

Frequency Reconfigurable Antenna for Portable Wireless Applications

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Received: 27 November 2020; Accepted: 25 January 2021

Abstract: In this paper, the design and experimental evaluation of a hexagonal-shaped coplanar waveguide (CPW)-feed frequency reconfigurable antenna is presented using flame retardant (FR)-4 substrate with size of $37 \times 35 \times 1.6 \text{ mm}^3$. The antenna is made tunable to three different modes through the status of two pin diodes to operate in four distinct frequency bands, i.e., 2.45 GHz wireless fidelity (Wi-Fi) in MODE 1, 3.3 GHz (5G sub-6 GHz band) in MODE 2, 2.1 GHz (3G Long Term Evolution (LTE)-advanced) and 3.50 GHz Worldwide Interoperability for Microwave Access (WiMAX) in MODE 3. The optimization through simulation modeling shows that the proposed antenna can provide adequate gain (1.44~2.2 dB), sufficient bandwidth (200~920 MHz) and high radiation efficiency (80%~95%) in the four resonating frequency bands. Voltage standing wave ratio (VSWR) <1.5 is achieved for all bands with properly matched characteristics of the antenna. To validate the simulation results, fabrication of the proposed optimized design is performed, and experimental analysis is found to be in a considerable amount of agreement. Due to its reasonably small size and support of multiple frequency bands operation, the proposed antenna can support portable devices for handheld 5G and Wireless LAN (WLAN) applications.

Keywords: LTE; WiMAX; coplanar waveguide; frequency reconfigurable antenna

1 Introduction

Communication systems have undergone several improvements during the last few decades to provide advanced on-demand services to the public. Through the development of internet-of-things (IoT) and consequent increase in number of devices to be connected, the demand of multiple wireless services using a single handheld device has increased significantly. Operating



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over a wide range of frequencies, the new 5G radio access networks are expected to simultaneously support the number of connections. To enable 5G services, Federal Communications Commission (FCC) has divided the main spectrum into low bandwidth (600, 800 and 900 MHz bands), medium band as sub-6 GHz (2.4, 3.5 and 3.7–4.2 GHz), and high frequency mmWave band (28, 38 and 60 GHz) [1,2]. The mmWave transmission offers multi-Gbps data rates by utilizing the large available bandwidth in the mmWave band. It is clearly desirable to use the 5G mmWave spectrum to achieve the ultra-high data rates [3], however, there are some critical challenges that need to be addressed before mmWave mobile communication can be implemented commercially. As mmWaves are prone to atmospheric attenuation and cannot propagate longer distances, the sub-6 GHz waves is an alternate choice for long range and considerably high data rate communication systems. The standardization of mmWave technology will take time for 5G networks and below 6 GHz spectrum is being auctioned by the spectrum regulatory bodies. Since 5G communication below 6 GHz can send high data rates over long distances, it is suitable for use in both urban and rural areas. For dense user environments where high interference in a specific frequency band can be anticipated, the switching capability between multiple frequency bands is of key importance. Conventional antennas fail to meet such requirement and advanced designs are mandatory to address such functionality demands. Reconfigurable design for the antenna has recently considered by a lot of researchers, with the focus to enable it to change its characteristics according to the requirement. Reconfigurable antennas are used for diverse wireless applications that function in a wide range of frequency. As reconfigurable antennas can alter their behavior according to the requirements, their ability to handle the same operation as that of several antennas without increasing the overall size make them an excellent choice for handheld devices [4]. There are three basic types of reconfigurable antennas depending on the independent parameter from the set of basic characteristics such as resonant frequency, state of polarization and radiation pattern. The tunable frequency feature of a reconfigurable antenna according to the user requirements has several applications in multi-radio wireless and satellite communication applications [5]. 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 [6]. Polarization reconfigurable antennas reduce multipath fading, improve communication signal reception and reduce co-channel interference [7].

The antenna can be made reconfigurable by using different types of switching techniques [8]. For instance, as literature review, [9] presents a liquid metal to obtain reconfigurability in a frequency-reconfigurable patch antenna for industrial, scientific and medical (ISM)/ global positioning system (GPS) band. Radio frequency positive-intrinsic-negative (PIN) diodes are used in [10] to obtain reconfigurability for nine different frequency bands. Varactor diodes are used for reconfigurability of the antenna reported in [11], which operates in the range of 1.64 to 2.12 GHz. In [12], RF-micro-electromechanical system (MEMS) switches are used for switching purposes at a faster rate with dual frequency reconfigurable bands (4.57 and 4.88 GHz). Electrically tuned plasma is used to achieve reconfigurability in low profile broad band plasma antenna for very high frequency (VHF) and ultra-high frequency (UHF) applications [13]. In [14], a set of optical (photo conductive) switches is 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 are used as a switching device [15] to achieve reconfigurability for WiMAX and WLAN applications. A MIMO antenna for cognitive radio applications is reconfigured through pin and varactor diodes in [16]. A CPW-feed antenna [17,18] is reconfigured via two pin diodes for wideband and multiband mobile applications. A frequency reconfigurable antenna

with differential feeding technique is presented for WLAN and Sub-6 GHz 5G radio Applications in [19] where the antennas can function in either single or dual band modes contingent on the state of switch. Lumped element switch is used to attain reconfiguration with hexagonal shaped CPW-feeding technique for 5G and WLAN application [20]. In [21], the authors have presented a review on reconfigurable antennas in which pin diodes, varactor diodes, RF MEMS and many other techniques have been discussed for reconfigurability purpose. A monopole frequency reconfigurable antenna is introduced in [22]. Three pin diodes are employed for the purpose of reconfigurability, which enables four modes of operation to serve a different application. Mode 1 for GSM, Mode 2 for 3G advanced/LTE, Mode 3 for WIFI/WLAN/ISM and Mode 4 is for Airport Surveillance Radar band/WLAN applications. In [23], a small size antenna with tunable frequency characteristics is presented. The antenna operates in Hexa band mode such as WLAN, WiFi, WiMax and UMTS. To attain frequency shifting in simulation environment, switches from lumped element are used. Pin diodes are used as switches in fabricating and measuring an antenna prototype. In [24] Frequency reconfigurable antenna with Multiband is presented for multiple wireless operation i.e., satellite communication application Pin diodes are employed in the feed line to achieve frequency reconfiguration between the satellite link receiver and the navigation state of the proposed antenna. In [25], an F-inverted shape frequency reconfigurable antenna with multiple bands is presented for wireless implementation which covers four bands i.e., 1900, 900, 2400, and 1800, MHz A dual novel-shaped antenna with tunable frequency features with origami magic cube is provided in [26] which operates in different bands of wireless sensor networks operating in 1.57 and 2.4 GHz bands, in the folded mode. In unfolded mode, it resonates at 900 MHz and 2.3 GHz frequency bands. However, as the 5G services and multiple autonomous applications [27] will cover a wideband around 3.3 GHz [28] in the sub-6GHz band, the requirement is to have a design which can cover this band, as well as the legacy standards.

A novel Hexagonal-shaped frequency reconfigurable CPW-feed multi band monopole antenna, which is designed on an FR-4 substrate, is presented in this work. This antenna radiates in four different bands with promising gain and radiation efficiency relatively compact size as compared with existing antennas.

2 Methodology

Hexagonal-shaped frequency reconfigurable antenna geometry and design theory is discussed in this section. Frequency reconfigurability is achieved in simulations through lumped element model of the pin diode and pin diodes (SMP1345-079LF) in the measurement setup. The designed antenna can be operated in various frequency ranges by using the on/off condition of pin diodes. The front of the antenna is provided with a CPW feeding to achieve better efficiency and adequate far field radiation plans.

2.1 Design Theory and Evolution

The geometrical structure and design evolution of Hexagonal-shaped CPW-feed based antennas and their corresponding return loss are shown in Figs. 1 and 2. The antenna dimensions $37 \times 35 \times 1.6 \text{ mm}^3$ are based on a 1.6 mm FR-4 substrate. The substrate has relative permittivity (ϵ_r) of 4.3 and loss tangent (δ) of 0.025, supported by a metallic CPW feed to obtain better gain, improved efficiency, and high directivity. For pin diode insertion, a slot of 1 mm was kept between the switches point of the hexagon shape. A feed width of 3 mm having 50Ω impedances used for the excitation purpose of the antenna. A detailed summary of the antenna dimensions is presented in Tab. 1.

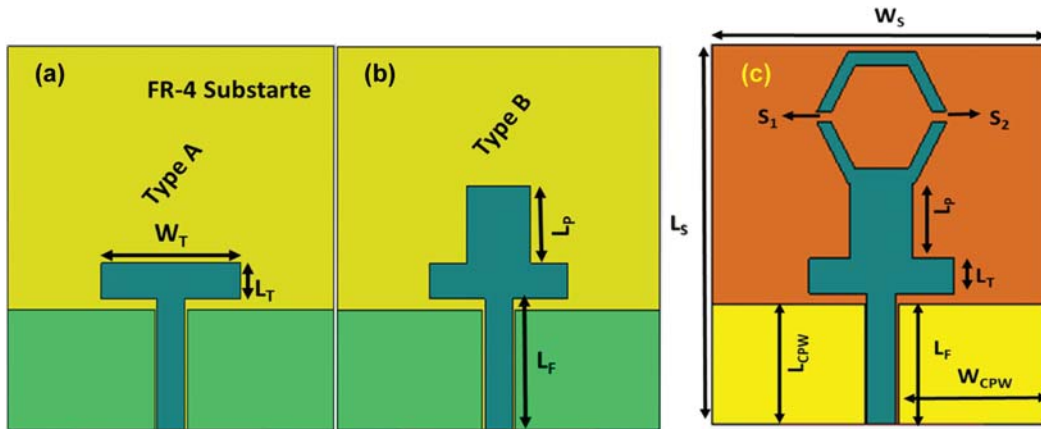


Figure 1: Design evolution of the proposed hexagonal-shaped CPW-feed antenna: (a) Type A (b) Type B (c) front view

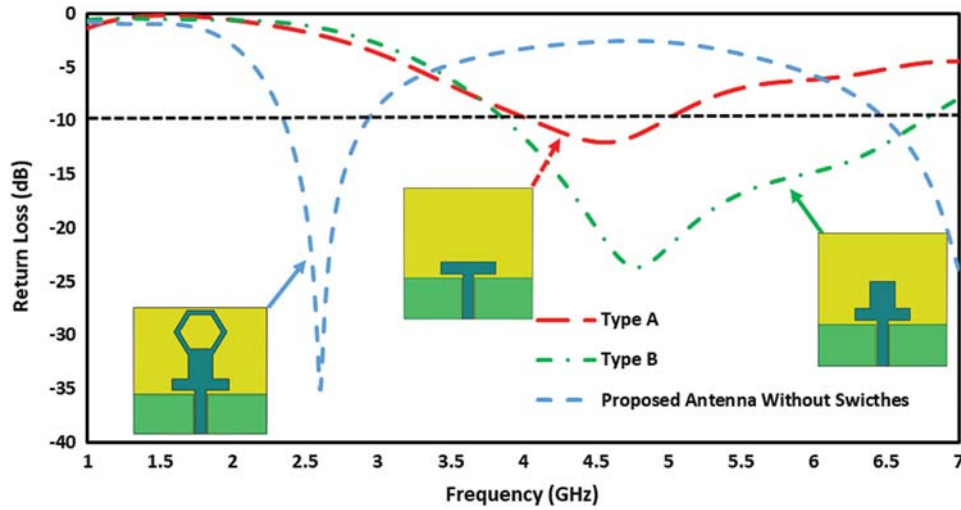


Figure 2: Simulated return loss of the antenna by evolving the radiating structure

Table 1: Purposed antenna dimension

Parameters	Values (mm)	Parameters	Values (mm)
L_T	7.50	W_f	3
W_T	7.42	W_f	3
L_P	5.63	L_S	37
W_P	1.98	W_S	35
H_S	1.6	W_{cpw}	17
L_f	13	L_{cpw}	9

The length (L), width (W) and width of feed (W_f) of the designed monopole antenna are obtained by through the well-known equations of the transmission line model theory [29].

$$w = \frac{c}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (1)$$

$$L = \frac{c}{2f_r\sqrt{\epsilon_{re}}} - 2\Delta l \quad (2)$$

Due to fringing field, the effective dielectric constant can be considered, and the effective dielectric constant can be computed by using the following equation

$$\epsilon_{re} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[\frac{1}{\sqrt{1 + 12\frac{h}{w}}} \right] \quad (3)$$

where “ c ” velocity of light in vacuum, “ ΔL ” is the extension length, “ ϵ_{eff} ” is effective dielectric constant, “ ϵ_r ” represents relative permittivity, thickness is represented by “ h ” and “ w ” is the substrate width, respectively.

$$f_w = \left(\frac{377}{Z_0\sqrt{\epsilon_r}} - 2 \right) h \quad (4)$$

The designing steps involve transformation from Type A to Type B for the proposed antenna. Changes has been made for improvement in antenna performance in term of driving point impedance bandwidth and the return loss. The steps for designing the proposed structure are depicted in Fig. 1 and the corresponding return loss plots are compared in Fig. 2, Fig. 1 depicts that type B is designed by introducing a rectangular patch upon T-shape in Type A. Finally, a hexagonal shape is embedded on the top of Type B to achieve the resonance in the targeted frequency band proposed antenna. It is evident from Fig. 2 that the step wise modifications improve return loss of the proposed design.

2.2 Switching Technique

For switching, pin diodes (SMP1345-079LF) are used in the RF frequency spectrum. The equivalent circuit for the ON and OFF switching states-based PIN diode is shown in Fig. 3, which shows that the diode behaves as a series RL circuit in ON state and as an RLC circuit in the OFF state, having an inductor in series with a parallel RC network. Pin diode of model Skyworks SMP1345-079LF is 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 $C = 0.15 \text{ pF}$.

3 Fabrication, Experimental Results and Discussion

3.1 Reconfigurability

For the proposed antenna, the frequency reconfigurability is attained in the ON and OFF states of each pin diode as it operates in three modes, each have unique scheme of resonant frequencies. In Mode 1 and 2, the designed antenna works at single bands. Mode 3 operate at unique dual bands as shown in Fig. 5. In Mode 1 ($S_1 = S_2 = \text{ON}$), antenna operates at 2.45 GHz. For Mode 2 ($S_1 = S_2 = \text{OFF}$), the purposed antenna resonates at 3.2 GHz. The antenna shows

dual band behavior and covers 2 and 3.5 GHz at Mode 3 ($S1 = ON, S2 = OFF$). The conditions of the pin diodes for different modes and respective resonant bands are summarized in [Tab. 2](#).

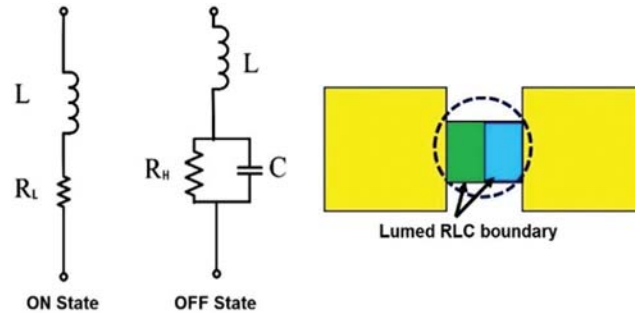


Figure 3: PIN diode model and its equivalent circuits for ON and OFF states

Table 2: Conditions of the PIN diodes for different resonant bands

MODES	S1	S2	Resonant bands
1	ON	ON	2.45 GHz
2	OFF	OFF	3.2 GHz
3	ON	OFF	2.1 and 3.5 GHz

The modeling and parametric analysis of the proposed antenna is carried out in CST microwave studio (MWS) v. 2019. To excite the radiating structure, a waveguide port is used and the S-parameters, gain, VSWR, far field radiation patterns are evaluated with standard boundary conditions. The simulated results are experimentally validated at National University of Science and Technology (NUST) in the anechoic chamber. [Fig. 4](#) shows the experimental setup and picture of the fabricated antenna.

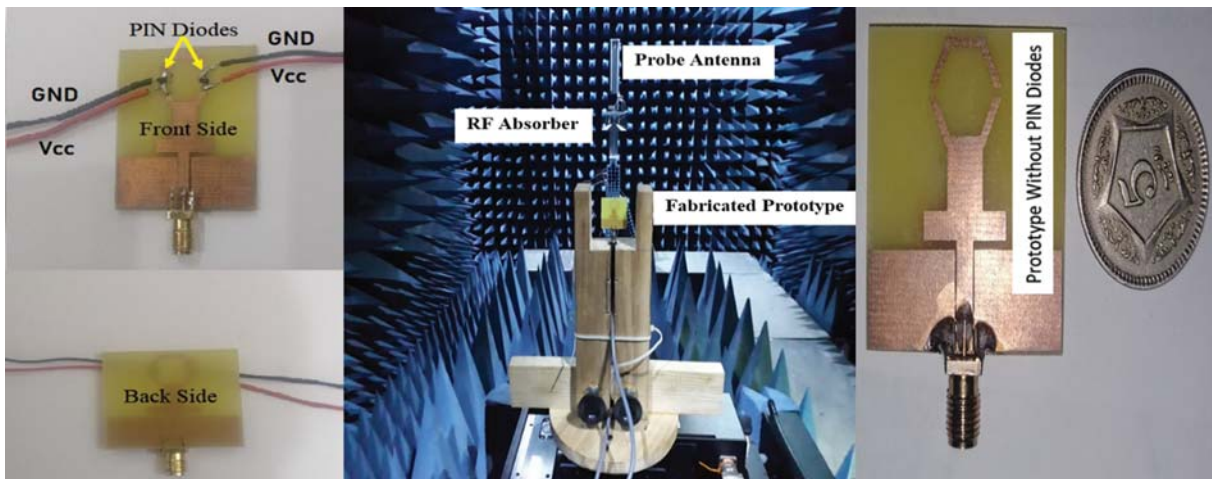


Figure 4: Anechoic chamber and fabricated prototype with PIN diodes

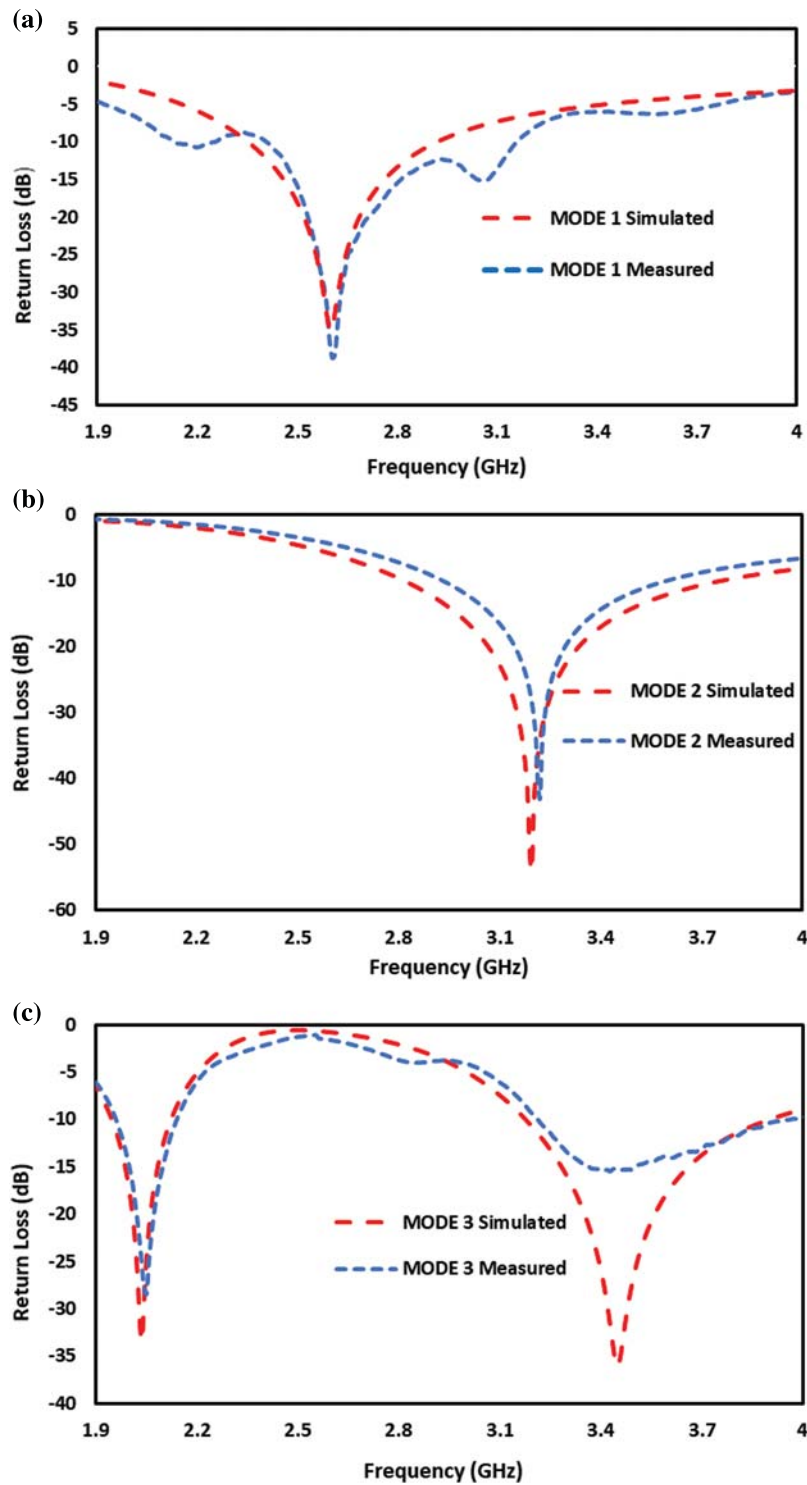


Figure 5: Simulated estimation and measured return loss for (a) Mode 1 (b) Mode 2 and (c) Mode 3

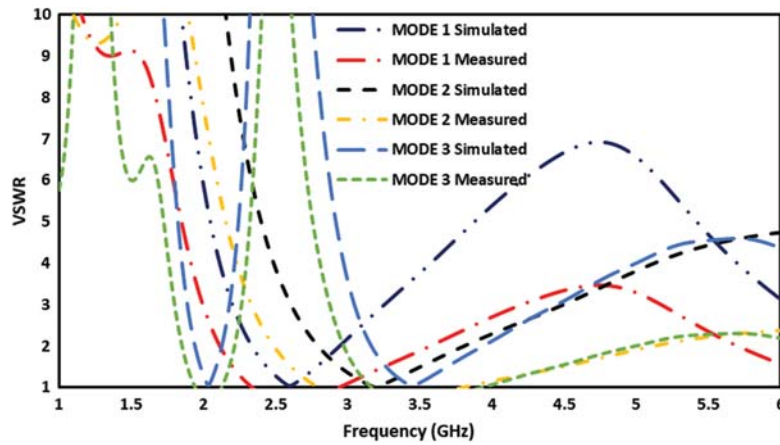


Figure 6: Simulated and measured VSWR in the three operating modes of the designed antenna

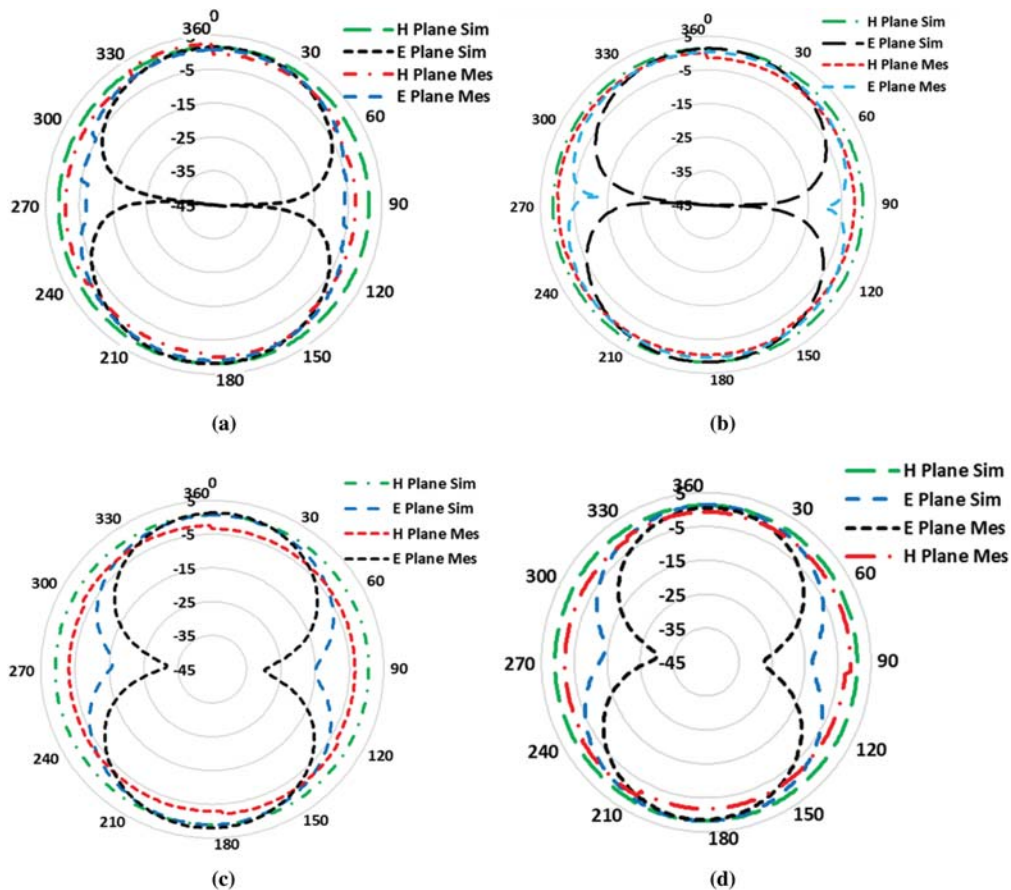


Figure 7: Simulation and experimental results comparison for E and H plane (a) 2.45 GHz (b) 3.2 GHz (c) 2.1 GHz (d) 3.5 GHz

3.2 Return Loss and Bandwidth

The case where ON state is selected for both switches ($S1 = S2 = ON$), the proposed antenna works in MODE 1, resonating at 2.45 GHz with return loss of -35.33 dB and simulated -10 dB

bandwidth of 602 MHz (2.34–2.941 GHz). In MODE 2 ($S1 = \text{OFF}$, $S2 = \text{OFF}$), the presented antenna resonates at 3.2 GHz with return loss of -42.17 dB and simulated -10 dB bandwidth of 923 MHz (2.81–3.73 GHz). In MODE 3 ($S1 = \text{ON}$, $S2 = \text{OFF}$), the proposed antenna operates in a dual band mode i.e., 2.1 and 3.45 GHz with return loss of -33.16 and -35.16 dB and simulated -10 dB bandwidth of 204 MHz (1.94–2.14 GHz) and 740 MHz (3.17–3.91 GHz), respectively. Fig. 5 illustrate the comparison of the simulation results and measured return loss of the purposed antenna in the three switching modes.

Fig. 6 shows that a voltage standing wave ratio (VSWR) of less than 1.5 is observed in all the resonant bands, which indicates optimum matching of the design.

3.3 Far Field Radiation

The simulated gain plots of the designed antenna are examined using the finite integration technique (FIT) used in CST MWS. The far-field radiation pattern in the three operating modes is a figure of eight in the E-plane and omni-directional in the H-plane. The radiation pattern of the antenna is displayed in Fig. 7 where simulated and measured results are compared. The peak gain of the antenna at 2.45, 3.2, 2.1, and 3.5 GHz, is 1.63, 1.97, 1.31 and 2.2 dBi, respectively. The gain versus frequency graph for the three switching MODES of the antenna is shown in Fig. 8. The three-dimensional directivity patterns of the antenna in the given resonant bands are shown in Fig. 9. At MODE 1 (ON state of both switch), the antenna functions at 2.45 GHz having directivity 2.2 dBi. In MODE 2 (Both Switches OFF), the directivity is 2.344 dBi at 3.2 GHz. In MODE 3 (only one switch ON), directivity of 2.01 and 2.25 dBi are achieved at frequencies 2.1 and 3.4 GHz, respectively.

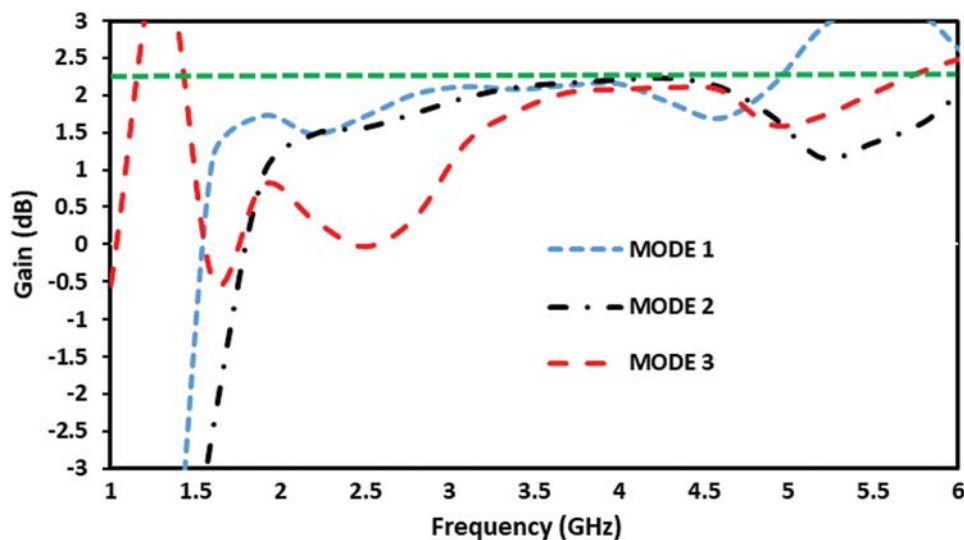


Figure 8: Simulated gain versus frequency plot of all three operating modes

3.4 Surface Current Distributions

The surface current distribution along the structure of the antenna is analyzed in CST microwave studio at 2.45, 2.1, 3.1 and 3.45 GHz as shown in Fig. 10. At lower frequencies of 2.45 and 2.1 GHz, the surface current intensity is maximum throughout the hexagonal

segment of the antenna which contributes to radiation at these frequencies. At 3.2 and 3.5 GHz a relatively smaller segment of the hexagonal geometry is contributing to radiation at these higher frequency bands.

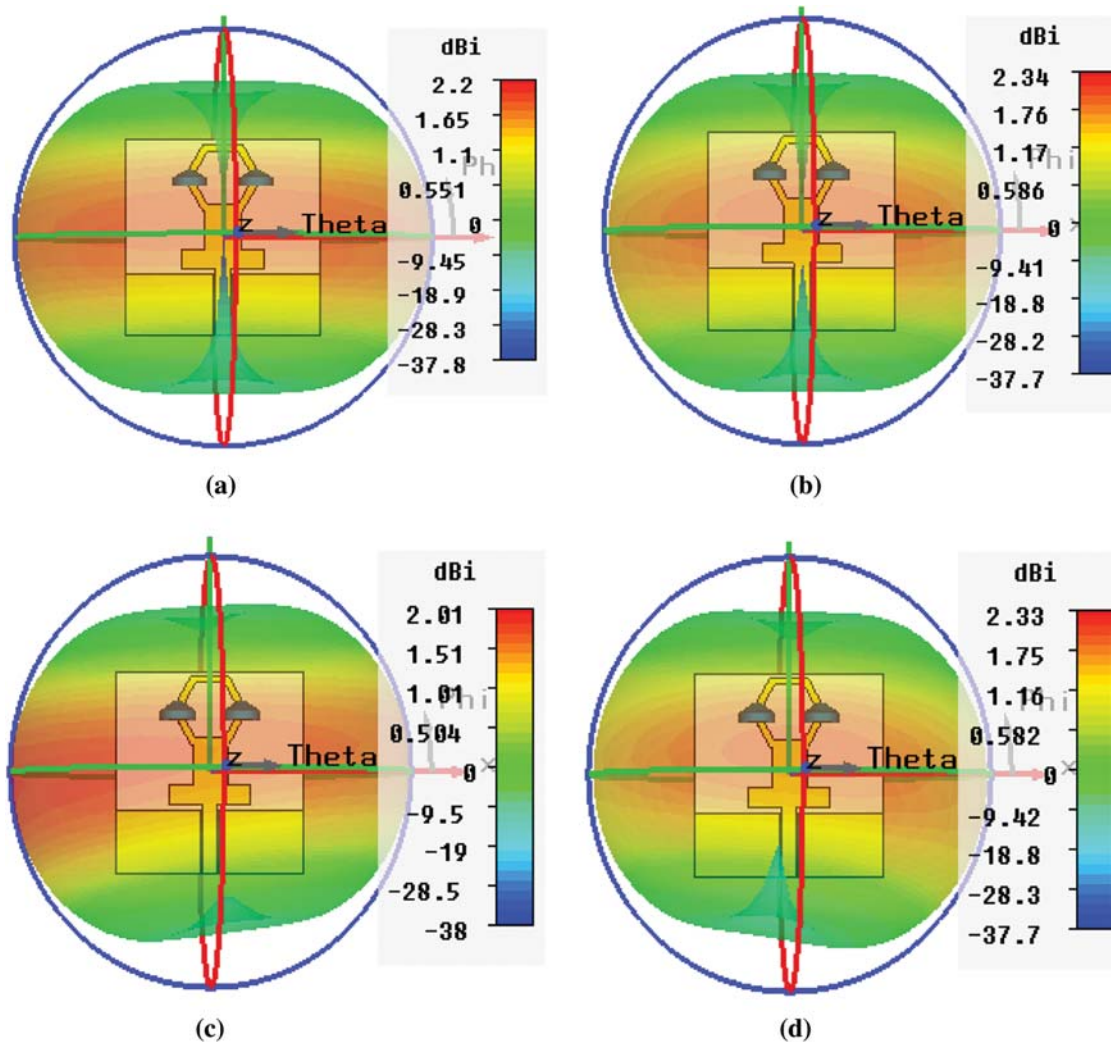


Figure 9: Three-dimensional directivity patterns for all operating MODES at (a) 2.45 (b) 3.2 (c) 2.1 (d) 3.5 GHz

The performance parameters of the hexagonal shaped antenna are summarized in [Tab. 3](#). The radiation efficiency of the proposed antenna is 91%, 92%, 78% and 89% at 2.45, 3.1, 2.1 and 3.5 GHz, respectively. The gain for all the bands is satisfactory for the intended application. The performance metrics of the proposed antenna are compared with the latest reported work in [Tab. 4](#). The comparison table demonstrates that the this antenna is relatively compact in size, with greater number of working bands, better gain, and better bandwidth as related to [29–34].

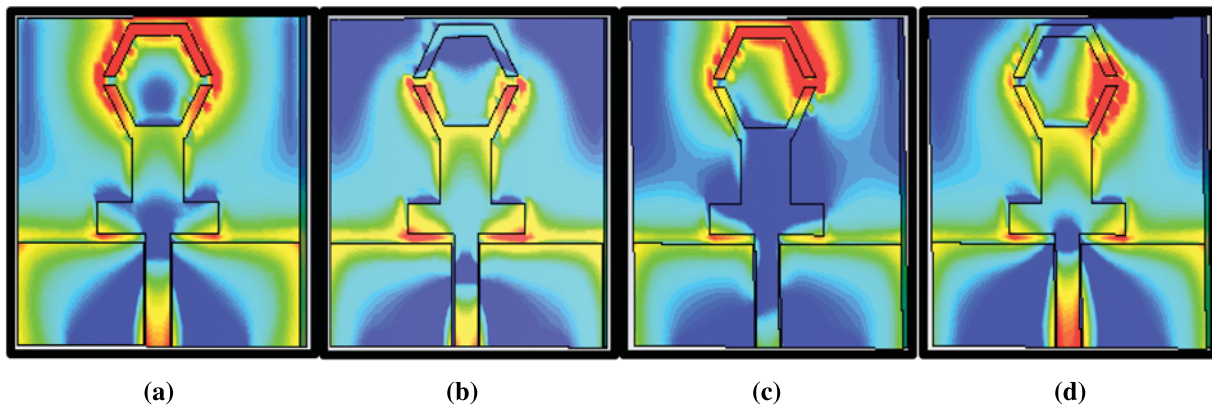


Figure 10: Surface current distribution for all operating MODES at (a) 2.45 (b) 3.2 (c) 2.1 (d) 3.5 GHz

Table 3: Simulation results summary

Mode	Conditions	Bands (GHz)	Gain (dBi)	Directivity	Bandwidth (MHz)	Efficiency (%)
1	Switches ON	2.45	1.73	2.2	602	80
2	Switches OFF	3.2	1.97	2.34	920	90
3	SW1 ON	2.1/3.5	1.01/1.86	2.01/2.25	204/740	91/95

Table 4: Proposed antenna as compared with other reported work

Ref.	Dimensions (mm ³)	No of operating bands	No of diodes	Operating frequencies (GHz)	Bandwidth (MHz)	Peak gains (dBi)
[30]	53 × 35 × 1.6	3	1	2.45, 3.50, 5.20	147–1820	1.7–3.4
[31]	100 × 65 × 1.6	3	N/A	0.9, 1.8, 3.28	N/A	0.2, 0.6, 3.28
[32]	113 × 113 × 1.6	3	2	1.32, 1.66, 2.54	134–370	N/A
[33]	40 × 35 × 1.6	3	1	2.45, 3.5, 5.2	330–1250	1.48–3.26
[34]	40 × 35 × 1.6	6	2	2.10, 2.40, 3.35, 3.50, 5.28, 5.97	335–1220	1.92–3.8
[35]	39 × 37 × 1.6	3	1	2.4, 5.4, 3	550–1220	1.27–2.34
[36]	116 × 141 × 1.6	3	3	1.6, 2.5, 3.2	wideband	N/A
This work	37 × 35 × 1.6	4	2	2.1, 2.45, 3.2, 3.5	200–920	1.25–2.2

4 Conclusion

A Hexagonal-shaped frequency reconfigurable CPW-fed antenna has been designed and experimentally validated in this article. The presented antenna has switching-dependent frequency characteristics via ON and OFF conditions of the integrated two switches. When both the switches are in ON condition (MODE 1), the antenna functions in a single frequency band (2.45 GHz). Antenna operates at 3.2 GHz when OFF condition is selected for both switches, whereas the proposed antenna works in a dual band frequency mode (2.1 and 3.5 GHz) when S1 is in ON condition and S2 is in OFF condition. The proposed antenna has many advantages like compact size, low cost, light weight, and ease of fabrication, over previously presented designs. The antenna has been designed for 3.5 GHz (WiMAX), 2.1 GHz (3G UMTS and LTE), 3.3 GHz (5G sub-6 GHz band) and 2.45 GHz (Wi-Fi) frequency bands with miniature design for portable devices.

Funding Statement: This research was supported by SUT Research and Development Fund.

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

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