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Frequency Reconfigurable Circular Monopole Antenna with Key Shaped Ground Stub

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ABSTRACT: In this paper, a unique low profile double stubbed ground plane frequency reconfigurable circular monopole antenna is introduced. The ground plane contains two RF-PIN diodes that enable the antenna to be reconfigured in ultra-wideband (3.2–10.8 GHz) and dual frequency (2.8–4.01 GHz and 7.56–8.2 GHz) modes. The proposed antenna is designed using an FR-4 substrate with the dimension about $33 \times 28 \times 1.6\,\text{mm}^3$. The impedance matching of the antenna at ultra-wideband operation is improved by a defected ground structure. The measured and simulated results of the antenna are in close agreement. This antenna is useful for cognitive radio application.

1. INTRODUCTION

With the advancement of wireless technology, achieving adequate coverage across multiple frequency bands using a single antenna while maintaining appropriate gain and wide bandwidth poses a great challenge for antenna designers. The device's cost and dimensions will increase if it includes multiple antennas for different operating frequencies [1]. One possible solution is to use a frequency reconfigurable antenna, which can lower the size and cost of the device by altering its operating frequency to a desired one.

Today, ultra-wideband (UWB) technology is of tremendous interest to researchers due to its unique attributes such as high data rate, broad bandwidth, low profile, low power transmission, omnidirectional radiation pattern, and ease of fabrication [2]. One of the key research subjects in antenna design and development is the design and development of miniaturized antennas capable of providing reconfigurable wideband/multiband operating phenomena due to their multiple resonance frequencies [3]. Narrow band operations in the 3.1–10.6 GHz frequency range generate electromagnetic interference, which degrades UWB antenna performance [4]. Reconfigurable antennas are made to play a crucial part in managing antenna responses and minimizing the drawbacks of UWB antennas. Microstrip antennas are well suited for the usage in wireless communication due to their small size, low cost, and ease of production [5]. Reconfigurable antennas were designed using a variety of techniques, including MEMS (micro-electro-mechanical switch) [6, 7], PIN diodes [8], varactor diodes [9], etc. as switching elements.

Various types of frequency reconfigurable antennas according to the requirements and applications have been reported [10–28]. Frequency reconfigurable antennas have been presented in [10–14] to switch from one narrow single band frequency to another single band frequency. In contrast, single band to multiband frequency band was altered in [15–19]. Numerous studies [20–22] also addressed wide band to single band or multiband antenna integration. A UWB antenna with notch band was proposed in [23–25]. Apart from that, certain frequency-reconfigurable antennas with UWB to narrow band capabilities have also been described in [26–28].

A printed monopole antenna for wireless Local Area Networks (WLAN) and Universal Mobile Telecommunication System (UMTS) bands application was proposed in [10]. In every operating state, it only covered a single narrow band. In [11], a reconfigurable antenna that transitioned to a slot antenna was presented. Five RF-PIN diodes were employed in this antenna design, which functioned at 1.98 GHz and 3.59 GHz. A frequency-reconfigurable bow-tie antenna with six RF-PIN diodes was proposed in [13]. However, it was limited to certain frequency ranges. In [14], varactor diodes were used to create a grid slotted antenna with tunable frequency reconfigurability. The structure of this antenna is more intricate because it uses three separate layers. Only a single narrow band to dual band frequency reconfiguration was achieved in [16] using a single diode. A reconfigurable antenna in the shape of a key was designed in [18] for single-to-multi-band operations. In [20], a wide-band to narrow band antenna was designed. It has a narrow band dipole and a wideband magneto-electric dipole antenna. But because of its three-dimensional structure and complex geometry, it has limited uses. A wideband to narrow band antenna covering only 2 GHz to 6 GHz was demonstrated in [21] and was made using four RF-PIN diodes. In [22], a Vivaldi antenna with coplanar waveguide (CPW) to slot feed was suggested. Using six RF-PIN diodes switches, frequency reconfigurability from wide band to narrow band was accomplished. The antenna was excessively large in size. Ref. [23] suggested to reconfigure a maple leaf-shaped triangular hybrid fractal monopole that may be used to notch the bands using varactor diodes. In a previous study [24], it was proposed to use a slot antenna in combination with a

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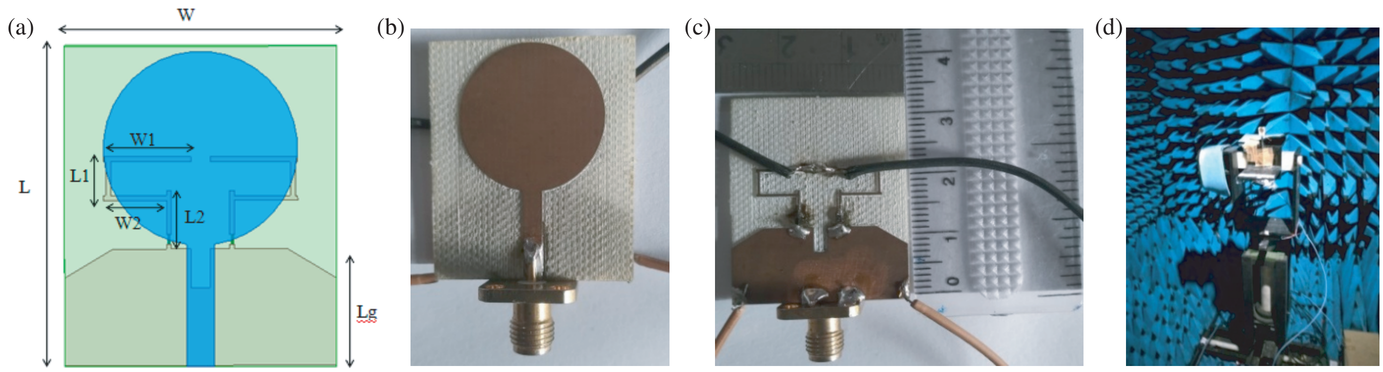

FIGURE 1. (a) Layout of the Proposed Antenna. (b) Fabricated proposed antenna (top view). (c) Fabricated proposed antenna (bottom view) (d) proposed antenna under test in Achonic chamber.

rectangular split ring resonator positioned below the antenna and three RF PIN diodes. Another study [25] presented a dual notch UWB reconfigurable antenna by employing double split ring resonators on both sides of the feed line and a pi slot on the octagon patch antenna. However, in these studies [10, 24, 25], the lumped elements were placed on the radiating patch side of the antenna, causing disruption in the radiation pattern. Five RF-PIN diodes were used in [27] to design a stepped slot UWB mode and narrow band mode of operation. Ref. [28] presented a liquid metal bandwidth reconfigurable antenna for narrow band and UWB applications. However, implementing a liquid metal switch is not simple.

This work presents a low profile, frequency reconfigurable antenna that can be used in dual band and UWB scenarios with two diodes operation. UWB frequency range (3.2 GHz to 10.8 GHz) is covered by the antenna while RF-PIN diodes are in the OFF state. In the ON state, the antenna functions as a dual-band antenna, covering frequencies of 2.8–4.01 GHz and 7.56–8.02 GHz. The proposed antenna's ground plane has two key-shaped stubs. These two stubs enable the antenna's dual modes of operation. This antenna is useful for cognitive radio applications; the basic requirement of the cognitive radio is to use two antennas: one antenna for sensing the whole UWB and the other for communication purpose [29]. The proposed antenna covers UWB (3.2–10.8 GHz) when both RF PIN diodes are in the OFF state and acts as a sensing antenna. For communication, when both RF-PIN diodes are in the ON state, it covers 2.8–4.01 GHz (5G applications) and 7.56–8.2 GHz (short-range point-to-point communication). This paper's contribution can be summed up as follows:

1. The antenna is beneficial for cognitive radio applications since the suggested antenna works for sensing (UWB) and communication (Dual bands) in a single port antenna on different modes of operation by using a time-sharing mechanism and single port antenna which reduces the extra isolation structure for two different antennas.
2. The proposed antenna uses only two RF-PIN diodes (Lumped components) that are placed on the ground plane, so these components do not disturb the antenna radiation characteristics.
3. The suggested antenna has a single layer of construction and is simple to install for any purpose.

2. ANTENNA CONFIGURATION AND EVOLUTION OF GEOMETRY

2.1. Antenna Configuration

The overall footprint of proposed frequency reconfigurable microstrip patch antenna is $33 \times 28 \times 1.6\,\text{mm}^3$. The proposed antenna is printed on an FR-4 ($\varepsilon_r = 4.4$) glass epoxy dielectric substrate with a thickness of 1.6 mm and loss tangent $\tan\delta$ of 0.02. The proposed antenna's structure is depicted in Fig. 1. The proposed antenna is fed by a 50-Ω feed line. The optimized feed length is 12.6 mm with the optimized feed gap, ans the gap between patch and ground plane is 0.6 mm. To achieve perfect matching between patch and the feed line, the width of feed line is calculated as given in [29]. The antenna has two identical stubs in the ground plane that resemble a key. They function as filters when being attached to the ground plane. Because of this, it only transmits in the 2.8–4.01 GHz and 7.56–8.2 GHz frequency ranges. These stubs are connected to the ground plane via two RF-PIN diodes (MA4AGBLP912). The stubs serve as a filter when the diodes are turned ON since they are grounded and only cross two bands of frequency. The length of the stub is approximately $0.25\lambda_0$, where λ_0 is the free space wavelength at frequency 3.0 GHz. The key-shaped stubs are used to reduce the size of the structure and increase the electrical length. The separation between two stubs is $0.06\lambda_0$ approximately. This antenna covers the whole UWB spectrum from 3.2 GHz to 10.8 GHz when the diodes are in the OFF state.

The lower band-edge frequency of UWB antenna is given by [2]

$$f_L = \frac{7.2}{(L + r + P)k}\ \text{GHz} \tag{1}$$

where P is the length of the 50 Ohm feed line in cm, $L = 2A$ and $r = A/4$, and A is the radius of the circular patch. k is

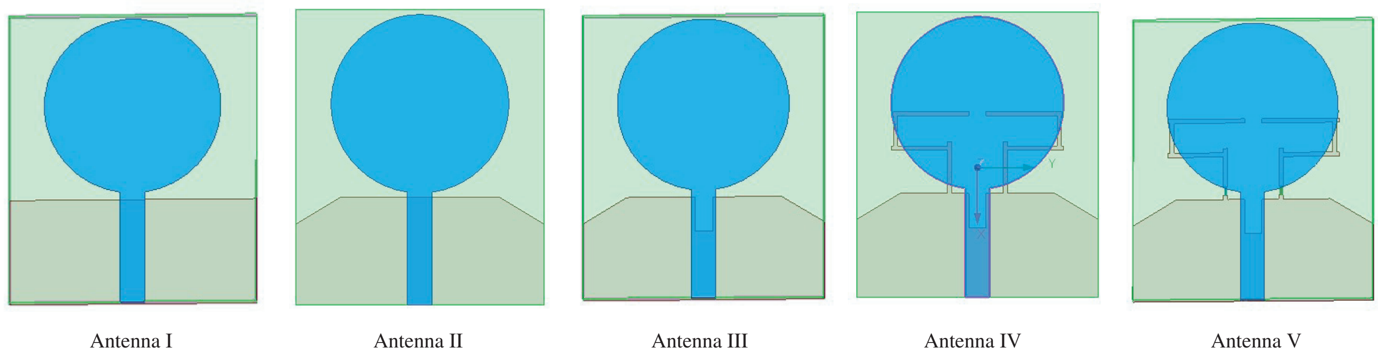

FIGURE 2. Evolution of Antenna geometry.

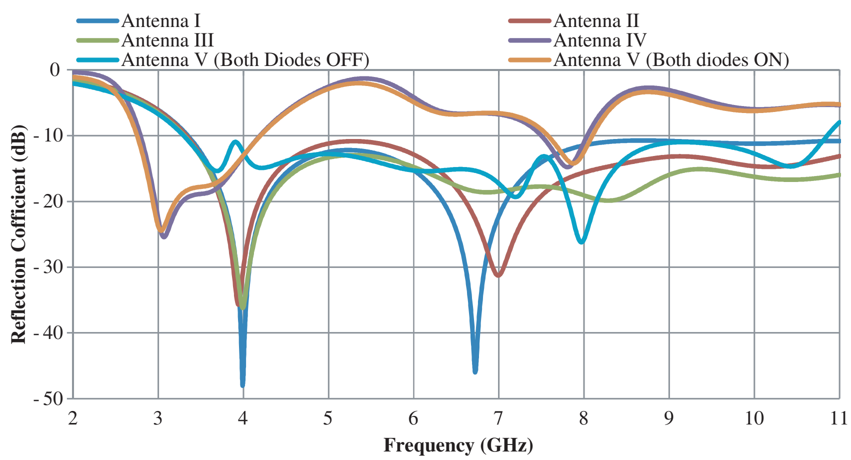

FIGURE 3. Simulated reflection coefficient at various stages of evolution of proposed antenna.

the empirical constant due to the dielectric layer present in the printed antenna.

2.2. Evolution of Geometry

The evolution of the proposed antenna geometry is depicted in Fig. 2. The proposed antenna is evolved in five design steps. The first step is to design an elementary circular monopole antenna (Antenna I) with a partial ground plane that covers UWB as shown in Fig. 2. The width of the ground plane is optimized for getting the best result. The optimized width 12 mm is considered, and the length of the ground plane is the same as the length of the dielectric substrate. Two triangular slots on the upper edge of the ground plane that creates a DGS as shown in Antenna II improve the UWB responsiveness of the antenna. In Antenna III, a rectangular slot is also included on the centre of the upper edge of the ground plane for the further improvement of UWB response. Now the next step is to achieve the dual frequency bands of operation by using UWB antenna. Two key-shaped stubs on the ground plane are used to get this purpose as shown in step IV. When two key shaped stubs are connected with the ground plane, extra resonances are produced by varying the length and placement of stubs or slots in the ground plane. These stubs alter the patch antenna's effective electrical length and current distribution, enabling it to resonate at dual frequencies. Now, two RF-PIN diodes are used to connect these two stubs with the ground plane so that Antenna III and Antenna IV responses are combined, and the proposed antenna works as a frequency reconfigurable antenna in two modes, UWB mode and dual frequency response mode. Due to the presence of RF-PIN diodes and key-shaped stubs that work as parasitic elements, when the diodes are in OFF state, they affect the reflection coefficient at state V. The S_{11} (Reflection Coefficient) responses of Antennas I, II, III, IV, and V are shown in Fig. 3.

2.3. Parametric Study

Table 1 presents the optimized dimensions of the proposed circular monopole frequency reconfigurable antenna. In order to

TABLE 1. Optimized dimension of the proposed antenna.

Parameter	Dimension (mm)	Parameter	Dimension (mm)
$L1$	3.5	$W2$	6.5
$L2$	4.5	Lg	12
$W1$	9	R	10
L	33	$L3$	4
W	28	$W3$	2

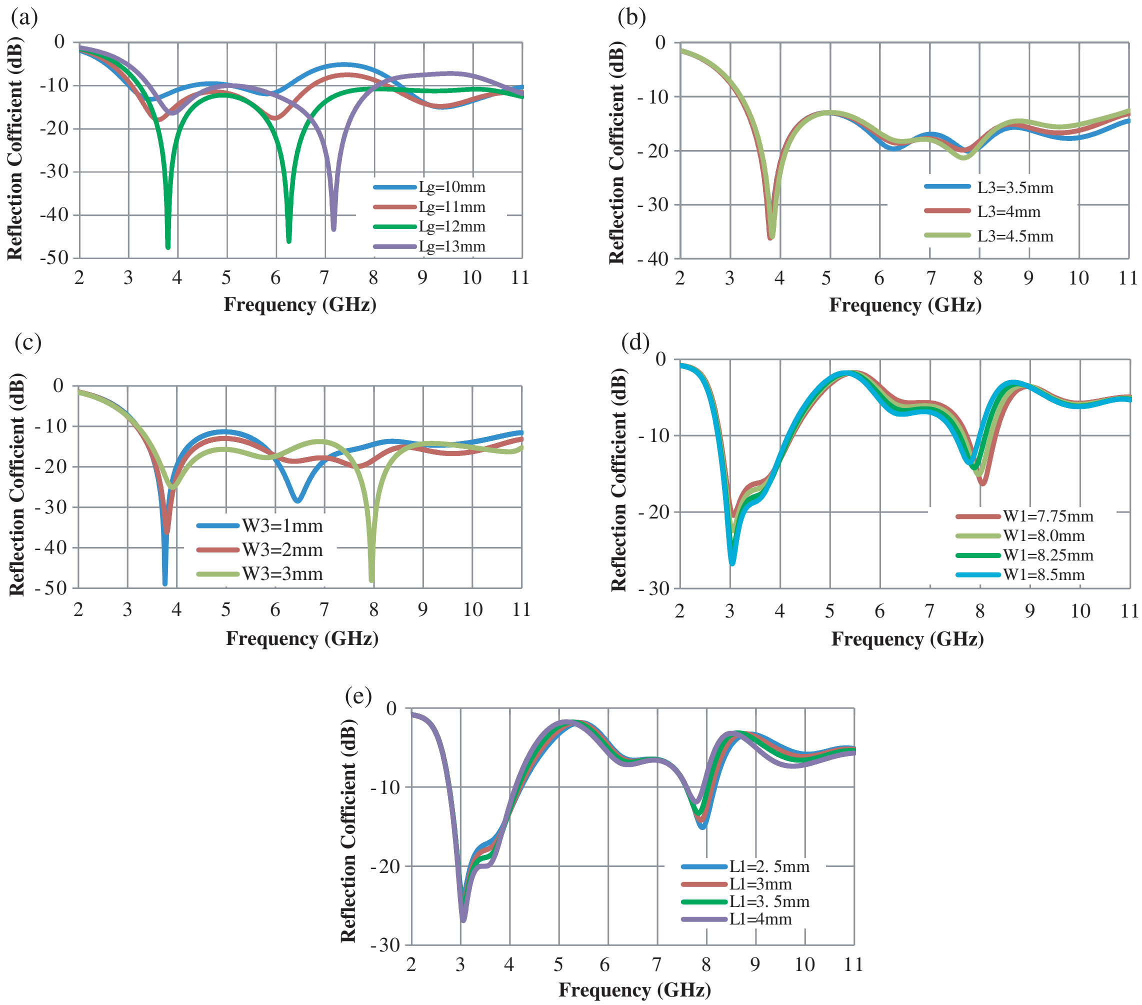

FIGURE 4. (a) Effect of the width of the ground on the performance of antenna (state 1). (b) Effect of the length of rectangular slot loaded in the ground plane. (c) Effect of the width of rectangular slot loaded in the ground plane. (d) Variation in $W1$ response when both diodes are at ON state. (e) Variation in $L1$ response when both diodes are at ON state.

comprehend the impact of antenna dimensions on resonant frequency and impedance matching, a comprehensive parametric study is conducted on various parameters, including the width of the ground plane (Lg), the length and width of the rectangular slot positioned on the ground plane ($L3$ and $W3$, and the stub length $(L1$ and $W1)$.

2.3.1. Effect of Ground on the Performance of Antenna

As shown in Fig. 2, the proposed antenna is designed using partial ground with DGS having a rectangular slot at the upper edge of the ground and two triangular slots at the two ends of the upper edge. Fig. 3 shows the effect of the ground plane (variation in the ground plane design) on the antenna performance.

The width of the ground plane is an important parameter for UWB operation. Fig. 4(a) shows the variation of width of the ground plane on the refection coefficient in step 1 of the ground plane, which shows that by changing the width of the ground plane, impedance matching is affected. It gives optimized result at the value of $Lg = 12$ mm. Figs. 4(b) and (c) demonstrate how the variation in the length and width of a rectangular slot placed on the ground plane affects the reflection coefficient (S_{11}). In Fig. 4(b), it can be observed that the length of the slot has minimal impact on the antenna's performance. However, Fig. 4(c) clearly shows that the width of the slot plays a significant role in the antenna's performance.

This can also be looked into using the parametric analysis of the antenna, when both diodes are at ON conditions in Figs. 4(d) and (e). It demonstrates that the modification of the dual mode frequencies is accountable for the variance in the length of the stubs.

The current distribution at frequencies of 3.5 GHz and 7.9 GHz when both diodes are in the OFF state is shown in Fig. 5(a). It shows the UWB operation due to the circular patch. In this case, grounded stubs are not involved. In Fig. 5(b), the current distribution is at 3.0 GHz and 7.9 GHz when both diodes are in the ON state. It was observed that more current is flowing in the key-shaped stubs in both cases. The current flowing in the key-shaped stub is responsible for the dual modes of operation when both diodes are in the ON state.

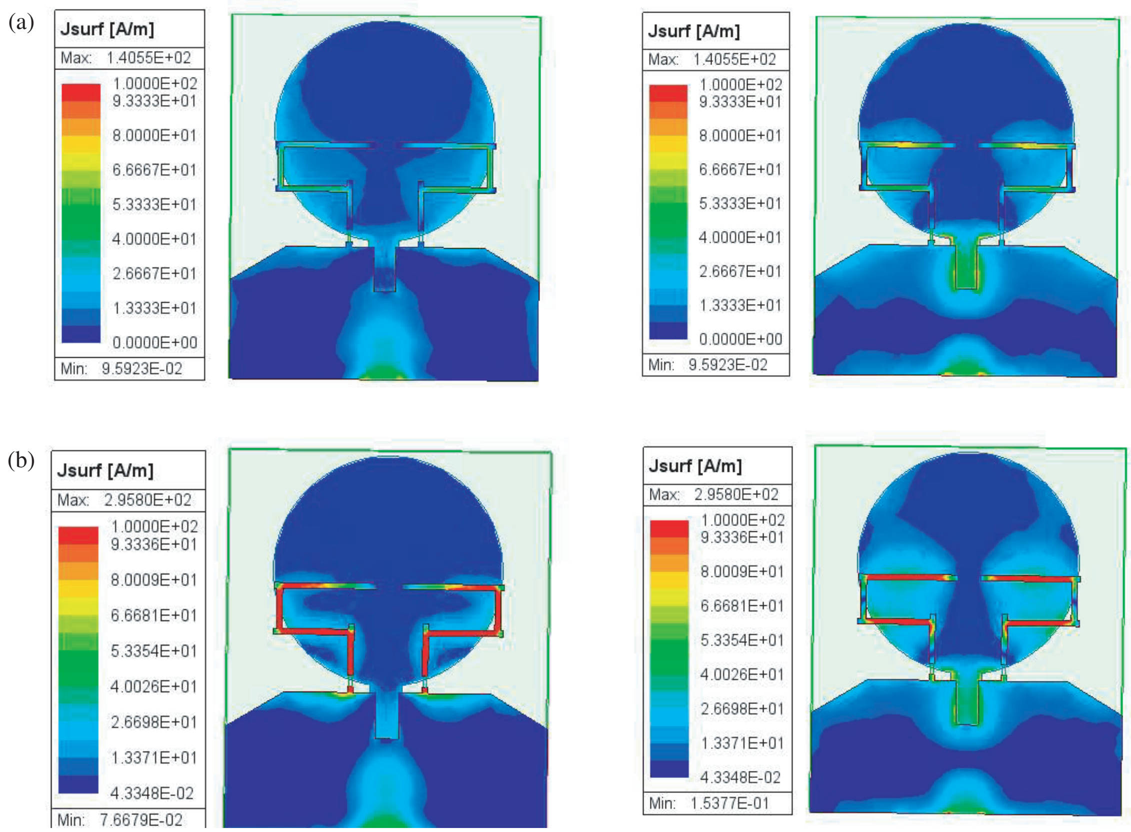

FIGURE 5. (a) Current distribution when both diodes are at OFF state at frequency 3.5 GHz and 7.9 GHz on the surface of stubbed ground plane. (b) Current distribution when both diodes are at ON state at frequency 3.0 GHz and 7.9 GHz on the surface of stubbed ground plane.

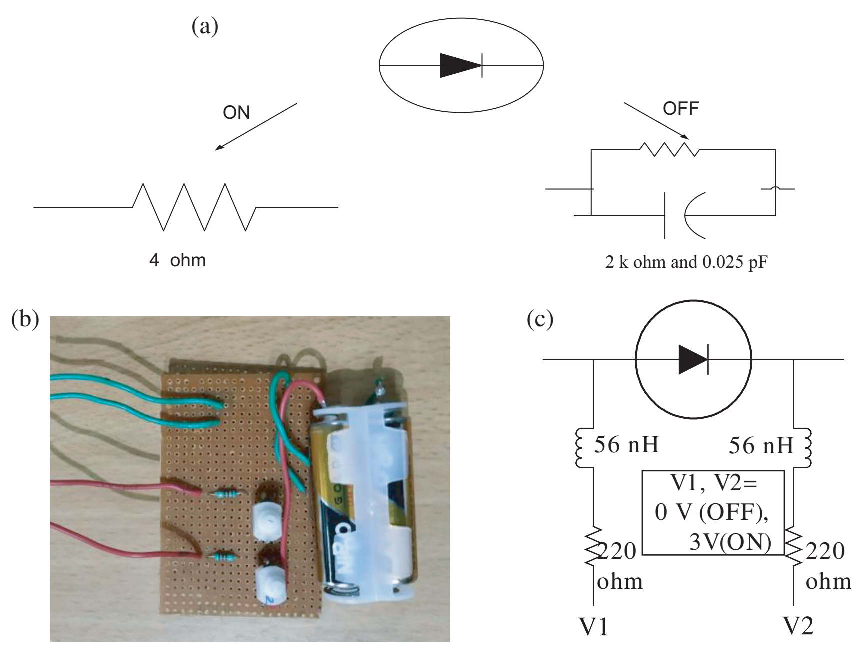

FIGURE 6. (a) Equivalent value of PIN diode *MA4AGBLP912 at OFF and ON state*. (b) and (c) External biasing circuit used for PIN diode.

3. RESULT AND DISCUSSION

Two RF PIN diodes MA4AGBLP912 are employed to accomplish frequency reconfigurability. The data sheet [30] states that it has a parallel circuit response of 2 kΩ resistance and 0.025 pF capacitance in the OFF state and that it exhibits 4 Ω resistance in the ON state as shown in Fig. 6(a). An external biasing circuit is created for the biasing of the RF-PIN diodes as shown in Figs. 6(b) and (c).

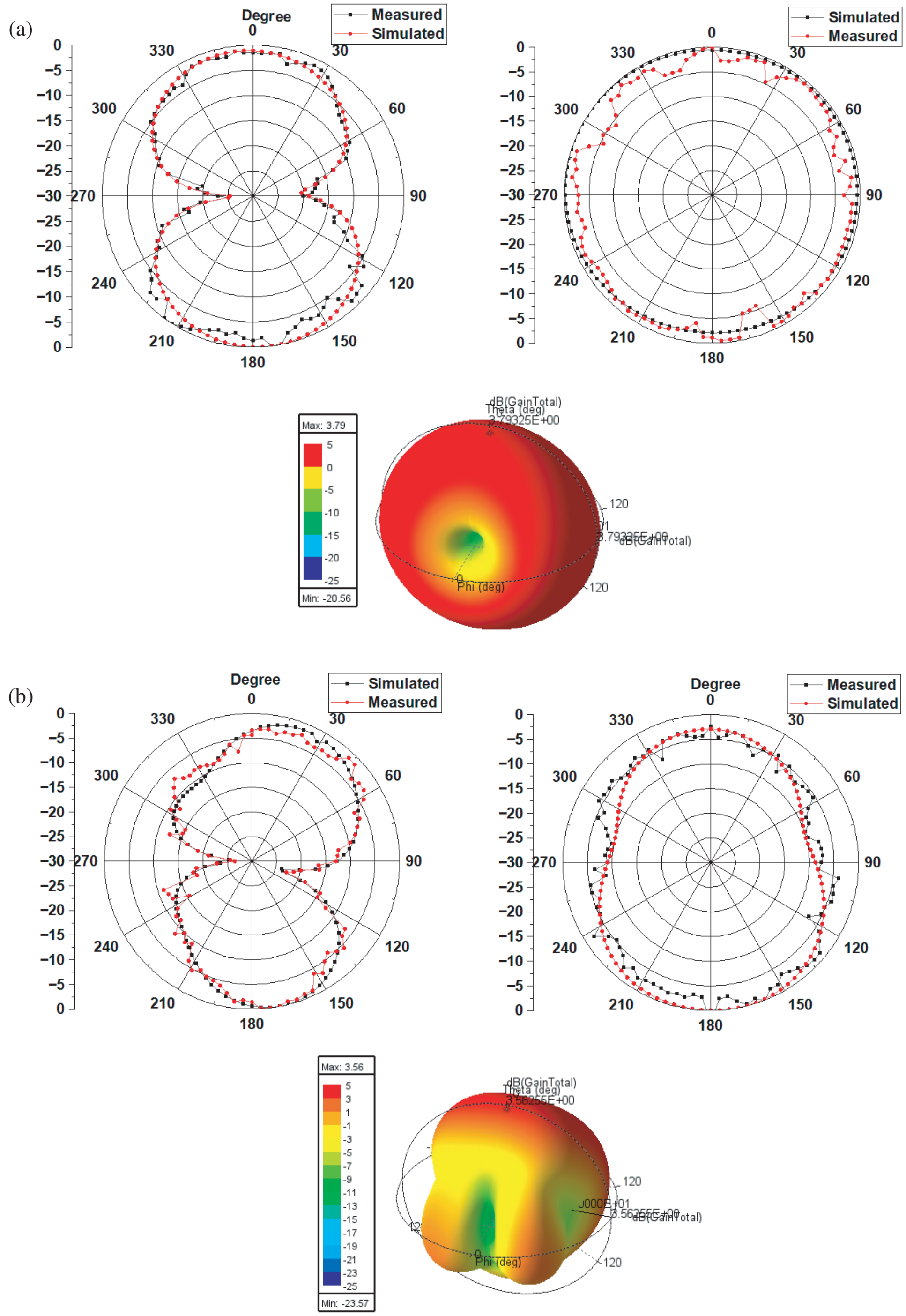

FIGURE 7. (a) Radiation pattern at frequency 3.5 GHz (Antenna V) Simulated and measured at E-Plane and H-plane at both diodes D1 and D2 are at OFF state. (b) Radiation pattern at frequency 7.9 GHz (Antenna V) Simulated and measured at E-Plane and H-plane at both diodes D1 and D2 are at OFF state.

EM full-wave simulator HFSS version 19.1 [31] is used to simulate the proposed antenna. The predicted outcome of two circumstances with the two diodes D1 and D2 ON and OFF states is shown in Fig. 3. Due to the absence of interference from dual stubs on the ground plane when both diodes D1 and D2 are OFF, the antenna covers the entire UWB (3.2–10.8 GHz). When both diodes are ON, the antenna operates in dual modes and covers two frequency bands (2.8–4.01 GHz and 7.56–8.02 GHz). The dual stubs operate in dual bands as a result of being attached to the ground plane. Size of the stub is approximately $0.25\lambda_0$ (λ_0 for 3 GHz). This demonstrates that the second resonance is the higher mode of the frequency and that it resonates in accordance with the length of the stub. The diode circumstances for which the suggested antenna operates are shown in Table 2.

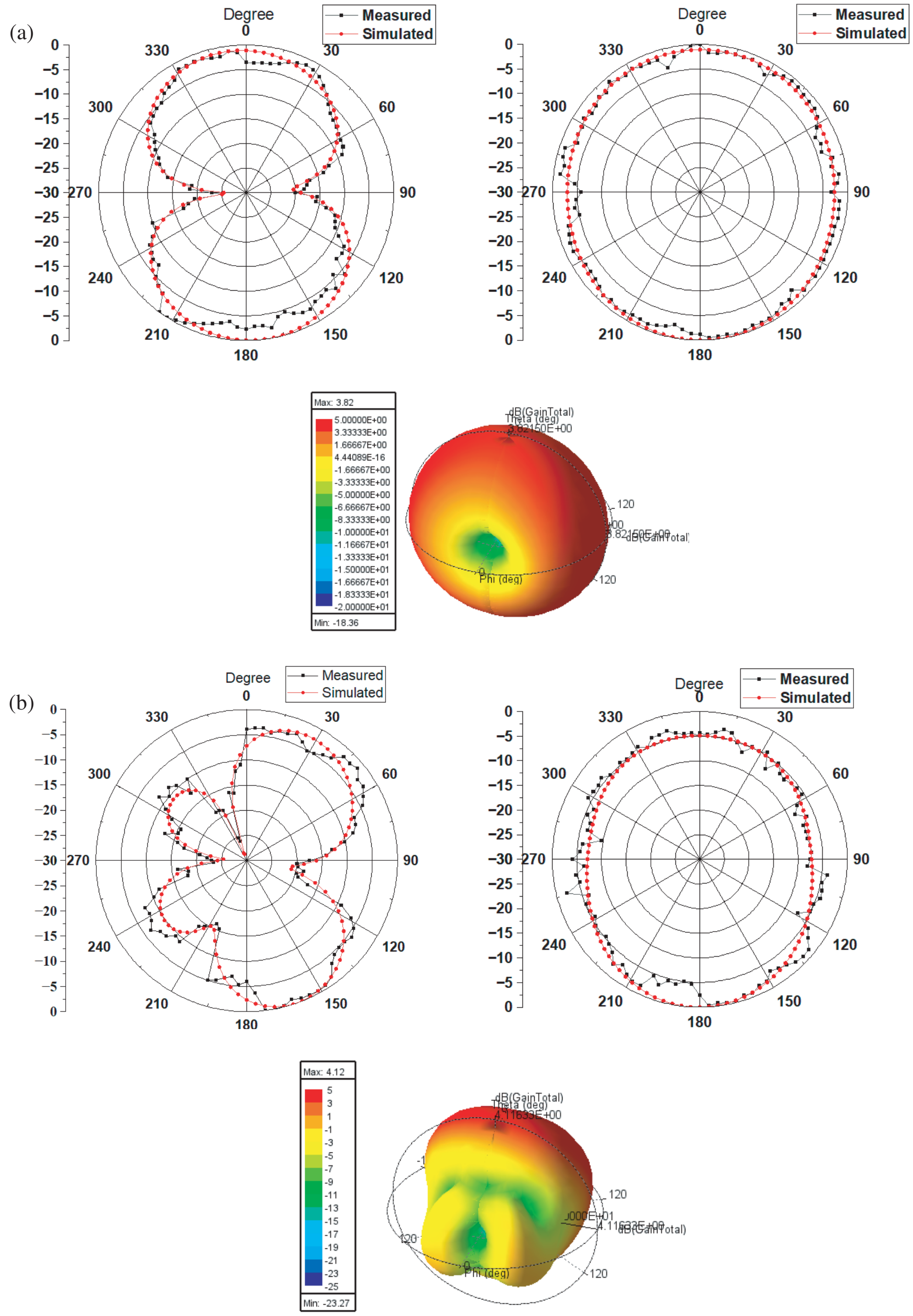

FIGURE 8. (a) Radiation pattern at frequency 3.0 GHz (Antenna V) Simulated and measured at E-Plane and H-plane at both diodes D1 and D2 are at ON state. (b) Radiation pattern at frequency 7.9 GHz (Antenna 3) Simulated and measured at E-plane and H-Plane at both diodes D1 and D2 are at ON state.

TABLE 2. Diode Operating Conditions for Proposed Antenna.

S No.	D1	D2	Operation
1	OFF	OFF	Covers (3.2 to 10.8 GHz)
2	ON	ON	Covers dual-band (2.8–4.01 GHz, 7.56–8.2 GHz)

The prototype of the proposed antenna is made using MITS-Eleven Lab Prototype machine and characterised in an anechoic chamber using Anritsu MS2038C vector network analyser. Radiation pattern measurement has been done in the anechoic chamber. The separation between the source and the antenna under test was 5 metres.

The simulated and measured 2-D radiation patterns at E-plane and H-plane and 3-D radiation at frequencies of 3.5 GHz

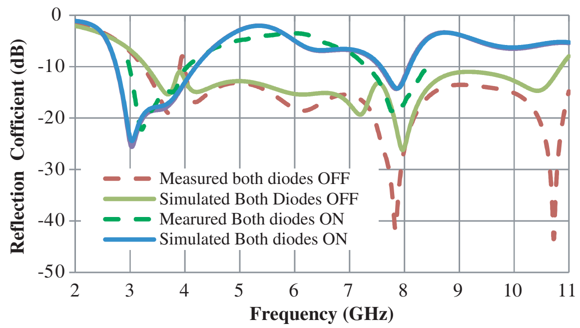

FIGURE 9. Simulated and Measured S_{11} of proposed antenna at condition when both diodes are at OFF and ON state.

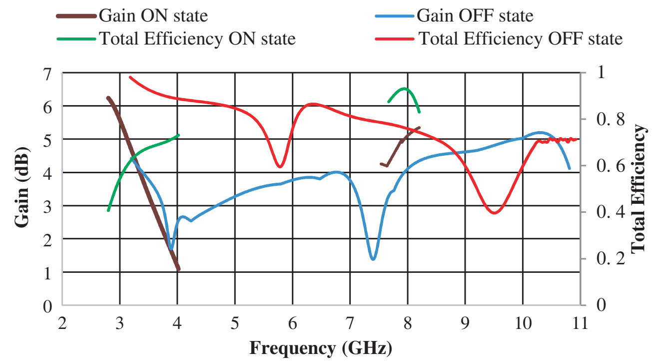

FIGURE 10. Gain and Total Efficiency of proposed antenna at condition when both diodes are at OFF and ON state.

TABLE 3. Comparison of proposed antenna with other presented work.

References	Size in wavelength	Frequency covered	Types of ground Used	No. of RF switch used
[11]	$0.33\lambda_0 \times 0.33\lambda_0 \times 0.020\lambda_0$	1.98–3.59 GHz	Slotted ground	05
[17]	$0.37\lambda_0 \times 0.37\lambda_0 \times 0.008\lambda_0$	3.8–5.9 GHz	Ground with rectangular ring slot	02
[18]	$0.32\lambda_0 \times 0.16\lambda_0 \times 0.010\lambda_0$	2–4 GHz	Partial ground	02
[19]	$0.30\lambda_0 \times 0.25\lambda_0 \times 0.017\lambda_0$	3.2–3.5 GHz and 5.2–5.8 GHz	Partial ground	01
[20]	$0.58\lambda_0 \times 0.58\lambda_0 \times 0.010\lambda_0$	2–6 GHz	Partial slotted ground	04
[25]	$0.41\lambda_0 \times 0.41\lambda_0 \times 0.014\lambda_0$	2.8–10.96 GHz	Partial Slotted ground	04
Proposed Work	$\mathbf{0.28\lambda_0 \times 0.33\lambda_0 \times 0.017\lambda_0}$	**UWB (3.2–10.8 GHz)/Dual band (2.8–4.01 GHz and 7.56–8.2 GHz)**	**Partial defected Ground with two stubs**	**02**

Note: — λ_0 is lower wavelength frequency of operation.

and 7.9 GHz are depicted in Figs. 7(a)–(b) when both diodes D1 and D2 are in OFF conditions. Antennas provide an omnidirectional radiation pattern in both situations. The measured E-plane and H-plane radiation patterns of the designed antenna at frequencies of 3.0 GHz and 7.9 GHz with all diodes in the ON state are depicted in the Figs. 8(a)–(b). From these figures, it is observed that the radiation patterns are omnidirectional at both frequencies.

Figure 9 shows the simulated and measured results of reflection coefficient when both diodes are in the OFF and ON states. Simulated and measured results are observed in close agreement. An external biasing circuit is employed to bias the diodes.

Figure 10 shows the simulated gain and the total efficiency of the proposed antenna at both conditions when both diodes are at OFF state and ON state. The gain varies from 1.5 dB to 5.2 dB in OFF state, and in ON state it varies from 2.9 dB to 5 dB. The maximum total efficiency of the antenna when both RF-PIN diodes are at OFF state is 98%, and when both diodes are at ON state, its maximum value is about 95%.

Table 3 shows the comparative analysis of proposed antenna with previously reported literature.

4. CONCLUSION

The suggested antenna has performed as a frequency-reconfigurable antenna. The proposed antenna covers UWB (3.2 GHz to 10.8 GHz) while two diodes are in the OFF conditions and placed on the ground plane. Additionally, the antenna has worked as a dual-band antenna and covered 2.8–4.01 GHz and 7.56–8.2 GHz, when both diodes are in the ON state, and the two stubs are attached to the ground plane. The nature of radiation pattern is omnidirectional at both states of operation, when both RF PIN diodes are at OFF state and ON state. The proposed circular monopole antenna with two stubs can be considered as a good candidate for cognitive radio application.

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