Reconfigurable ultra wideband to narrowband antenna for cognitive radio applications using PIN diode

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Article Info	ABSTRACT
	Frequency reconfigurable antennas are very attractive for many wireless applications. They offer many advantages such as simplicity and compactness. In this electronic paper, we propose a reconfigurable antenna operating in the S and C bands. The proposed antenna uses a BAP65-02 RF diode to switch between the ultra wideband from 2.92 to 6.19 GHz to the narrowband from 2.92 to 3.93 GHz. The ultra wideband is obtained by a partial rectangular ground plane with a symmetrical rectangular slot and the narrowband is obtained by adding a parasitic element electrically connected to the ground plane by the PIN diode when it is positively biased. This patch antenna operates in the Federal Communications Commission band (FCC) and can be used for biomedical applications such as radiometry imaging. The numerical simulation results based on the finite element method and the finite integral method show a very good agreement between them. *This is an open access article under the CC BY-SA license.*

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1. INTRODUCTION

The modern wireless communication technology is becoming increasingly important role in our daily lives. In fact, antenna theory and experimental research results have evolved rapidly to give to a new technology called reconfigurable antenna [1, 2]. The reconfigurable antenna concept means that its technical performance can be modified in a flexible way according to the electrical, mechanical modifications or changing the material properties that can be adjusted according to the actual situation. The reconfigurable antenna term was proposed for the first time in 1960 to distinguish four main families, frequency reconfigurable antennas, antennas reconfigurable in radiation, antennas reconfigurable in polarization and antennas with multiple reconfigurations [3, 4]. By modifying the antenna structure, electrical length, substrate thickness, relative permittivity, geometry. It is possible to reconfigure one or more parameters such as the frequency, the lobe diagram and the polarization mode of the antenna. For these considerations, it has attracted several researchers to developer several designs and optimization techniques for various applications [5–7].

With the rapid development of modern radar and communication systems, the number of antennas

required is increasing for the purposes of communication, navigation, guidance, and alerting. This increases weight, congestion, complexity and energy consumption which seriously affects the normal operation and performance of the system. In order to solve these technical problems, it is recommended to use a single antenna to perform the function of several antennas by continuously adjusting its structure [8–12].

The principle of reconfigurable frequency antennas is to change the current distribution by changing the effective electrical length. Therefore, such an antenna can change continuously or discretely in a certain band according to the technique used such as PIN diodes, switch MEMS, varactor, the modification of the mechanical structure of the antenna and the modification of the dielectric properties of the substrate [13–18]. On the other hand, ultra wideband microstrip antennas, intended to monitor a band for detecting the free radio spectrum, offer several advantages such as high data throughput and reduced power consumption, but have a disadvantage of interfering with other bands particularly the WiMAX band from 3.3 to 3.9 GHz. For this purpose, the frequency reconfigurable UWB antenna can be a better choice to overcome this problem [19–21]. In the following sections, will be seen successively, a detailed study on the evolution of the ground plane of the proposed antenna, a comparison between the ideal switch and the real switch, the performances obtained and finally the analysis of the specific absorption rate to check the level of security of our structure.

2. PIN DIODE MODEL

PIN diodes are widely used, from low frequency to high frequency applications, mainly used in the RF domain. Because the RF resistance of the PIN diode is related to the DC bias current, it can be used as a good RF switches or RF protection circuits. When the diode is positively biased, it is turned on short circuit and when it is reverse biased, it is turned on open circuit. Typically, The resistance of the diode can vary from 10 $k\Omega$ to less than 1 Ω by controlling its bias current. Though all the junction diodes show this type of characteristic; structure and doping profile of PIN diodes are designed to achieve a wide range of variable resistance and linearity with low bias current level [22].

The internal resistance of the PIN diode is the most fundamental electrical parameter that determines the performance of the RF switch. Under the direct bias condition, the amount of charge stored in I-layer corresponds to the direct bias current I_d multiplied by the ambipolar lifetime τ_a. The total current is calculated by the following equation with Q_d is stored charge:[23]

$$I_d(t) = \frac{Q_d}{\tau_a} + \frac{dQ_d(t)}{dt} \tag{1}$$

The selected PIN diode is the BAP65-02, SOD523 (NXP Semiconductors), its technical features, extracted from its datasheet [24], are as follows : continuous reverse voltage: 30 V, continuous forward current: 100 mA, forward voltage: 1.1 V (max) at IF = 50 mA, reverse leakage current: 20 nA (max) at VR = 20 V, applications: mobile communication transmit/receive switch, bandswitch for TV tuners. Figure 1 shows the two equivalent models of the PIN diode (ON and OFF states).
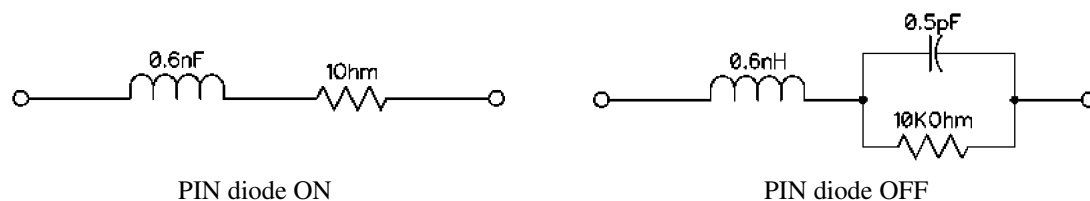

PIN diode ON   PIN diode OFF

Figure 1. Equivalent models of the PIN diode in both switching mode

3. ANTENNA DESIGN

The geometry of the proposed structure of the reconfigurable frequency antenna using the PIN diode is illustrated in Figure 2. It is printed on a dielectric substrate FR4 of thickness 1.6 mm, with a permittivity of 4.4 and loss tangent of 0.02. The configuration of the antenna is composed of a simple monopole circular patch fed by a feed line, connected to a 50 Ω SMA connector, placed on the opposite side of a partial ground plane where a rectangular slot has been inserted. Frequency reconfigurability was achieved by a parasitic element electrically

connected by a PIN diode with the modified ground plane. The switching of the PIN makes it possible to switch from an ultra wideband to a narrowband. The optimized size of the compact antenna proposed is $31 \times 38 \times 1.6$ mm^3. In order to justify the choice of the proposed structure, a series of parametric studies were investigated, Figures 3 (a) , 3 (b) and 3 (c) show the evolution of the modification of the ground plane. The idea of adopting the Defected Ground Structure made it possible to integrate a RF switch (PIN diode) without changing the performance characteristics of the ultra wideband configuration.
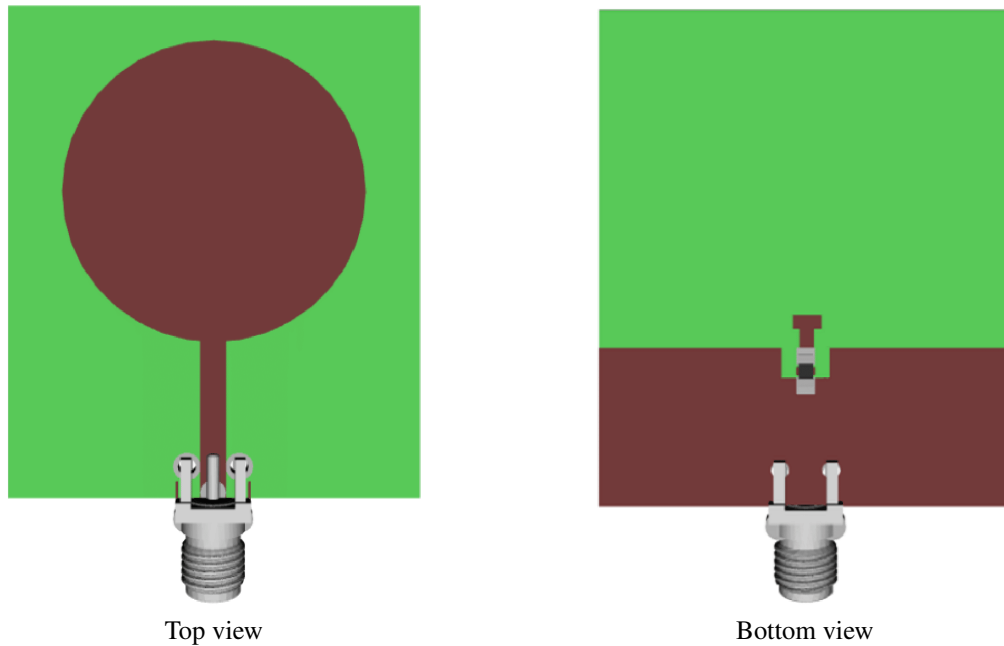

Top view   Bottom view

Figure 2. Top and bottom views of the proposed antenna

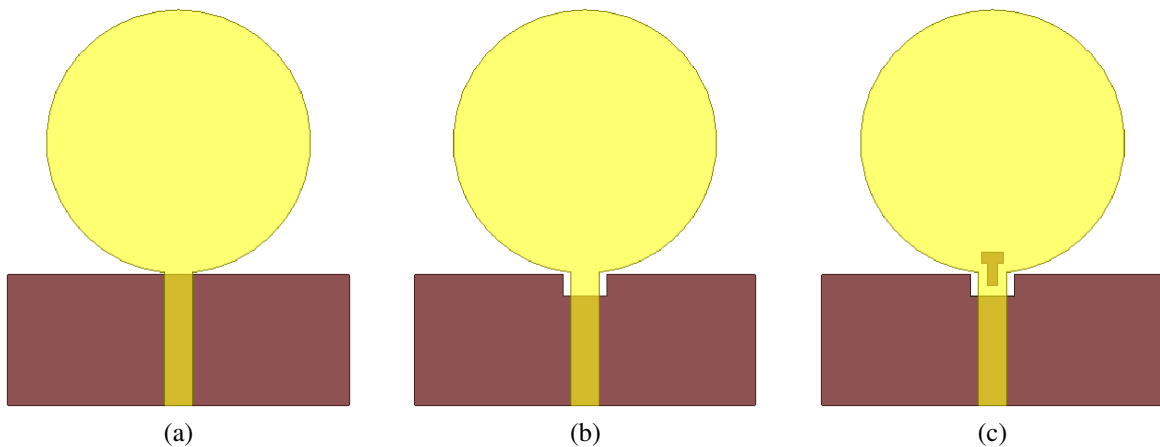(a)   (b)   (c)

Figure 3. Different ground plane structures: (a) ordinary rectangular ground,
(b) rectangular ground with a rectangular slot, (c) proposed ground

Their frequency responses (return loss parameter vs frequency) are shown in Figure 4. As it observed in this figure, the three ultra broadband structures have practically the same bandwidth. Therefore, it can be concluded that the parasitic element has no effect on the performance of the UWB configuration but offers the advantage of integrating a PIN diode to be able to switch from the ultra wideband to the narrowband (WiMAX band).
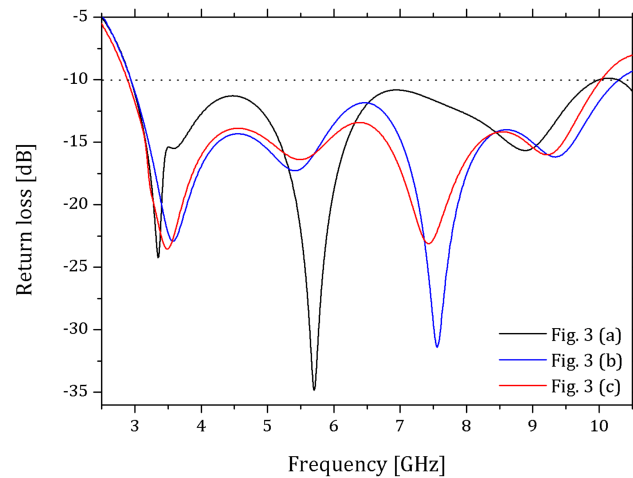
Figure 4. Reflection coefficient vs frequency of all the ground plane structures

4.   RESULTS AND DISCUSSION
4.1.   Proposed antenna analysis

The proposed antenna operates in two modes, narrowband mode for the WiMAX band when the switch is in the ON state and ultra wideband mode intended for cognitive applications in S and C bands when the switch is in the off state. A study on the bandwidth limitation behavior was performed using two ideal and real switches. The numerical simulation results are shown in Figures 5 and 6.
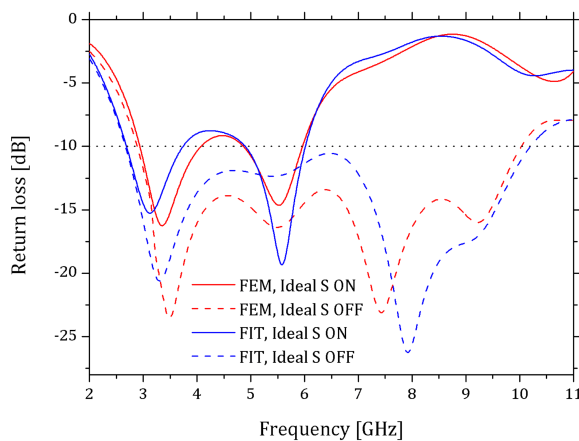

Figure 5. Frequency response of the reconfigurable antenna with ideal switch calculated by FEM and FIT solvers
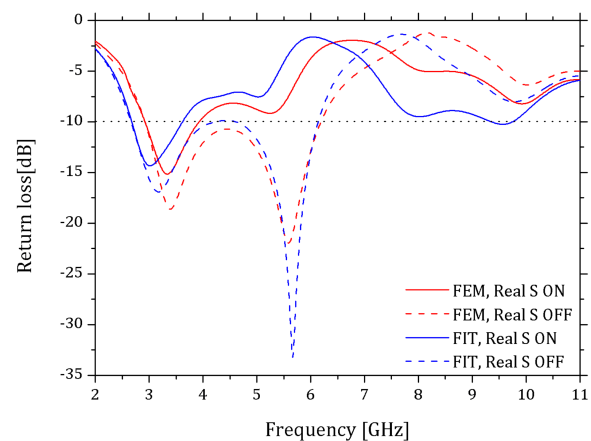

Figure 6. Frequency response of the reconfigurable antenna with real switch calculated by FEM and FIT solvers

As can be seen from the graphs, the actual RF switch reduces the band in wideband mode. This limitation is mainly due to the parasitic effect of the passive components: inductance, capictity and resistance. On the other hand, there is a good agreement between the values calculated by the finite element method and the finite integral method. However, there are small shifting between solvers that may be due to reasons such as the approximations and the three-dimensional mesh adopted by each method. The status report of the ideal and real switches at ON and OFF states using the two solvers FEM and FIT is described in Table 1. The transition between ultra wideband and narrowband behavior can be explained by the change in surface current distribution. Indeed, the state of the RF switch, activated or deactivated really defines the electrical length of the antenna structure. The state of the ON switch forces the antenna to operate in narrowband mode

while the OFF state forces the antenna to operate in ultra wideband mode. Figure 7 shows the surface current distribution calculated using the finite element method at the 3.34 GHz resonance frequency. The current is weakly distributed in the blue regions while the distribution intensifies in the red regions. It is evident that the RF switch in activated state (ON state) considerably modifies the electrical length of the structure.

Table 1. Status report of the ideal and real switches at ON and OFF states using the two solvers FEM and FIT

States	Solver	Switch	No. of band	Frequency [GHz]		Wideband [GHZ]	
	FEM	Ideal	2	2.94 - 4.08	4.87 - 5.96	1.14	1.10
3-8 State		Real	1	2.92 - 3.93		1.01	
2-8 ON	FIT	Ideal	2	2.68 - 3.74	4.89 - 6.01	1.05	1.11
3-8		Real	1	2.67 -3.62		0.94	
	FEM	Ideal	1	2.89 -10.3		7.14	
3-8 State		Real	1	2.92 - 6.19		3.27	
2-8 OFF	FIT	Ideal	1	2.66 -10.19		7.52	
3-8		Real	1	2.66 -6.13		3.47	

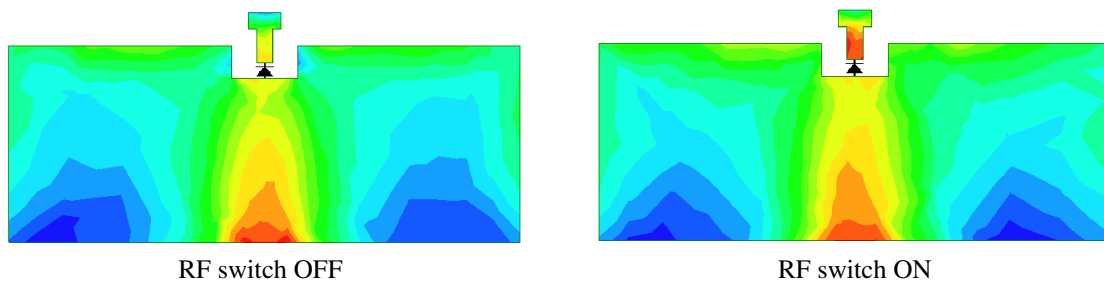RF switch OFF   RF switch ON

Figure 7. Calculated current distribution of the proposed antenna at 3.34 GHz

4.2. Proposed antenna performance

Finally, The proposed design values of the reconfigurable frequency antenna are optimized by a solver based on the finite element method (FEM) and validated by the finite integral method (FIT). The final geometry of the proposed antenna is shown in Figure 8 and the optimized dimensions are listed in Table 2.
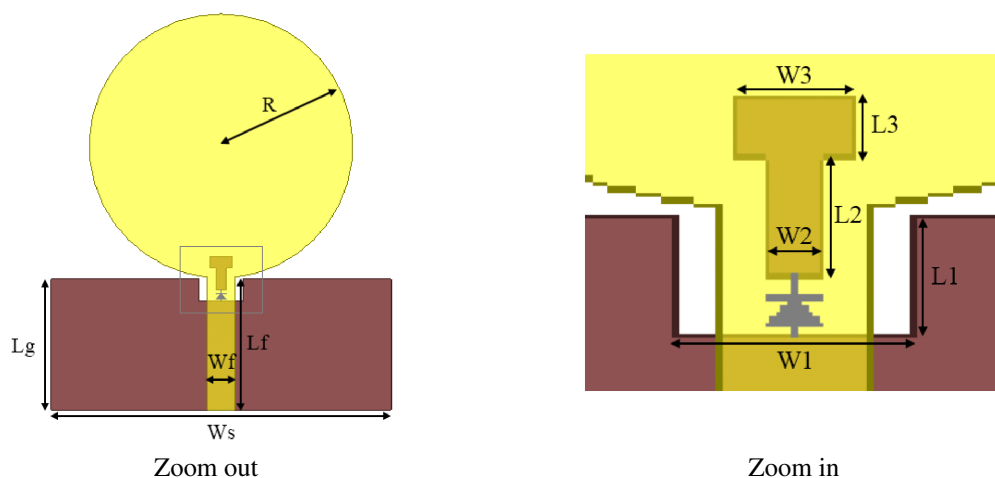

Zoom out   Zoom in

Figure 8. Final geometry of the proposed reconfigurable antenna

The radiation patterns in the E-palne ($\phi = 90°$ - XY plane) and H-plane ($\phi = 0°$ - XZ plane) are calculated at 3.34 GHz at ON state and at 3.39 GHz and 5.59 GHz at the OFF state, as shown in Figures 9, 10, and

11. It is observed that the E is in symmetry while the H is omnidirectional. The rectangular representation of the simulated peack gain in the activated and deactivated state of the PIN diode switch of the antenna designed is shown in Figure 12. In both modes, the gain achieved is very good, greater than 4.96 dB when the switch is ON and greater than 3.65 when the switch is OFF. It can be observed that the PIN diode significantly influences the gain when it is activated.

Table 2. Optimized dimensions of the proposed reconfigurable antenna

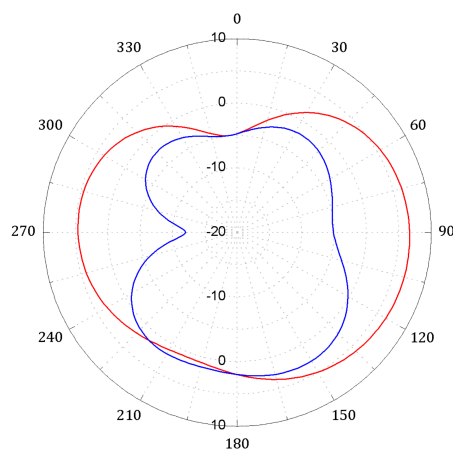| Parameter	W_s	L_s	L_g	R	W_f	L_f	W_1	L_1	W_2	L_2	W_3	L_3
Value [mm]	31	38	11.9	12	2.5	12	4	2	1	2	2	1

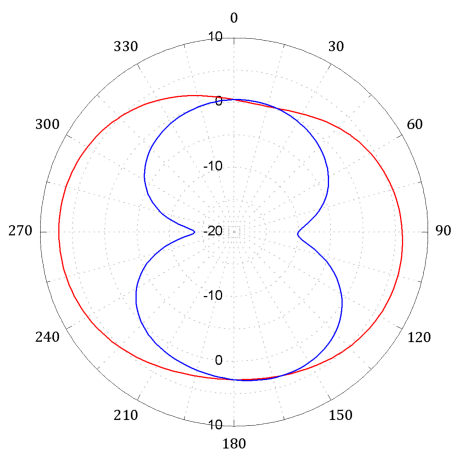Figure 9. Radiation pattern at 3.28 GHz, RF switch ON; ____ $\phi = 0°$, ____ $\phi = 90°$

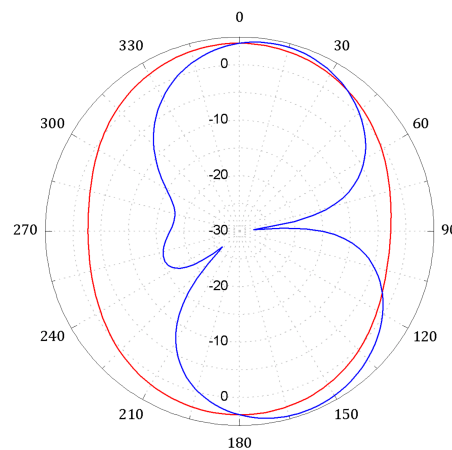Figure 10. Radiations pattern at 3.39 GHz, RF switch OFF; ____ $\phi = 0°$, ____ $\phi = 90°$

Figure 11. Radiations pattern at 5.59 GHz, RF switch OFF; ____ $\phi = 0°$, ____ $\phi = 90°$

4.3. Specific absorption rate evaluation

The proposed structure covers the band [2.92 - 6.19] GHz in ultra wideband mode and the band [2.92 - 3.93] GHz in narrowband mode, both modes are included in the FCC (Federal Communications Commission) [3.1 - 10.6] GHz band to be used safety for communication systems [25, 26]. However, the study of the level of the specific absorption rate on the human body should be done carefully. According to the IEEE C95.3, 2002 safety recommendations [27], the average SAR for 1 g of human tissue must be less than 1.6 W/kg. The study conducted in this paper was performed at a distance of 10 mm on body phantom of $50 \times 57 \times 21$ mm^3 composed

of bone, muscle and skin tissues, their physical properties are respectively ϵ^r_{bone} = 12.03, σ_{bone} = 0.2156 S/m, ϵ^r_{muscle} = 54.066, σ_{muscle} = 1.1553 S/m, ϵ^r_{skin} = 39.59, σ_{skin} = 1.0465 S/m [28]. As shown in Figure 13, the designed antenna can operate safely up to an input power of 29 mW at 3.34 GHz where the max SAR is 1.562 W/Kg.
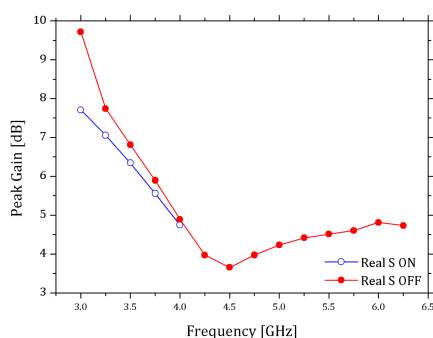

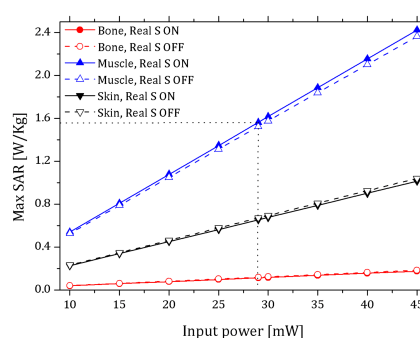Figure 12. Peak gain vs frequency of both RF switch states

Figure 13. Calculated distribution SAR on body phantom at 3.34 GHz in both ON and OFF states

5.   CONCLUSION

In summary, a compact frequency reconfigurable circular antenna has been designed, studied and analyzed in this paper. This structure, intended for wireless cognitive applications in the S and C bands, works in the narrowband mode from 2.92 to 3.93 GHz when the RF switch is activated and in the ultra wideband mode from 2.92 to 6.19 GHz when the switch is deactivated. The antenna is designed on a dielectric substrate FR4 of thickness 1.6 mm, with a permittivity of 4.4 and loss tangent of 0.02 uses the diode switch BAP65-02,SOD523 to change the effective electrical length of the antenna to obtain frequency reconfigurability. The results calculated using the finite element method and the finite integrals method are very coherent, which allows this antenna to be a candidate choice for wireless cognitive applications.

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