF states

2.4 Design Evolution

The evolution of the proposed antenna's design involves several steps as depicted in the Fig. 3. All steps along with their return loss characteristic are illustrated in Figs. 3–6. For achieving Mode 1, a monopole antenna excited with a microstrip feedline was designed to cover the 5.8–8.2 GHz frequency band. For achieving the lower frequency bands the length L_1 was increased from 17 to 21 mm. To achieve the better bandwidth and enhanced impedance matching for the intended resonant bands, the parameter W_1 was increased, from 3 to 11 mm as shown in Fig. 4.

For Mode2, a parasitic patch was introduced, connected in cascade with the primary radiator. It may be noted that the value of W_1 was kept constant in this mode, equal to 11 mm. At width $W_2 = 3 \text{ mm}$, the antenna was covering the impedance bandwidth of 3.6–4.1 GHz. For achieving the intended band of 3.5 GHz, the width W_2 was increased from 3 to 3.4 mm as shown in Fig. 5a. For Mode 3, another parasitic patch was connected to the first one, as shown in Fig. 5b.

The dual band of 2.6 and 6.2 GHz was achieved by increasing the width W_3 of the parasitic patch up to 9 mm. For Mode 4, another parasitic patch was connected to the previous ones, as shown in Fig. 6. The triple band of 2.1, 5 and 6.4 GHz was achieved by increasing the width W_4 of that parasitic patch from 3 to 16 mm.

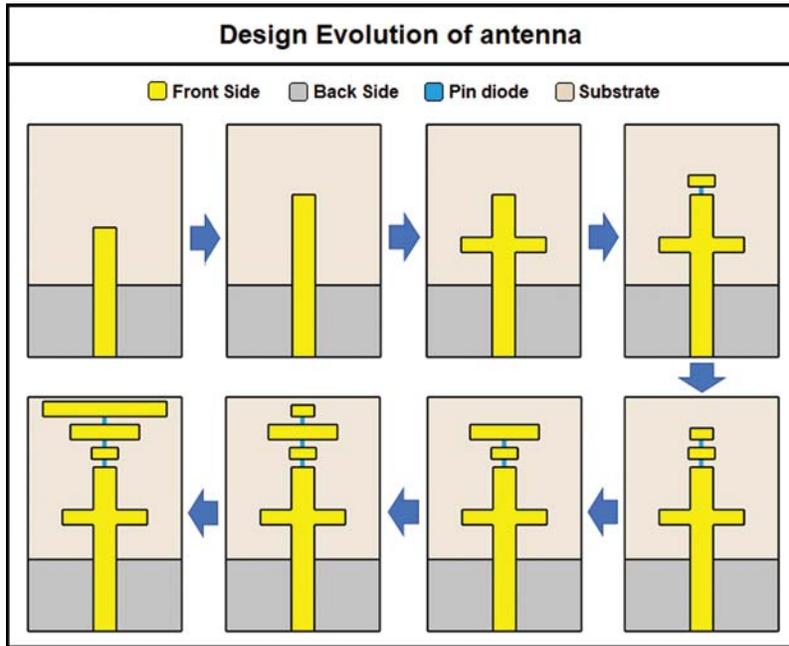


Figure 3: The evolution map highlighting various design stages of the proposed antenna

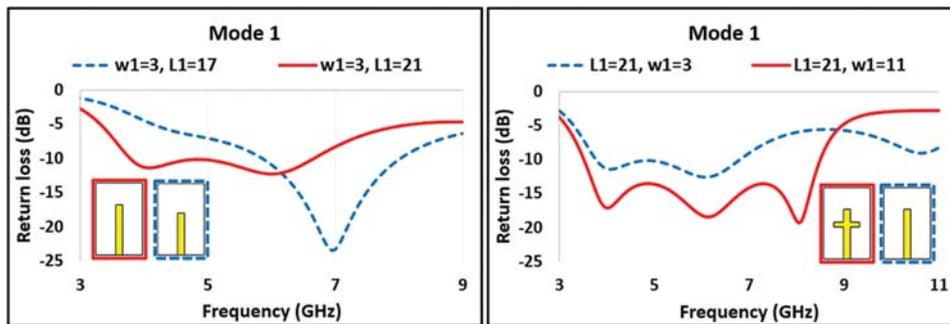


Figure 4: Design evolution of Mode 1 of proposed antenna

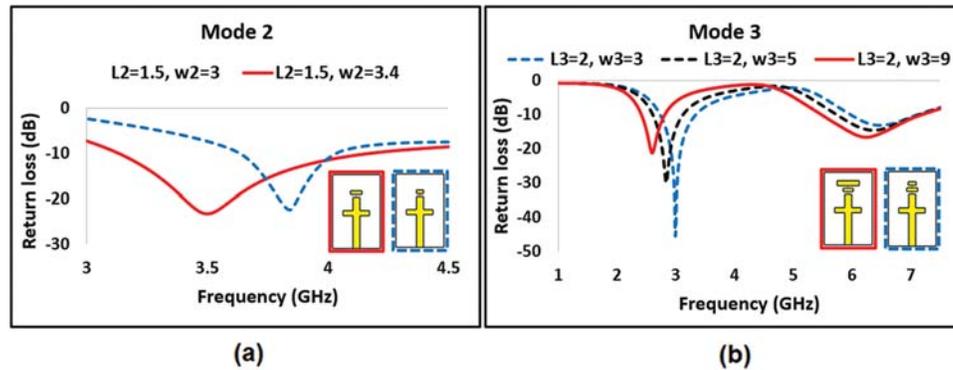


Figure 5: Design evolution of Mode 2 and Mode 3

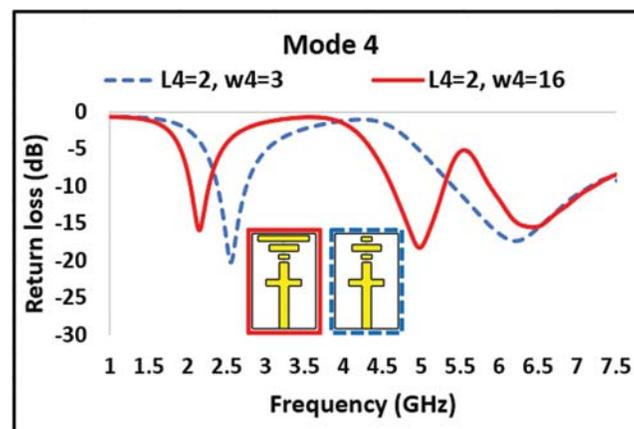


Figure 6: Design evolution of Mode 4

3 Results and Discussion

The proposed structure is designed and analyzed using Computer Simulation Technology microwave studio (CST MWS). To excite the radiating structure, a waveguide port of standard dimensions is assigned. The performance parameters i.e., return loss, gain, surface current plots are obtained by using the standard boundary conditions in CST microwave studio. The simulated results are experimentally validated in the antenna measurement facility located at National University of Science and Technology (NUST) Islamabad. The experimental setup to measure the radiation pattern of the proposed antenna in mode 1 is depicted in Fig. 7.

3.1 Return loss and Bandwidth

The simulated return loss of all modes of the proposed antenna are depicted in Fig. 8. When all switches (SW1 to SW3) are OFF, the proposed antenna operates in MODE 1, covering 3.51–8.51 GHz band with maximum return loss of -19.33 dB at 8 GHz. In MODE 2 (When SW 1 is ON), the presented antenna resonates at 3.5 GHz with return loss of -24.17 and -10 dB bandwidth of 1010 MHz (3.10–4.11). In MODE 3 when two switches (SW1, SW2) are ON and the SW3 is OFF, the proposed antenna operates at two different bands i.e., 2.6 and 6.2 GHz with

a return loss of -21.5 , -17 and -10 dB bandwidth of 400 MHz (2.41–2.81 GHz) and 1710 MHz (5.47–7.18 GHz), respectively. When all switches (SW1 to SW3) are ON, the antenna switch to its MODE 4 and operates at 2.1, 5, and 6.4 GHz with return loss of -16 , -18 , -15.8 dB and -10 dB bandwidth of 240 MHz (2.03–2.27 GHz), 740 MHz (4.61–5.35 GHz) and 1350 MHz (5.87–7.22 GHz), respectively at the operating frequencies.

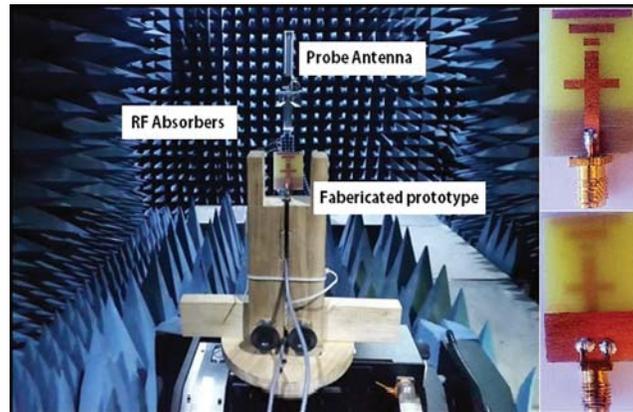


Figure 7: Setup for measuring radiation pattern of the proposed antenna in Mode 1

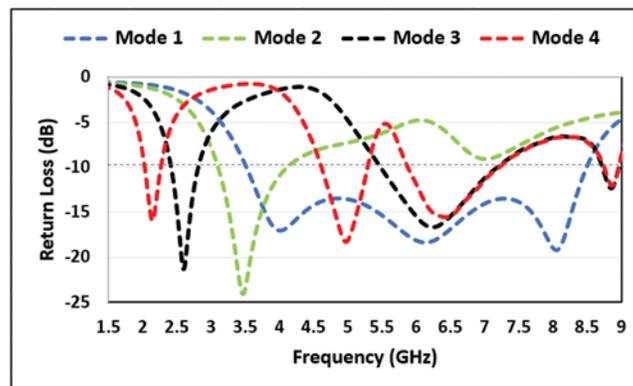


Figure 8: Return loss for all operating modes

The simulated and measured return loss of each mode is compared in Fig. 9. The comparison shows a good agreement between measured and simulated results. The VSWR of less than 1.5 is observed for all resonant bands, which indicates optimum driving-point impedance matching of the antenna, as depicted in Fig. 10.

3.2 Far Field Radiation Pattern

In MODE 1, proposed antenna operates at 3.51–8.51 GHz band with a simulated peak gain and radiation efficiency of 2.5 dBi and 84%, respectively. In MODE 2, a central frequency of 3.5 GHz has been achieved with peak gain and radiation efficiency of 1.95 dBi and 82%, respectively. A dual band is achieved in MODE 3 with gain of 1.54 and 2 dBi and radiation efficiencies of 83% and 70% at 2.6 and 6.2 GHz, respectively. The antenna operates at 2.1, 5 and

6.4 GHz in MODE 4, with peak gains of 1.2, 1.7 and 1.64 dBi and radiation efficiencies of 80%, 71% and 70%, respectively.

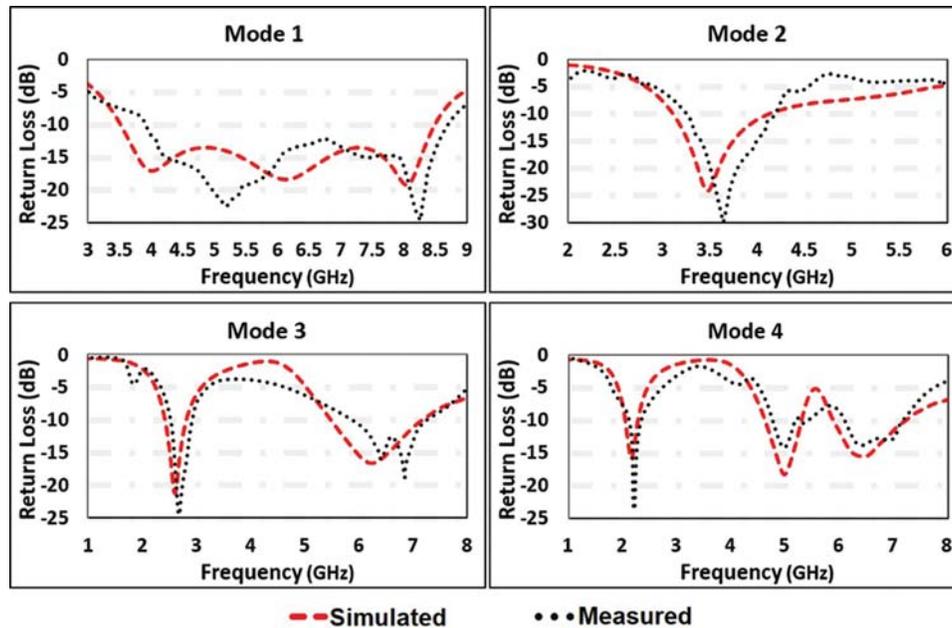


Figure 9: Comparison of simulated and measured return loss

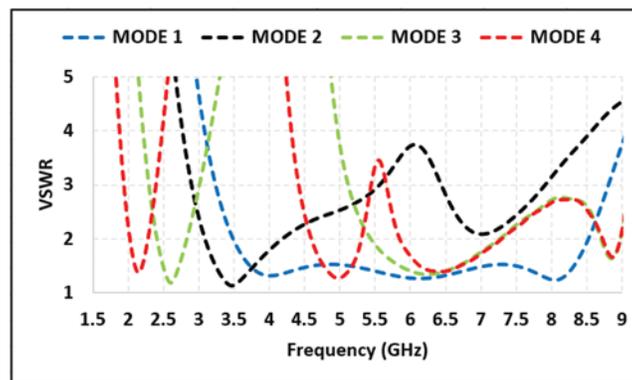


Figure 10: VSWR of proposed antenna at various operating modes

The comparison of simulated and measured gain of proposed antenna is depicted in Fig. 11 showing that the measured gains are in a good agreement with the simulated ones. It is worth mentioning that the antenna gives optimum values of average gain, i.e., 2.05 dBi in mode 1, 1.87 dBi in mode 2, 1.4–1.75 dBi in mode 3, 1.05–1.56 dBi in mode 4.

The simulated and measured radiation pattern of the antenna in both E-and H-plane at the operating frequency bands, are compared in Fig. 12. The shape of the radiation pattern in the E-plane, resembles the figure-of-eight at frequencies of 2.1, 2.6, 3.5 GHz. The radiation properties

of the antenna in the H-plane are predominantly Omni-directional in nature in most of the frequency bands. The half power beamwidth (HPBW) and main lobe direction (MLD) were deduced from the E-plane radiation pattern of the antenna in all resonant modes, and the same are summarized in [Tab. 3](#).

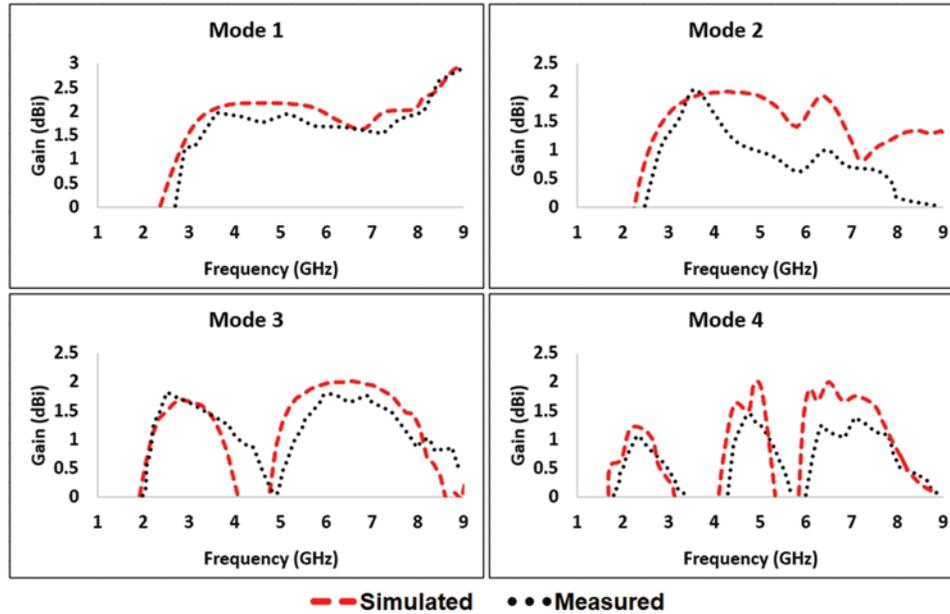


Figure 11: Comparison of simulated and measured gain

The simulated co-and cross-polar radiation patterns for both E-plane (y-z) and H-plane (x-z) are presented in [Fig. 13](#). It is evident from the results that in the co-polarization state, the antenna radiates adequately in both E-and H-planes. While, in cross-polarization state, the antenna gain is predominately negative and hence the radiation is extremely poor in both principal planes. For further clarity about the radiation properties of the antenna, the three-dimensional gain plots are portrayed at the resonant frequencies in [Fig. 14](#).

3.3 Surface Currents

The surface current distribution on the radiating structure of the antenna at different frequency bands is shown in [Fig. 15](#). For Mode 1, antenna operates at a wideband of 3.51–8.51 GHz, the density of the surface currents is higher on the lower side of the feedline, which is contributing to radiation at 5.5, 4.8, 4.5GHz, low concentration for high frequency and more concentrated surface currents are observed for lower frequencies bands. In Mode 2, the surface currents indicate an increase in the contributing resonant length, thus operation shifts to 3.5 GHz. In Mode 3 dual band operations (i.e., 2.6 and 6.2 GHz) are achieved, the surface currents indicate the dominant contribution of larger portion of radiator for lower bands and smaller portion of radiator for the upper bands. In Mode 4, triple band (i.e., 2.1, 5 and 6.4 GHz) operation is achieved, the higher surface current density along the entire length of the radiator indicate that the whole metallic radiator is contributing to radiation in the lower frequency band (i.e., 2.1 GHz). It is worth mentioning that relatively smaller segments of the radiator are contributing to radiation at the upper bands (5.5 and 6.4 GHz). These surface currents indicate that the contributing

resonant length for respective frequency decreases as resonant frequency increases, thus proves the inverse relation of frequency with resonant length. Performance matrices of proposed antenna are summarized in Tab. 4. The power consumption by the parasitic resistance of the pin diodes and as well as the power loss in the dielectric substrate were analyzed for each operating frequency. The average power consumption or loss contributed by the pin diodes and dielectric substrate is 0.023 and 0.031 w, respectively.

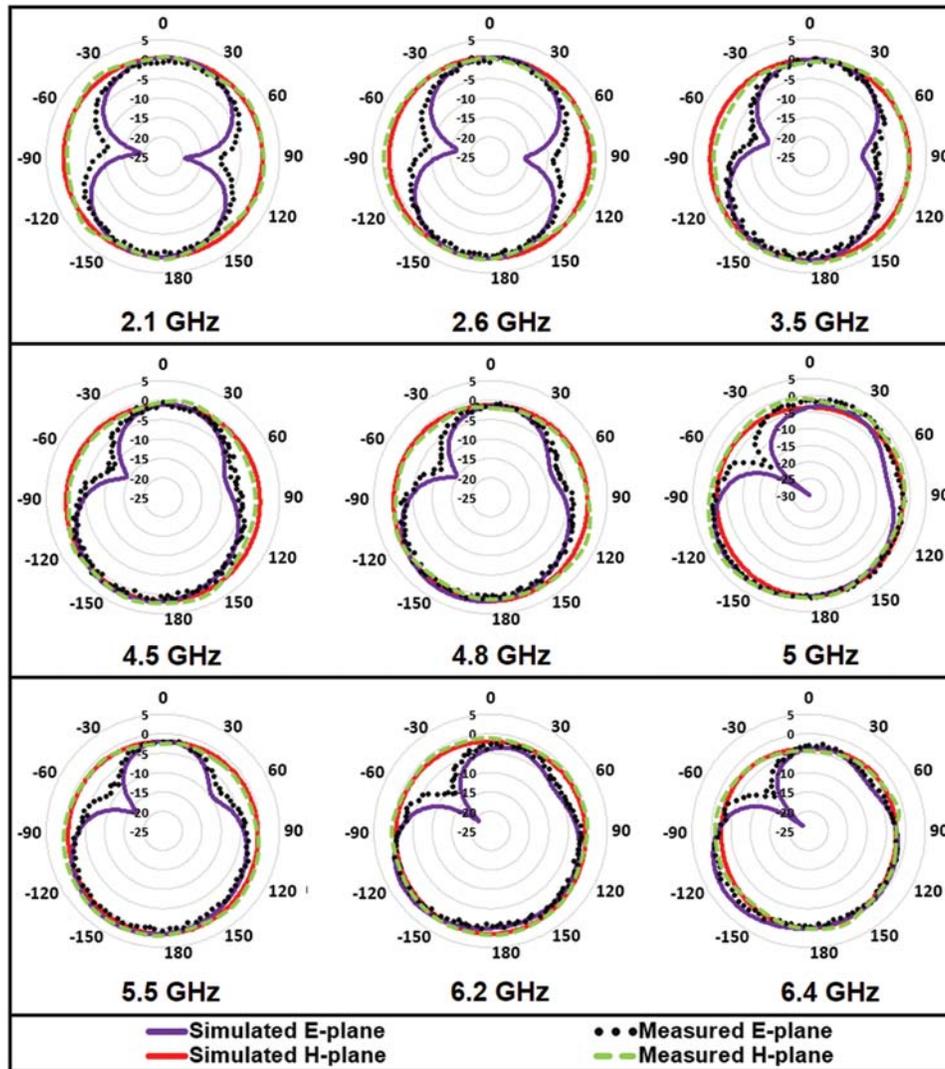


Figure 12: Comparison of simulated and measured radiation pattern in both principal planes

In terms of size, the proposed antenna is more compact than all the antennas reported in the comparison table. The proposed antenna has impedance bandwidth (BW) ranges 240–5000 MHz which offers larger bandwidth than antennas designed in [31–38]. The comparison is given in Tab. 5.

Table 3: Summary of half power beamwidth and main lobe direction

Mode no	Operating frequencies	HPBW (in degrees)	MLD (in degrees)
1	4.5/4.8/5.5	108/113/126	-161/-160/-155
2	3.5	95.3	-168
3	2.6/6.2	90.3/158	-172/-130
4	2.1/5/6.4	90/124/130	-173/-140/-130

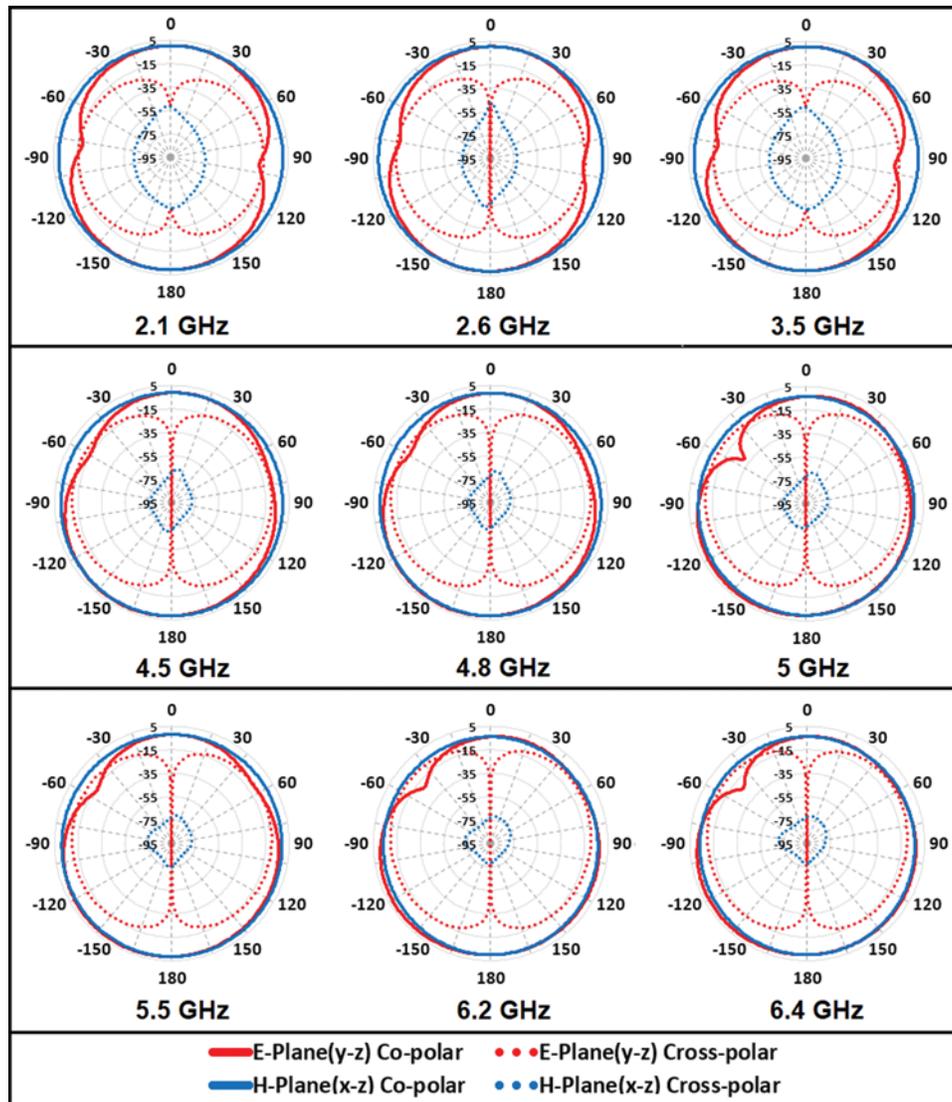


Figure 13: Co- and cross-polar radiation pattern for both principal planes

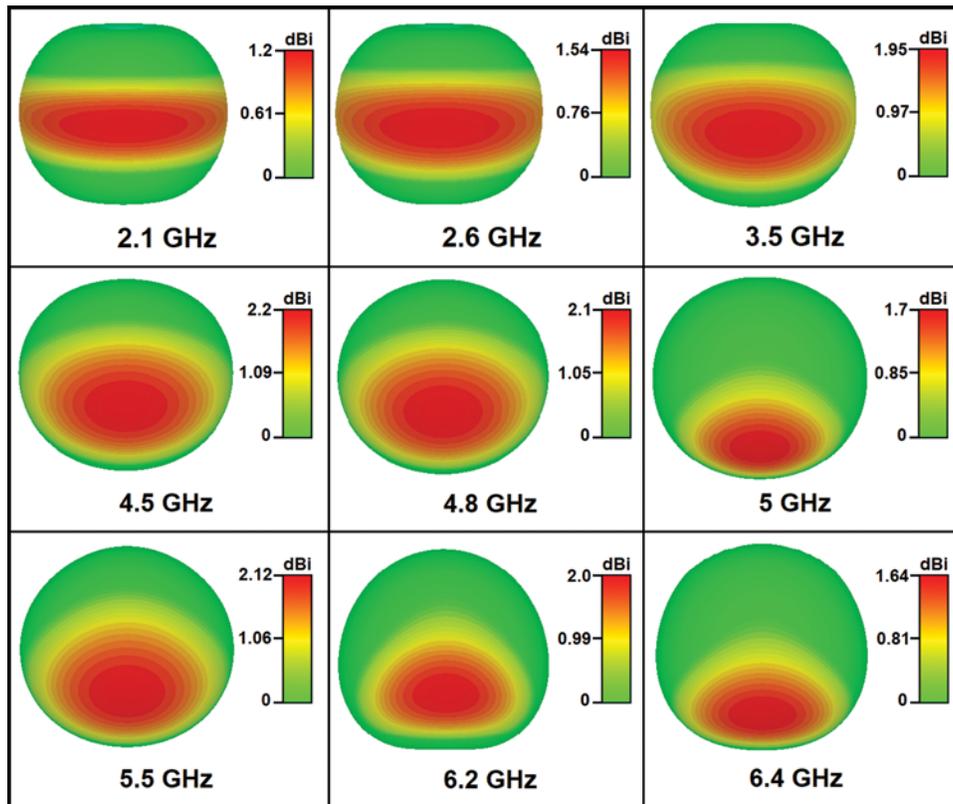


Figure 14: The three-dimensional plots of gain pattern

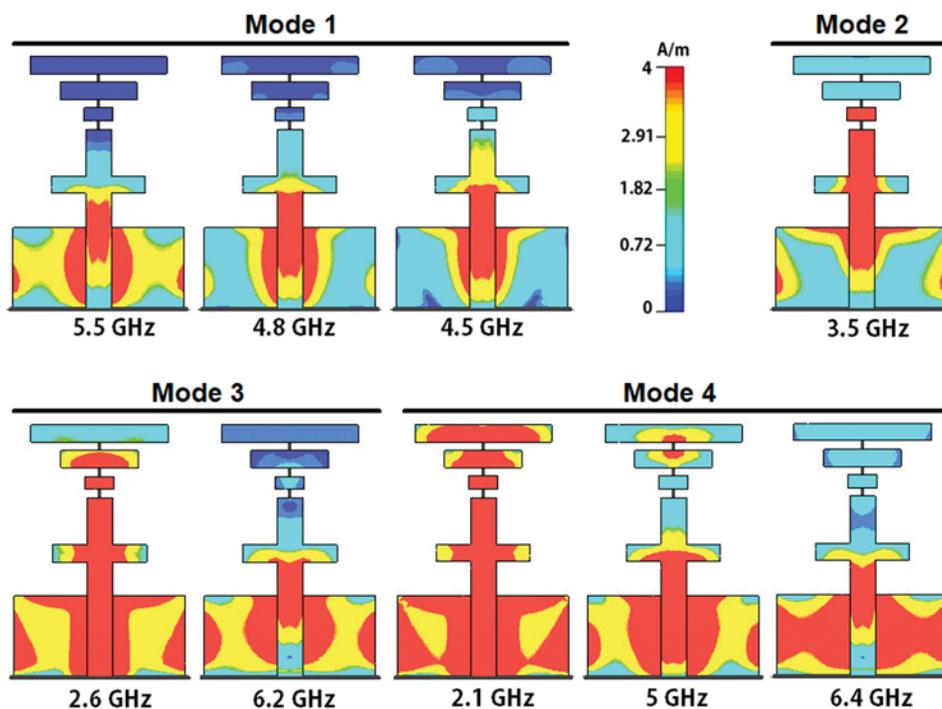


Figure 15: Surface currents plots of antenna at various modes

Table 4: Summary of the antenna's performance

Mode	Conditions	Operating bands (GHz)	-10 dB Bandwidth (MHz)	Gain (dBi)	Directivity (dBi)	Return loss (dB)	Rad. Efficiency (%)
1	All switches are OFF	Wideband	3.51–8.51 (5000)	2.05	2.80	-19.33	84
2	SW1 is ON	3.5	3.10–4.11 (1010)	1.95	2.82	-24.17	82
3	SW1 and SW2 are ON	2.6/6.2	2.41–2.81 (400) /5.47–7.18 (1710)	1.54/2	2.35/3.5	-21.5/-17	83/70
4	All switches ON	2.1/5/6.4	2.03–2.27 (240) /4.61–5.38 (770) /5.87–7.22 (1350)	1.2/1.7/1.64	2.17/3.2/3.19	-16/-18/-15.8	80/71/70

Table 5: Proposed antenna's comparison with other reported works

Ref.	Dimensions (mm^3)	No. of switches	Total No. of operating bands	Operating frequencies (GHz)	-10 dB BW (MHz)	Peak gains (dBi)	Rad. efficiency (%)
[21]	40 × 33 × 1.6	2	5	1.8, 2.4, 5.4, 3.5, 5.4	–	1.7–2.5	76.68–92
[31]	40 × 35 × 1.6	1	3	2.45, 3.5, 5.4	490–1360	1.92–3.02	76.4–86.5
[32]	60 × 60 × 1.6	3	5	2.4, 4.26, 4.32, 4.58, 5.76	60–170	1.31–2.77	–
[33]	53 × 35 × 1.6	1	3	2.45, 3.50, 5.20	147–1820	1.7–3.4	85–90
[34]	40 × 22 × 1.6	1	4	2.45, 5.13, 3.49, 5.81	750–1260	1.72–2.96	76.4–92
[35]	39 × 37 × 1.6	1	3	2.4, 5.4, 3	550–1220	1.27–3.8	>90
[36]	37 × 35 × 1.6	2	4	2, 3.4, 2.4, 3.1	200–960	1.76–1.98	>85
[37]	40 × 35 × 1.6	1	3	2.45, 3.5, 5.2	330–1250	1.48–3.26	84–93.5
[38]	40 × 35 × 1.6	2	6	2.10, 2.40, 3.35, 3.50, 5.28, 5.97	335–1220	1.92–3.8	92.5–97
This work	30 × 20 × 1.6	3	7	2.1, 2.6, 3.5, 5.0, 6.2, 6.4, 3.51–8.51	240–5000	1.2–2.5	70–84

4 Conclusion

A frequency reconfigurable antenna has been designed, simulated, and experimentally validated in this paper. The proposed antenna is reconfigured depending on the ON and OFF states of the pin diode switches. When all the switches are OFF, the antenna covers a wide band of 3.51 to 8.51 GHz. Antenna operates at 3.5 GHz when only SW1 is ON. The prototype works in dual band mode, resonating at 2.6 GHz and 6.2 GHz, when SW1 and SW2 are ON. Triple band (2.1, 5 and 6.4 GHz) functionality is realized when all the switches are kept in ON condition. The proposed antenna has many advantages like compact size, low cost, light weight and easy of fabrication and supports sub-6 GHz 5G bands (2.1, 2.6, 3.5 and 5 GHz) with an extended application for wireless local area networks, the 6 GHz fixed satellite services as well as IoT enabled wireless terminal and systems in smart cities.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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