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Frequency reconfigurable circular microstrip patch antenna with slots for cognitive radio

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ABSTRACT

In this paper, a novel multi-frequency microstrip antenna with complementary ring slot resonator (CRSR) structure that satisfies Bluetooth, worldwide interoperability for microwave access (WiMAX), and wireless local area network (WLAN) applications is proposed. The conventional antenna consists of a circular microstrip patch at a resonance frequency band of 2.5 GHz. By loading two CRSR at the radiating element, three operating frequency bands 2.5 GHz, 3.6 GHz, and 5.2 GHz are achieved. The operational bands covered by the antenna are Bluetooth 2.5 GHz, WiMAX 3.6 GHz, and WLAN 5.2 GHz. The insertion of CRSR to patch antenna has made it possible to compact and simple design, and miniaturized antenna for cognitive radio. Moreover, the directivity of the proposed antenna is adequate with acceptable radiation properties and perfectly matches with the simulated and measured results.

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1. INTRODUCTION

With the increasing number of standards used for wireless communication devices and mobile phones, such as frequency modulation radio (FM), global system for mobile communication (GSM), global positioning system (GPS), universal mobile telecommunications system (UMTS), Bluetooth, wireless fidelity (WIFI), wireless local area network (WLAN), it becomes necessary to make these different standards coexist on the same mobile and a single receiving antenna. The frequency reconfigurable microstrip patch antenna with a software cognitive radio is a solution allowing the achievement of a receiver that can be adapted to multiple standards. This solution is the main aim of this work.

Cognitive radio is an intelligent communication system that can include a lot of functionality to meet the needs of coexisting multiple standards on a single device [1]. It is a radio that can change dynamically and autonomously its operating parameters. The cognitive radio requires antennas able of operating in different wireless standards, such as ultra-wideband antennas [2]-[6], but this type of antenna uses filters to eliminate interference between frequencies that makes the device more complex and heavier. To remedy this problem, it is better to use reconfigurable microstrip patch antennas (RMPA). The reconfigurable antennas for cognitive radio must be able to match with their environment by changing the operating frequency, polarization, or radiation pattern.

To achieve reconfigurability, several methods can be used, either by adding electrical components for example radio frequency micro-electro-mechanical systems (RF-MEMS), optical switches, and positive intrinsic negative diode (PIN) diodes, or by changing the geometry and the radiating element structure [7]-[9]. The patch could be of different shapes such as: square, triangular, elliptical, rectangular, or circular. The difference between the circular and the rectangular microstrip patch antenna is the number of the parameter to control, it has only one parameter i.e. radius for the circular antenna as compared to the rectangular microstrip that is two i.e. length and width.

Notice that, the frequency of circular microstrip patch antenna depends on three parameters, which are, ε_r dielectric constant of the substrate, h thickness of the substrate, and a radius of the patch. Since the thickness and dielectric constant of the substrate are fixed parameters. The radius of the patch will be used as a variable parameter.

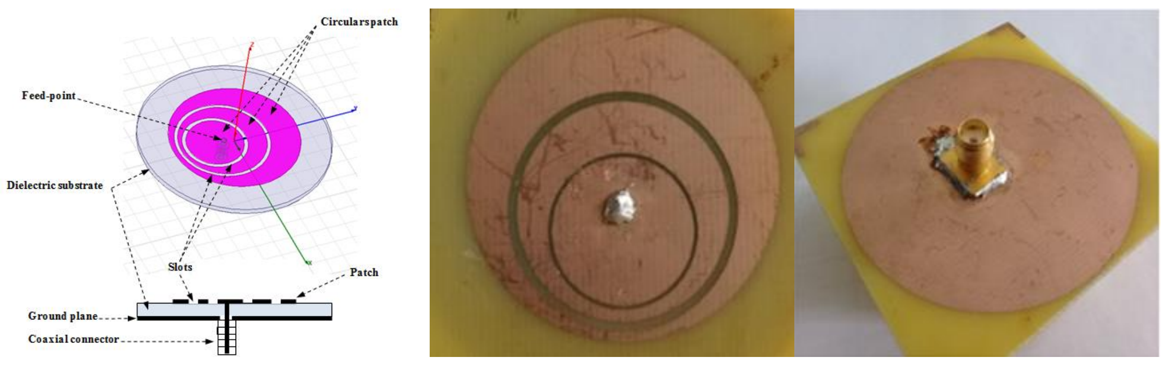
In recent years, different designs of patch antennas for multi-frequency operation have been presented by many researchers. In [10], [11] proximity coupled feed technique was used for dual-band frequency operation, this technique was very difficult to design and manufacture for real-world antennas. A new compact antenna design has been presented for cellular and WLAN communications. Jhamb *et al.* [12] it uses the coaxial feed technique with defected ground structure (DGS) to create such a compact design but the bandwidth of the proposed frequency bands has been increased. Malik *et al.* [13] have proposed a square patch antenna that operates in six different frequency bands, square loop elements are introduced to achieve multi-band characteristics, the proposed design is simple, on the other hand, it is larger in the area compared to the designs presented previously.

In this, paper a novel reconfigurable triple-band circular microstrip patch antenna using two complementary ring slot resonators (CRSR) is proposed. The insertion of CRSR's in the radiating element changes the electrical dimensions and the current distribution of the patch and hence gives a variation in the resonant frequency, but a significant impedance mismatch is observed, this problem gets solved by changing the position of CRSR relative to the center of the radiation element. The frequency agility was achieved by inserting six PIN diodes inside the CRSR's to eliminate its effect and consequently their resonances. The proposed antenna design was able to provide a tri-band response for desired norms (Bluetooth, worldwide interoperability for microwave access (WiMAX), and WLAN).

This paper is organized as follows: section 2 explains the design methodology and geometry of the proposed antenna. The effect of the feed point position, as well as the geometry and design antenna with variable frequency, are explained in section 3. The comparison between a simulation and measurement results of the reflection coefficient is presented in section 4. Finally, the conclusion of the paper is presented in section 5.

2. PROPOSED ANTENNA DESIGN

The design and prototype of the proposed circular microstrip antenna are shown in Figure 1(a) and Figure 1(b). The circular patch is mounted on the FR-4 epoxy substrate, which has a dielectric constant ε_r = 4.4 with a radius of the ground 25 mm and thickness h = 1.4 mm. About the excitation, there are several methods to feed microstrip patch antennas. The frequently used ones are microstrip line, coaxial probe, and aperture coupling [14], [15]. In the proposed circular patch antenna design, a coaxial probe is used.



(a) (b)

Figure 1. Design and prototype of the proposed circular microstrip antenna: (a) geometry of the antenna and (b) photograph of the top and bottom view fabricated antenna

At first, the design evolution of the antenna starts with a circular microstrip patch antenna as radiating element as shown in Figure 2. The radius of the reference patch antenna at the operating frequency 2.5 GHz is 17 mm [16], [17] by using (1) and (2).

$$a = \frac{F}{\left\{1+\frac{2h}{\pi\varepsilon_r F}\left[In\left(\frac{\pi F}{2h}\right)+1.7726\right]\right\}^{1/2}} \tag{1}$$

Where:

$$F = \frac{8.791x10^9}{f_r\sqrt{\varepsilon_r}} \tag{2}$$

ε_r = dielectric constant of the substrate
h = thickness of the substrate
a = radius of the patch
f_r = resonant frequency

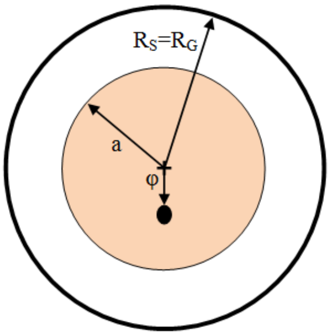
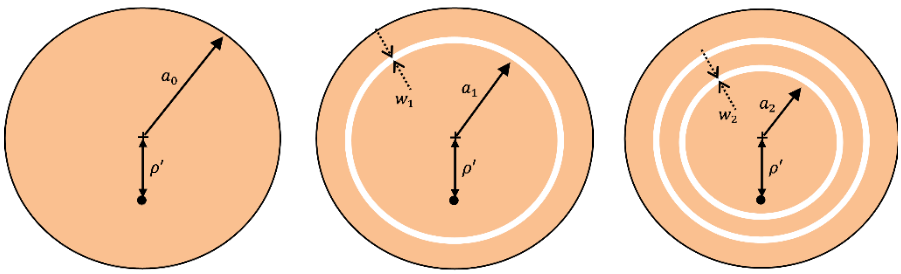


Figure 2. Reference antenna

To achieve a frequency offset function of the basic antenna as displayed in Figure 3(a), complementary ring resonator with the radius a_1 = 11.55 mm and width w_1 = 0.5 mm is etched in the circular radiating patch as shown in Figure 3(b), this addition of CRSR results in a frequency swing from 2.5 GHz to 3.6 GHz. Finally, another CRSR with an inner radius a_2 = 7.69 mm and width w_2 = 1 mm is etched to obtain a resonant frequency of 5.2 GHz as shown in Figure 3(c). The radius a_1 and a_2 for the two slots are obtained by using the (1). The design evolution of the antenna is presented in Figure 3.



(a) (b) (c)

Figure 3. The design evolution of antenna: (a) reference antenna, (b) antenna with CRSR, and (c) antenna with two CRSR's

Typically, the proposed circular patch antenna has a triple resonance frequency due to the CRSR introduced in the radiating patch [18]. These slots create two other modes for resonating at higher frequencies compared to the typical patch mode. This is due to currents resonating on a shorter geometric surface, as shown in Figure 3(b) and Figure 3(c). These modes are strongly dependent on the geometry of the slot (a_1, a_2, and w_1, w_2), while the reference patch mode depends mainly on the resonance length of the patch (a_0).

To provide a better understanding of the performance of the proposed antenna, a commercial electromagnetic solver, high-frequency structure simulator (HFSS), is employed to model the antenna. The results obtained from the three antennas are not satisfactory in the term of reflection coefficient 'S_{11}', because the final structure antenna shown in Figure 3(c) is not well adapted in impedance due to the addition of the two CRSR's in the radiating element patch and also to the position of the feed. To solve this problem a study was carried out in the next session.

3. PARAMETRIC ANALYSIS

The methodical parametric study was carried in order to interpret the mechanism of frequency variation and to recognize the influence of some physical parameters on the behavior of the antenna, such as the position of the feed point well as the position of the CRSR. The input impedance plays a very important role in the design of microstape antenna. The input impedance deends on the patch and the feed position as well. The feed point must be located at that point on the patch, where the input impedance is 50 Ω for the specified resonant frequency.

3.1. Effect of the feed point position ρ'

In this section, the effects of the feed point position on impedance and reflection coefficient are discussed. The input impedance at any radial distance $\rho' = \rho_0$ from the center of the circular patch is real and can be written as [14].

$$R_{in}(\rho' = \rho_0) = \frac{1}{G} \frac{J_m^2(k\rho_0)}{J_m^2(k\rho a_e)} \tag{3}$$

Where G is the conductance, J_m is the Bessel function of the first kind of order m, k is the phase constant, and a_e is the effective radius.

For the circular patch antenna, the resonant input resistance with an inset feed, which is usually a probe, can be written as:

$$R_{in}(\rho' = \rho_0) = R_{in}(\rho' = a_e) \frac{J_m^2(k\rho_0)}{J_m^2(k\rho a_e)} \tag{4}$$

The reflection coefficient is defined by the following relation:

$$\Gamma = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \tag{5}$$

Where Z_{in} is the impedance of the antenna and Z_0 is the characteristic impedance of the 50 Ω sub-miniature version A (SMA) port.

According to (4) and (5), the resonant input resistance and the reflection coefficient depend on the feed point position. To understand this effect, the simulated reflection coefficient for the operating frequency 2.5 GHz, 3.6 GHz, and 5.2 GHz is illustrated in Figure 4 when the position of the feed point alters from 0 mm to -17 mm, -11.55 mm, and -7.69 mm respectively. It is apparent from the (5) and Figure 4 that the maximum value of the reflection coefficient $|S_{11}|$ for the evolution antenna a, b, and c occurs at the optimum position feed point where the impedance of the antenna and SMA port are well matched. The minimum value occurs at the center and the edge of the radiating element patch.

It can be seen that the matching of the antenna is very sensitive around the optimal value of the feed point position. This study then made it possible to determine the most appropriate location to insert the SMA connector. Table 1 depicts the optimum values of the feed point position for the three circular microstrip antennas [19], [20].

Table 1. Values of the feed point position for the three antennas

Parameters	Reference antenna	Antenna with slot	Antenna with two slots
Radius of circular patch	17.00 mm	11.55 mm	7.69 mm
Operating frequency	2.5 GHz	3.6 GHz	5.2 GHz
Optimum feed point location from center (x, y)	(0 mm, -9 mm)	(0 mm, -4.3 mm)	(0 mm, -2 mm)

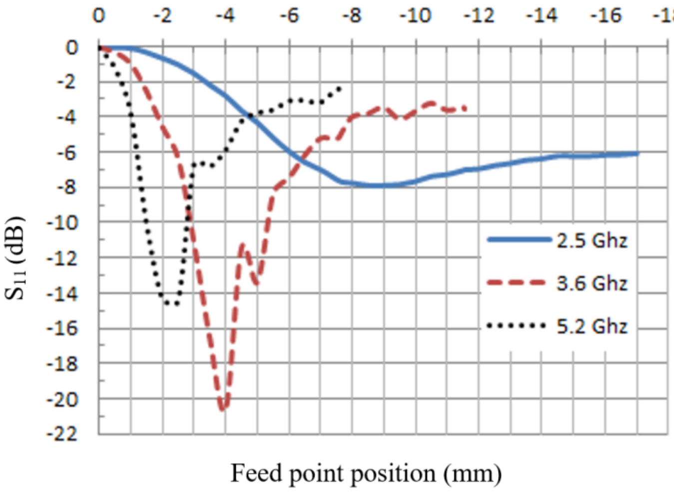


Figure 4. Reflection coefficient versus feed point position for circular microstrip patch operating in frequency 2.5, 3.6, and 5.2 GHz

3.2. Effect of the position of the CRSR

We are interested in this part, to investigate the effect of the position of the CRSR on the reflection coefficient S_{11}. The parametric analysis of different values of the position of the center $C_{3.6}$ for the resonant frequency 3.6 GHz is depicted in Figure 5 (where $C_{3.6}$ is the center of the complementary ring slot resonator). The values of the reflection coefficient S_{11} for C = 0, -0.5, -1, -1.5, -3, -3.5 and -4.5 mm are -20.73, -12.88, -11.61, -14.99, -12.12, -11.21 and -17.68 dB respectively. Therefore we can use this parameter as a solution for the following study.

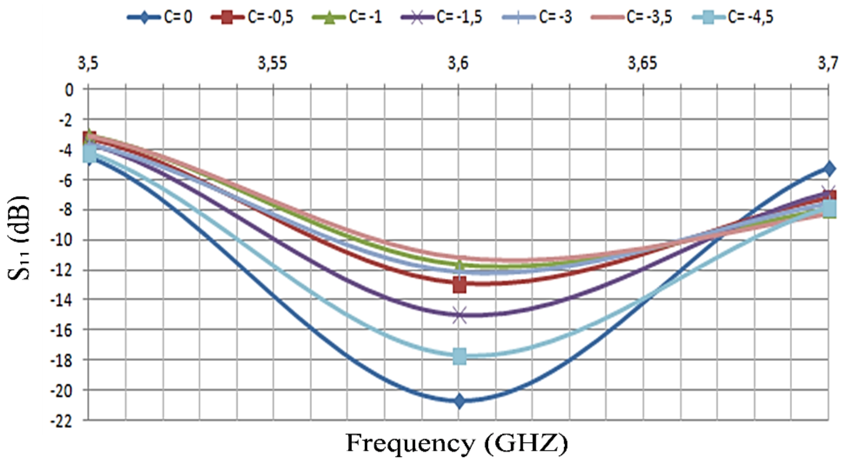


Figure 5. Simulated reflection coefficient for different values of the position annular slot center in the operating frequency 3.6 GHz

3.3. Design of the new circular microstrip patch antenna

According to Table 1, the value of the feed point position varies in the function of the resonant frequency of the antenna, and by consequent as a function of the radius of the radiating element patch, this variation will pose a problem with the connection of the coaxial cable, and to solve this problem, we will cheek on the geometry of the antenna presented in the Figure 6(a) by shifting the centers $C_{3.6}$ and $C_{5.2}$ of the CRSR's in such a way that the feedings points of the three circulars antennas are superimposed and well adapted. For the parametric study, we have fixed the value of the feed position at ρ' = -3 mm. The new design of the proposed antenna is shown in Figure 6(b). Table 2 depicts the various dimensions of the new circular microstrip antenna with two ring slots resonators.

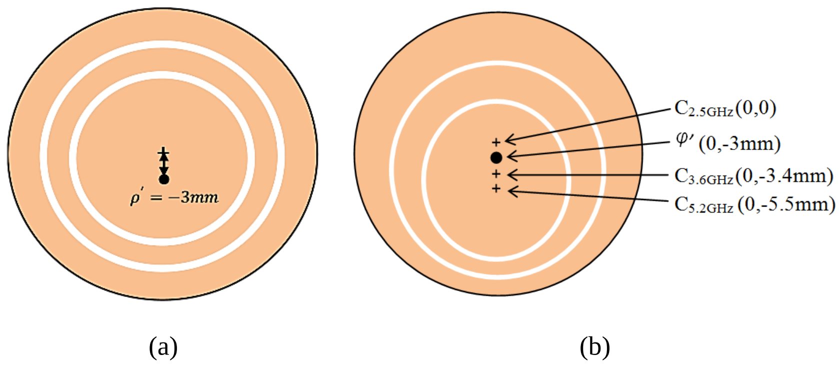


Figure 6. The new design of the proposed antenna: (a) before modification and (b) after modification

Table 2. Various dimensions of the proposed antenna

Parameters	Values
Radius of the substrate	25 mm
Substrate material	FR-4
Substrate thickness h	1.4 mm
Substrate dielectric constant ε_r	4.4
Radius of circular patch a_1	17.00 mm
Radius of circular patch a_2	11.55 mm
Radius of circular patch a_3	7.69 mm
Slot width	0.5 mm, 1 mm
Operating frequency	2.5 GHz, -3.6 GHz, -5.2 GHz
Radius of ground	25 mm
Feeding technique	probe feeding
Feed point location from the center (x, y)	(0 mm, -3 mm)
Center of annular slot $C_{3.6}$ (x, y)	(0 mm, -3.4 mm)
Center of annular slot $C_{5.2}$ (x, y)	(0 mm, -5.5 mm)

4. RESULTS AND DISCUSSION

4.1. Frequency reconfigurable using PIN diodes

The resonant frequency of the above structure can be tuned by changing the geometry of the antenna. For this, six PIN diodes have been inserted into the CRSR's between the radiations elements patch and it's are located such that turning them on allows only certain resonant frequencies. The final design is shown in Figure 7.

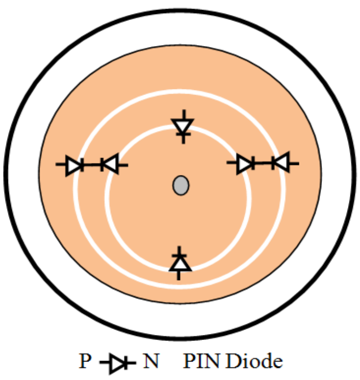


Figure 7. Design of the reconfigurable antenna

Table 3 shows the configuration of the PIN diodes and the simulated antenna properties of each switching band, where 1 represents the on state and 0 represents the off state in the table. Clearly, by controlling the on/off states of the six PIN diodes, three reconfigurable frequency bands can be obtained. And to simplify the simulation, the PIN diodes have been modeled by a short circuit (straps S1 to S6) for the on state and removed for the off state [21].

Table 3. Simulated resonance frequency

Diode	Values		
	F1	F2	F3
S1	0	1	0
S2	1	0	0
S3	1	0	0
S4	1	0	0
S5	1	0	0
S6	0	1	0
Frequency (GHz)	2.5	3.6	5.2
Value of S11 (dB)	-28	-17	-17.5
-10 dB bandwidth (MHz)	140	190	200

When the four straps S2, S3, S4, and S5 are in the on-state, the effect of both CRSR is eliminated, consequently, the three circulars patch of the reconfigurable antenna are excited, and the radius of the antenna becomes that of the frequency 2.5 GHz, which can cover the Bluetooth application as shown in Figure 8(a). When both straps S1 and S6 are in the on state, the effect of the inner CRSR is eliminated, therefore only two patch antennas are excited, the radius of the antenna becomes that of the frequency 3.6 GHz, which can cover the WiMAX application as presented in Figure 8(b). The last configuration is where all straps are in the off state, in this configuration the antenna is loaded by the two CRSR's, hence the centered circular patch is directly excited by the coaxial feed, the antenna resonates at the frequency 5.2 GHz, which can cover the WLAN application as illustrated in Figure 8(c). Therefore, the radius of the patch antenna has a direct influence on the operating frequency [22].

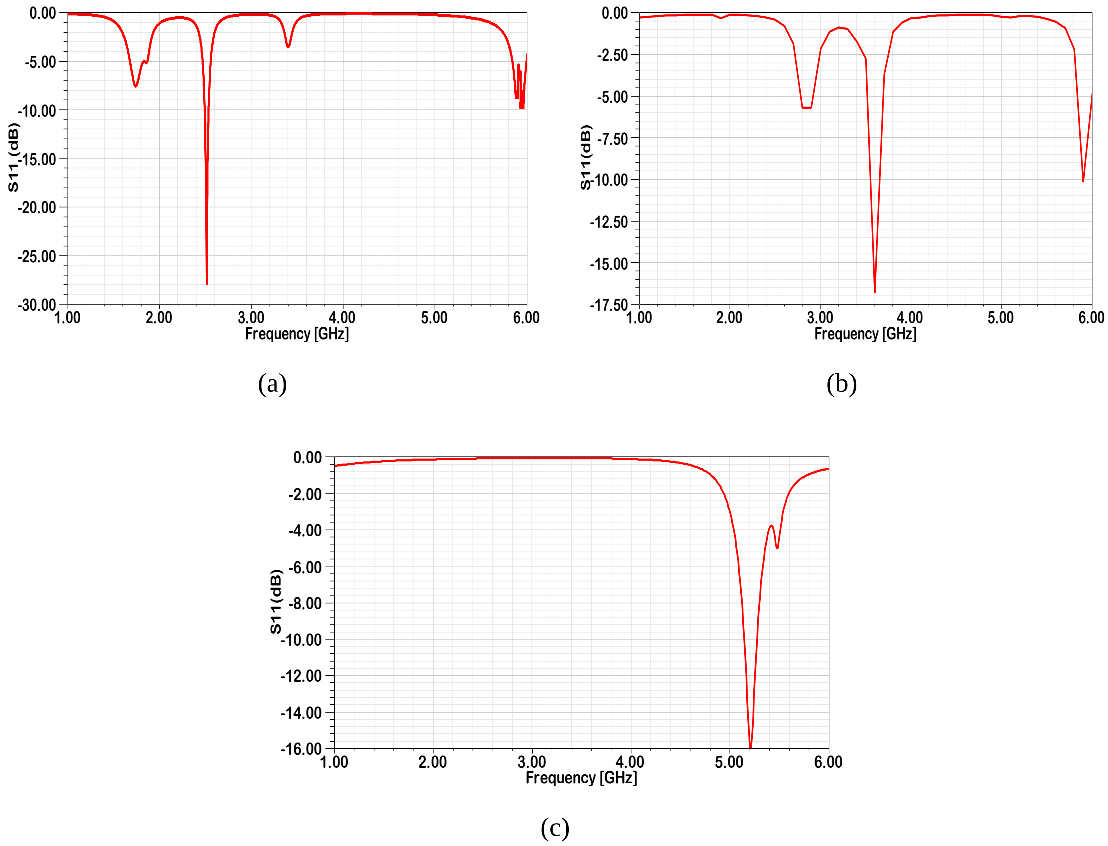
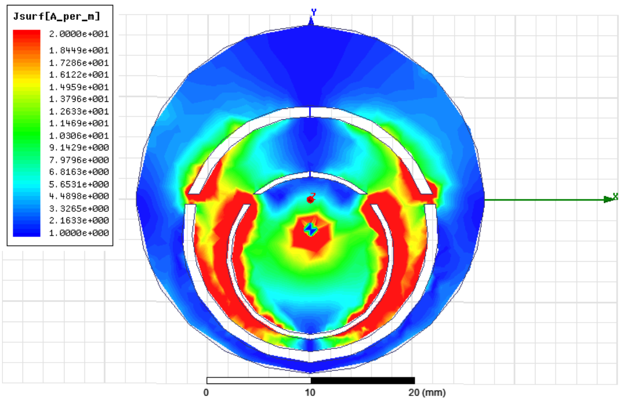


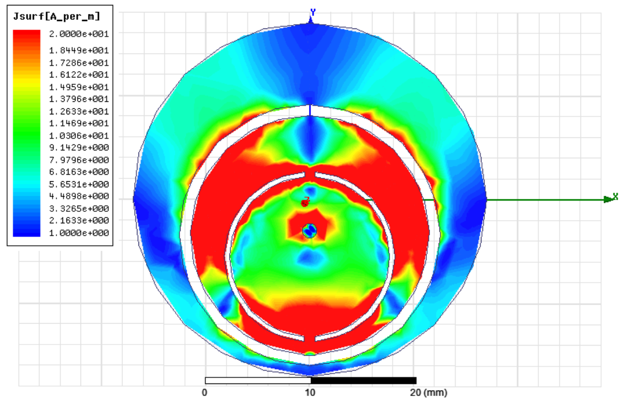
Figure 8. Reflection coefficient versus frequency (a) F1 state, (b) F2 state, and (c) F3 state

The simulated design and results for the three states are shown in Figure 8(a), Figure 8(b) and Figure 8(c). The reflection coefficient for the three antennas is less than -10 dB in the resonance frequency 2.5 GHz, 3.6 GHz, and 5.2 GHz with their impedance bandwidths are $BW1$ = 6.01 % (2.42 GHz to 2.57 GHz), $BW2$ = 5.34 % (3.46 GHz to 3.65 GHz), and $BW3$ = 3.8% (5.16 GHz to 5.36 GHz) respectively [23]. Furthermore, to validate the proposed antenna design, parametric studies have been discussed in a later section.

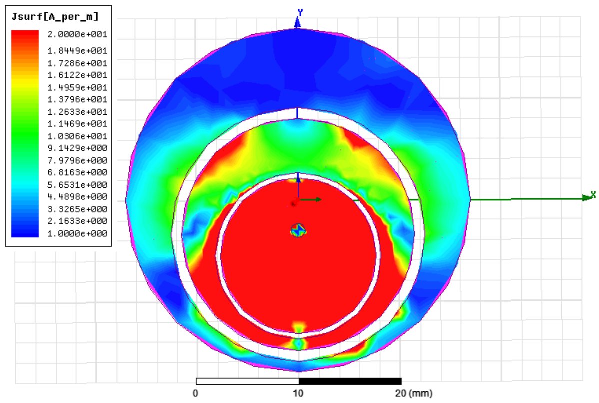
The current distribution depends on the states of the diodes as shown in Figure 9. This is the reason why the resonant frequency is associated with the dimension of the circular patch. It was observed that the radiation was caused by the current distribution in the three concentric circulars at 2.5 GHz as shown in Figure 9(a). According to the Figure 9(b), the current is concentrated along with the two internal concentric circulars at 3.6 GHz. When the diodes are turned off, the radiation is due to the main distribution current in the centered circular patch at 5.2 GHz as illustred in Figure 9(c).



(a)



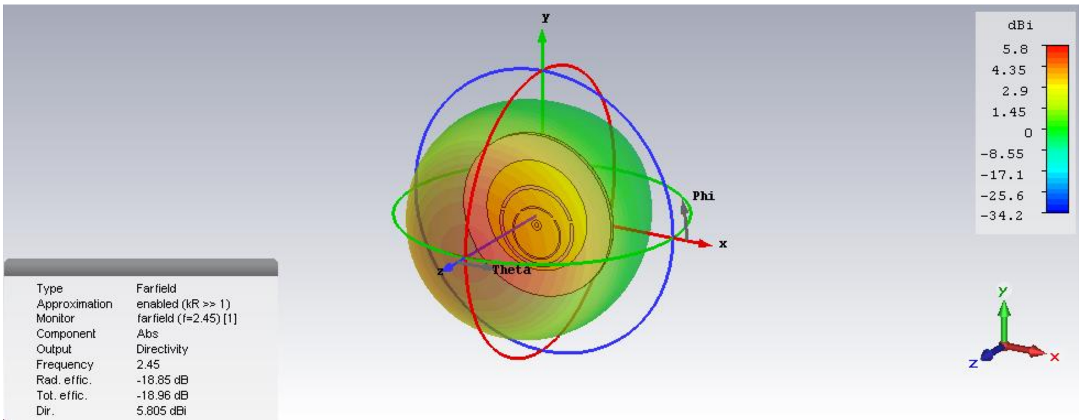
(b)



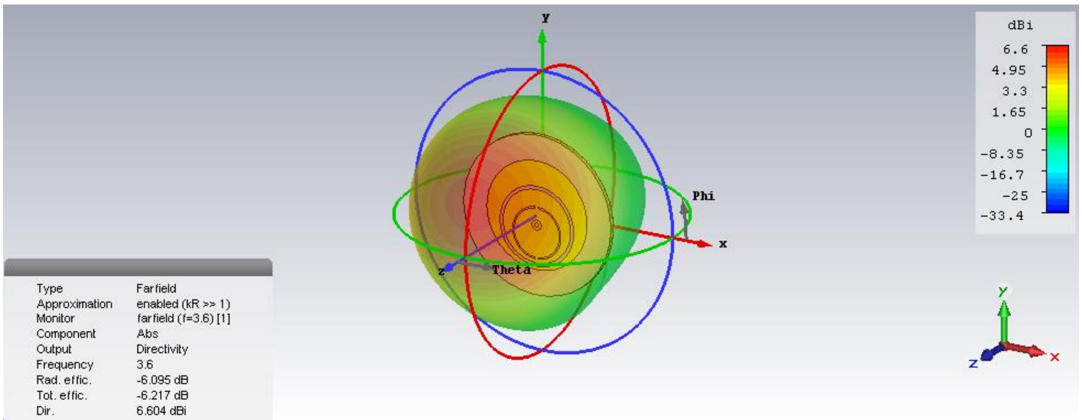
(c)

Figure 9. Simulated current density distribution of the antenna for different states: (a) 2.5 GHz, (b) 3.6 GHz, and (c) 5.2 GHz

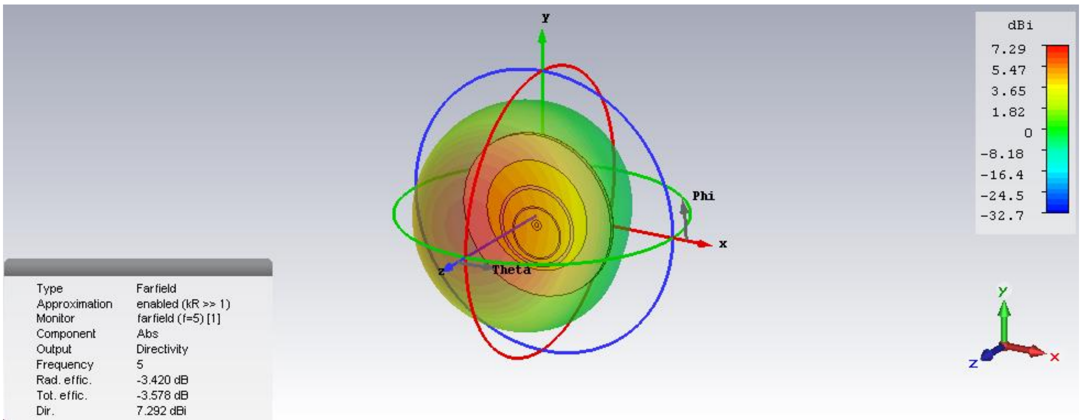
The radiation pattern is an important parameter for the antenna. Therefore, the 3D pattern simulated by the computer simulation technology-microwave (CST-MW) simulator for the three states is plotted as shown in Figure 10. It can be observed from the radiation patterns that there is a stable response throughout the operating bands with good pattern symmetry, and directivity of 5.8 dB for the first state, 6.6 dB for the second state, and 7.29 dB for the third state as shown in Figure 10(a), Figure 10(b), and Figure 10(c) respectively.



(a)



(b)

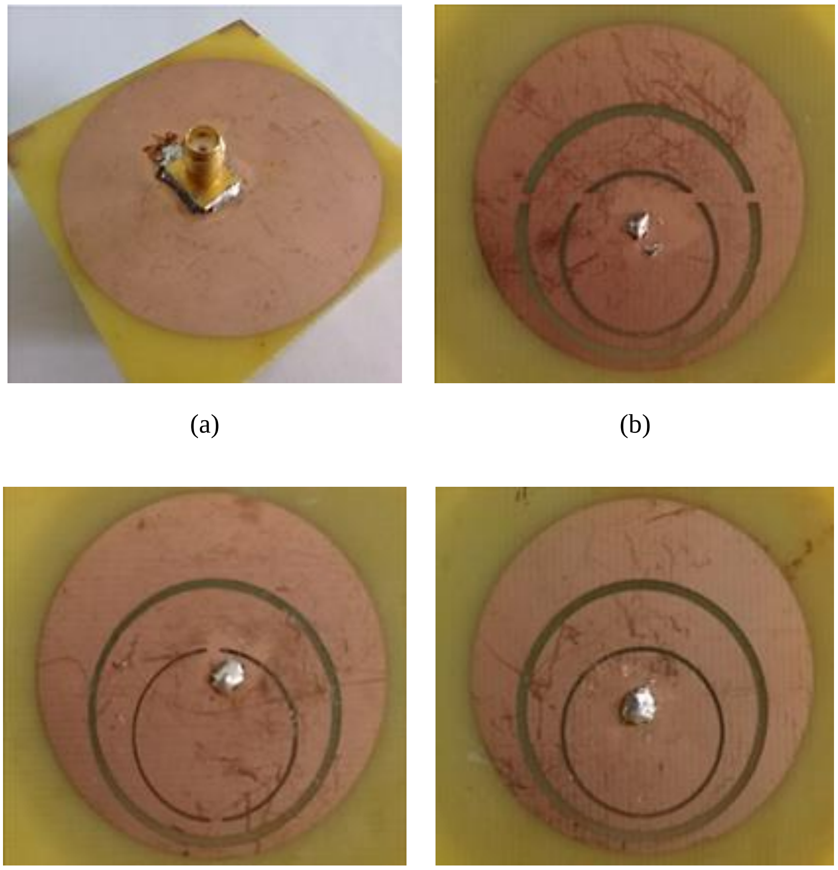


(c)

Figure 10. Radiation patterns for different states: (a) 2.5 GHz, (b) 3.6 GHz, and (c) 5.2 GHz

4.2. Experimental validation

The reflection coefficient (S_{11}) was measured at frequencies over 1.0 GHz to 7.0 GHz range using a vector network analyzer. Figure 11 shows the prototype of the three fabricated antennas, of which the Figure 11(a) present the rear view of the antenna and the Figure11(b), Figure 11(c) and Figure 11(d) present the front view of the antenna for the F1 state, F2 state and F3 state respectively. The simulated results with HFSS, CST, and measured reflection coefficient results for the proposed reconfigurable patch antenna are shown in Figure 12. The measured results show that the antenna operates for three frequencies and we can see a good agreement between simulated HFSS, CST, and measured results.



(a) (b)

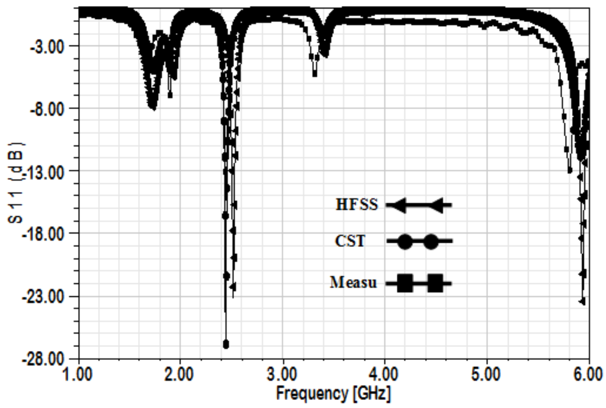
(c) (d)

Figure 11. Prototype of the three fabricated antennas: (a) bottom view, (b) top view 2.5 GHz, (c) top view 3.6 GHz, and (d) top view 5.2 GHz

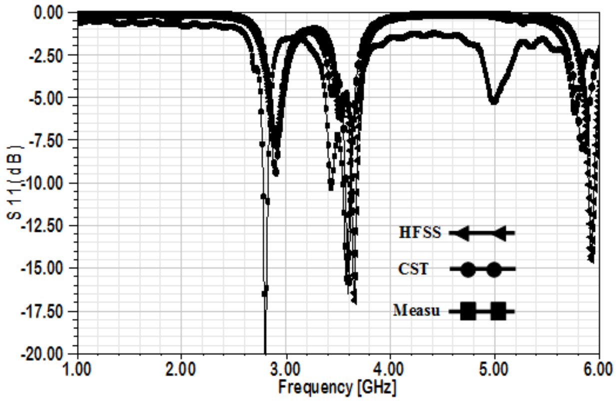
Table 4 summarizes simulated and measured results for each state. The disparities between the curves as shown in Figure 12(a), Figure 12(b) and Figure 12(c) can be attributed to the various numerical calculation methods used in each electromagnetic simulator as well as their boundary conditions. Moreover, the error introduced by the SMA connectors (they are not modeled under the simulators), the manufacturing and substrate tolerances also have a significant influence on the results.

Table 4. Simulated and measured results

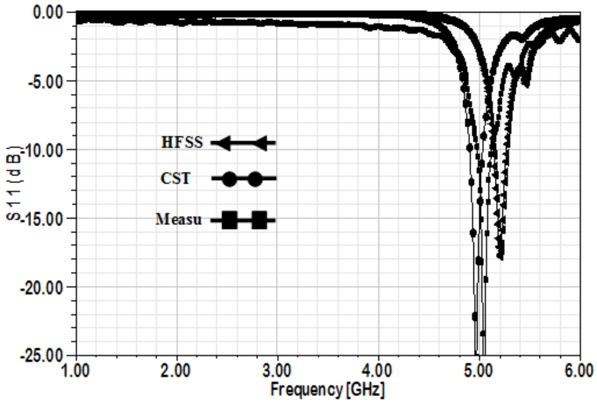
	Bandwidth at -10 dB (MHz)			Central frequency (GHz)		
State	Mesure	CST	HFSS	Mesure	CST	HFSS
F1	90	87	140	2.45	2.45	2.5
F2	75	69	190	3.57	3.58	3.6
F3	190	160	200	5.05	4.95	5.2



(a)



(b)



(c)

Figure 12. Simulated and measured reflection coefficient versus frequency for different state: (a) 2.5 GHz, (b) 3.6 GHz, and (c) 5.2 GHz

Nevertheless, the results of measurements and simulations show a good agreement, which validates the electrical properties of the structure in terms of adaptation and bandwidth. To demonstrate the validity of the proposed antenna, a comparison with another existing model in the literature is presented in Table 5. The summarized data reveal that the proposed antenna offers better reconfigurable operating frequency and wide bandwidth compared to the other antennas designed in [24], [25]. It can also be observed from Table 5, the proposed antenna has the better gain than the work reported in [24]-[27], moreover, the size of our antenna is very small which is an advantage in the design and conception of motherboards.

Table 5. Proposed antenna comparison with other reported works

Parameters	Proposed antenna	[24]	[25]	[26]	[27]
Dimensions (mm)	Radius = 25	Radius = 40	150×70	25×15	25×25
Operating frequency (GHz)	2.5 to 5.2	1.71 to 2.5	0.7 to 2.9	3.3 to 7.8	4.94 to 6.83
Bandwidth at -10dB (MHz)	140 to 200	60 to 96	40 to 200	900 to 1700	190 to 1400
Gain (dB)	5.8 to 7.29	4.69 to 7.1	3.9	3.4 to 4.1	1.25 to 3.6
Application mode	Bluetooth WiMAX WLAN	UMTS Wireless broadband (WiBro) Bluetooth	1 GHz 1.94 GHz 2.6 GHz	WiMAX Wave WLAN	WLAN WiMAX C-band

5. CONCLUSION

In this paper, a frequency reconfigurable antenna was studied. The antenna is designed and fabricated on an FR-4 substrate. The use of the circular patch and complementary ring resonator elements provides multiple resonances with good impedance bandwidth and good radiation characteristics with acceptable values of gain. The resonance frequency can be controlled by inserting six PIN diodes. Moreover, the simulated data with HFSS and CST simulator shows good agreement with the measured reflection coefficient result.

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