Frequency reconfigurable rectangular patch antenna for cognitive radio applications

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ABSTRACT

A frequency reconfigurable microstrip transformed rectangular patch antenna consisting of two slots able to radiate in S-band and C-band is proposed. Spectrum occupancy is first analyzed using the data from literature and internet sources and hence spectrum holes are identified. A rectangular radiating patch is then designed for 5.8 GHz resonant frequency. A coaxial feed is used in the bottom by a suitable feed point. Two slots at an angle of +45 degree are made at the two corners. The electrical length of the patch is changed by using two varactor diodes in the slots. The varactors enable frequency reconfiguration in the band of frequencies that are unused or the spectral occupancy is very less. The return loss, voltage standing wave ratio (VSWR), and 2D-radiation patterns are analyzed for various values of the capacitances. high-frequency structure simulator (HFSS) is used for simulation. FR4 substrate which is economical, is used with height, h=1.6 mm, width W=25.33 mm, and length L=21.34 mm. On the substrate the rectangular patch is of width 15.73 mm and length 11.74 mm. The return loss and radiation patterns for different values of capacitances is presented. The tunability ratio obtained is 1.93. The results obtained agree with the standards.

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1. INTRODUCTION

The rapid expansion and development of wireless communication technologies has supported a huge increase in the demand for multiband and frequency reconfigurable patch antennas (FRPA) [1], [2]. Transceivers in today's wireless communication systems must support many communication technologies at the same time, such as long term evolution (LTE), wireless local-area network (WLAN), Bluetooth, and worldwide interoperability for microwave access (WiMAX). Different frequencies are used by these technologies. Utilizing a single antenna capable of working in various bands is more convenient and efficient than using multiple antennas. A dynamical response will be provided by an antenna system that can operate in different bands and has frequency reconfiguration capabilities [3]–[5]. The reconfigurable antennas have advantages; reduces the number of antennas required, saves energy with reduced mutual interferences hence reduce the interferences between the users, and reduces congestion [6].

The reconfigurable antennas find applications as presented in [7]–[9], such as Spectrum re-allocation, multiple services in a single device, exclusion of filtering at front end. To improve out-of-band removal, compact antennas reduce the mobile devices' form factor, software defined radio, multiple input, multiple output (MIMO) antenna systems, and cognitive radios. Reconfigurable antennas can be classified based on frequency, polarization, radiation pattern, bandwidth, and an amalgamation of any two of the above [10]. Any of the approaches listed below can be used to develop frequency tunable antennas: i) electrical method: the surface currents are redirected by use of generally accepted auditing standards (GaAs) field-effect transistor (FETs), PIN diodes, varactor diodes or micro-electro-mechanical systems (MEMs) devices [11]–[13]. GaAs FET is used with drain to source biasing current being zero has low power consumption but exhibits higher loss with poor linearity. PIN diodes can be used with low cost and lower losses but has an ON state direct current (DC), which reduces power efficiency. By using varactor diodes continues reactive tuning can be achieved, but poor linearity is the major disadvantage; ii) optical method: integration of an optical switch reconfigures the antenna structure. No need of complicated biasing lines so there will be no distortion in the radiation pattern, losses and interferences [14], [15]. The photoconductive material is switched ON or OFF by illuminating light from light amplification by stimulated emission of radiation (LASER) diode. These exhibit linear property and does not produce inter-modulation products or harmonics. But optical switches need complex activation and has losses; iii) physical method: the radiating parts of the antenna are structurally modified by using some mechanical rotational mechanism such as a motor [16]. It is possible to avoid the use of switching devices and biasing lines. However, due to its larger construction, it is difficult to include into small and compact gadgets; and iv) material based method: reconfigurablity properties of an antenna can be obtained by using special materials like meta-materials or ferrites [17]. The relative permittivity or permeability of a ferrite material can be altered by applying an electric or magnetic field, respectively. Under different voltage levels, the dielectric constant can be altered by changing the direction of the liquid crystal molecules. From the above stated methods we can effectively achieve frequency reconfiguration.

Table 1 presents the comparison of FRPA found in the recent literature. The mechanical method presented in [18] does not suit for cognitive radio networks (CRN) applications. Khan *et al.* [19] have presented FRPA using 4 PIN diodes, though the gain obtained is above 0 dBi but the dimensions suggest the antenna is not compact, and the main disadvantage of such a radiating component is that it is not continuous frequency reconfigurable. For CRN, we require antennas able to transmit at adjacent channels if it is found vacant by sensing the spectrum. So is the case with the antennas proposed in [20]–[23]. Ahmad *et al.* [24] proposed a very compact square patch antenna with a horizontal slot placed with a varactor diode standard minute value (SMV) 1234. It is possible for tuning from 1 to 1.16 GHz by variation of applied bias from 0 to 7 V with a totable ratio of 1.15 which is very small. With a modification in varactor capacitance from 2.25 to 0.16 pF, Yoon *et al.* [25] built a reconfigurable antenna utilizing a varactor diode for LTE application in the frequencies of 690–804 MHz and 1,704–2,268 MHz. But the antenna is very bulky with a profile thickness of 8 mm. In [26] Meng designed a wideband tunable patch antenna, the measured frequency varying from 1.47 to 1.84 GHz. By changing the reverse bias voltage of the diodes from 0 to 20 V, the measured frequency agility was mentioned to be 24%. However, in order to achieve this quality, the layout used a great number of varactor diodes and had a large footprint. The proposed antenna is reconfigurable for continuous frequencies of minimum 20 MHz bandwidth and is tunable from 2.90 to 5.32 GHz in four bands.

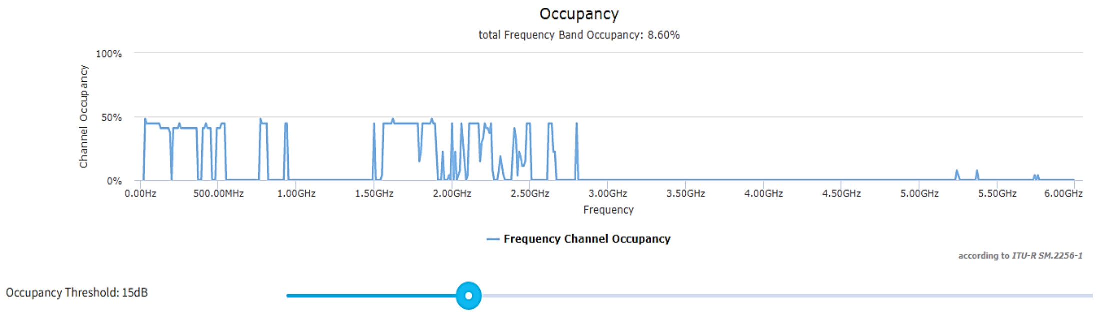
Table 1. Comparison of FRPAs in recent literature and this work

Reference#	Reconfiguration method	Continuous freq.	Tunability ratio
[18]	Mechanical	NO	1.41
[19]	4 PIN Diodes	NO	1.63
[20]	PIN Diode	NO	1.27
[21]	PIN Diode	NO	1.24
[22]	PIN Diode	NO	1.21
[23]	PIN Diode	NO	1.81
[24]	Varactor Diode	Yes	1.15
[25]	Varactor Diode	Yes	1.25
This Work	Two Varactor Diodes	Yes	1.93

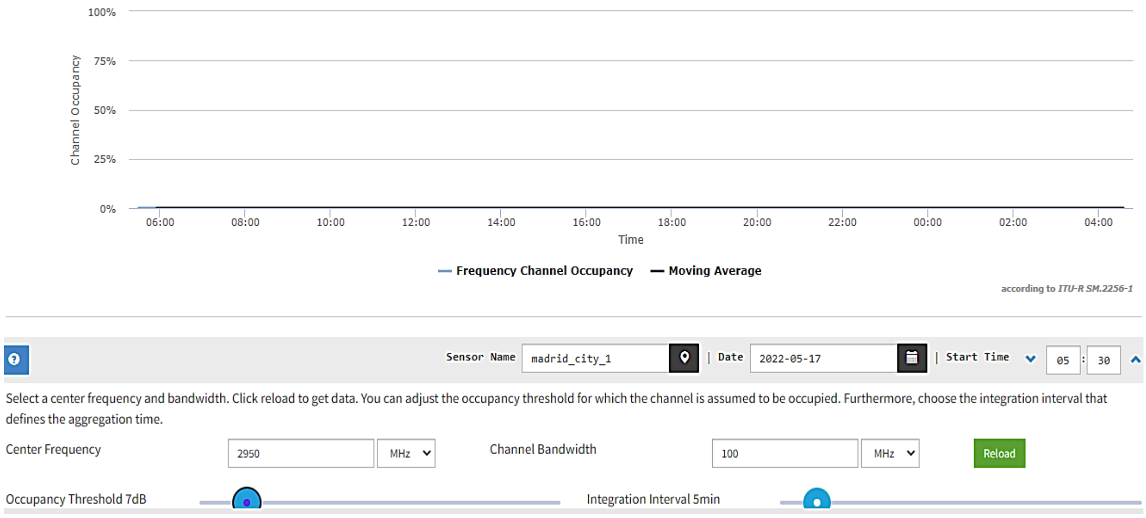
The constant development of new wireless communication technologies has increased the demand for frequency band. According to Federal Communications Commission (FCC) guidelines, a frequency spectrum is assigned to licenced and unlicensed users. To meet the demand for bandwidth, an analysis of spectrum occupancy is required. A large number of measurement campaigns were carried out around the world to analyse spectrum occupancy [27]–[30]. It varies between 15% and 60% factors such as location and time. This is useful for temporarily allowing secondary users to use the unused spectrum of licenced and unlicensed primary users' bands without interfering with them. This idea is used in cognitive radio, where an intelligent cognitive engine detects spectrum behaviour and predicts the channel's occupancy status.

The main motto of this article is to design a communication antenna for application in CRN. Chandhar and Pai [31], have identified the spectrum holes in the communication bands. Live spectrum occupancy can be observed in [32], according to this, with occupancy threshold of 15 dB for outdoor application, the channel occupancy is nil from 1.32 to 4.85 GHz and for except these frequencies the occupancy is less than 50%. The total band occupancy from 0.00 Hz to 6.00 GHz is about 8.60% as presented in Figure 1(a). The channel occupancy is 0 % in the frequency range 2.9 to 3.0 GHz measured for a bandwidth of 100 MHz as presented in Figure 1(b), even with a threshold of 7 dB in outdoor. Similarly it is observed that for a bandwidth of 120 MHz with centre frequency 2.96 GHz, the channel occupany is below 45%. With 4,650 MHz center frequency, 100 MHz bandwidth the spectrum occupancy is 0%, of threshold 12 dB in outdoor. It is also observed that with threshold values ranging from 0 to 13 dB, the average channel occupancy in the 5 GHz band of 320 MHz width is 50%, while occupancy above 13 dB threshold is 0%. At all locations, similar channel occupancy statistics are observed. These bands open up the spectrum for secondary users (SU) to communicate at lower power levels in cognitive radio (CR) environment.

As a result, for CR applications, we must construct an antenna that is frequency reconfigurable in the discovered spectrum holes for spectrum opportunistic SU. In subsection 2.1 design method is presented, in subsection 2.2 the use of varactor diode and in section 3, the simulated results obtained are presented and analysed to recognize the applied biasing voltage to the varactor diode to operate in the opportunistic spectrum white spaces.



(a)



(b)

Figure 1. Spectrum occupancy for outdoor CR application as in [32] (a) with threshold of 15 dB over 0 Hz to 6 GHz and (b) with threshold of 7 dB at 2.95 GHz over time

2. MICRO-STRIP RECTANGULAR PATCH ANTENNA

A rectangular patch antenna is extensively investigated because of the reasons mentioned in subsection 2.1. This patch has a ground plane on one side and planar or non-planar radiating geometry on the other side of the substrate material. The chosen substrate is FR4 of thickness 1.6 mm, the ground plane and the radiating patch is copper of thickness negligible, a pec (perfect electrical conductor). The following section presents the mathematical relations for designing a rectangular patch antenna at a resonant frequency.

2.1. Method

A microstrip patch antenna is simple, low profile, compact, economical, light weight, flexible to flat and non-flat surfaces and appropriate with monolithic microwave integrated circuits (MMIC) designs [33]. The basic shape of a microstrip patch antenna can be a rectangle, a square, an elliptical, a round, a triangle, a loop, a polygon, or their complicated permutations to fulfill specific design needs [34]. Figure 2 presents a basic and typical rectangular patch antenna with ground plane, substrate, radiating patch on the substrate in Figure 2(a), and coaxial feed from bottom via ground and substrate and e-field distribution in Figure 2(b). The effective relative dielectric constant is given by (1) [35]:

$$for \quad \frac{W}{h} > 1$$
$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-\frac{1}{2}} \tag{1}$$

where, L is length of the radiating patch, W is width, h is substrate height, and ε_r is substrate relative dielectric constant. The effective relative dielectric constant is a constant value for lower frequencies. But as the frequency increases, its value increases and reaches the actual value of ε_r for further increase in frequency.

Fringing effect makes the patch electrically greater than its physical dimensions. Therefore an approximate normalized extensions of the patch length is [36]:

$$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon_{reff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{reff} - 0.258)\left(\frac{W}{h} + 0.8\right)} \tag{2}$$

Therefore, the total length considering length extension on both side of the patch by ΔL, is expressed as (3).

$$L_{eff} = L + 2\Delta L \tag{3}$$

For good radiation efficiencies, the practical width of the patch is given by (4) [36]:

$$W = \frac{1}{2f_r\sqrt{\mu_0\varepsilon_0}}\sqrt{\frac{2}{1+\varepsilon_r}} = \frac{v_0}{2f_r}\sqrt{\frac{2}{1+\varepsilon_r}} \tag{4}$$

where, v_0 is equal to speed of light in vacuum and the actual length of the patch is, for frequency of resonance f_r,1.

$$L = \frac{1}{2f_r\sqrt{\varepsilon_{reff}}\sqrt{\mu_0\varepsilon_0}} - 2\Delta L \tag{5}$$

For f_r=5.8 GHz, with the help of above from (1) through (5), the dimensions obtained for the rectangular patch are length, L=11.74 mm, width, W=15.73 mm. The measurements for ground plane and the substrate are calculated to be as $6h+L$=21.34 mm, $6h+W$=25.33 mm. Figure 3 presents the basic rectangular patch antenna structure with patch and ground dimensions in Figure 3(a). Two slots of width 2 mm oriented at an angle of 45 degrees are made in the radiating patch at the corners as shown in Figure 3(b).

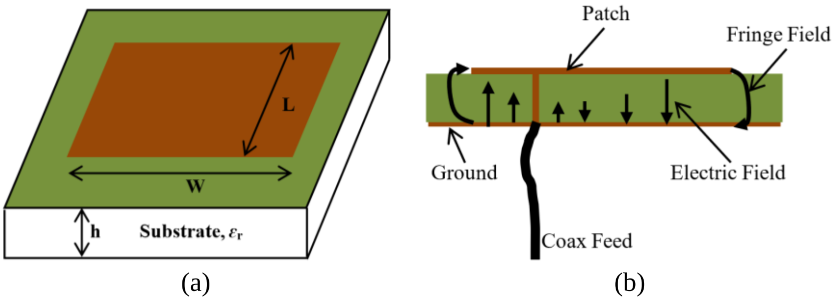
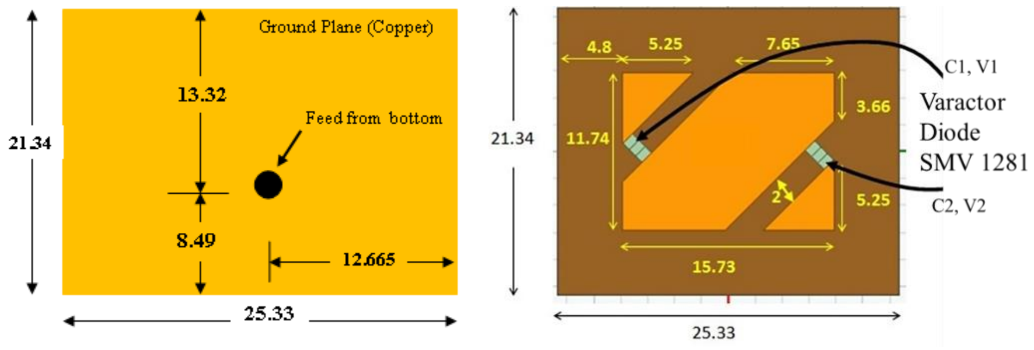


Figure 2. A typical rectangular microstrip coax feed patch antenna (a) top view and (b) side view showing coaxial feed

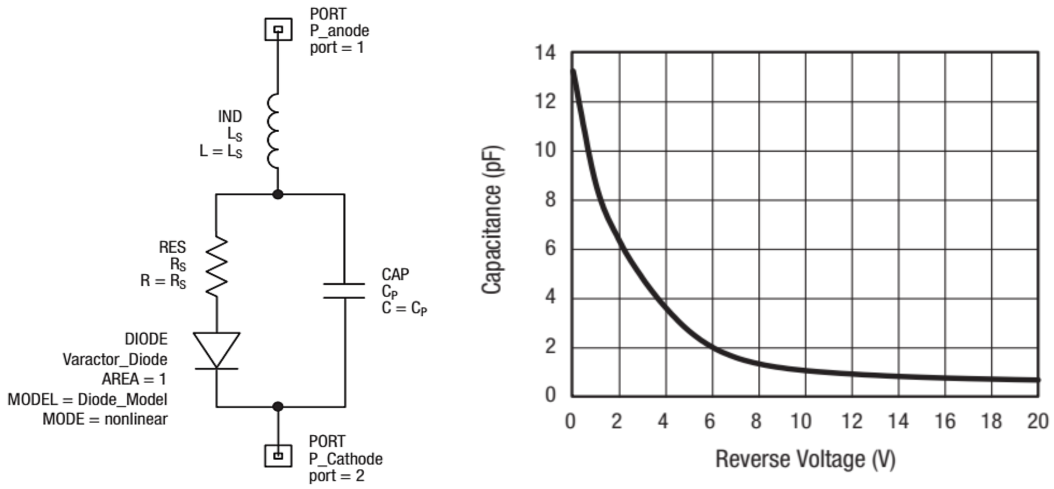


(a) (b)

Figure 3. Designed rectangular patch antenna with coax feed, (a) ground plane and (b) varactor diodes in slots on radiating patch on top

2.2. Variable capacitor diode

Varactor diode is a not a simple p-n junction diode, but it is a variable capacitance diode, whose internal capacitance can be changed continuously by changing the applied reverse bias voltage. Two varactor diodes are inserted in the slots, one each in the two slots. The varicap diodes are implemented as resistance, inductance, and capacitance (RLC) lumped boundary in high-frequency structure simulator (HFSS) electromagnetic (EM) simulation tool. The equivalent circuit of a RF varactor diode with applied reverse voltage is presented in Figure 4(a). By continuous changing the DC bias voltage to the varactor diodes, the effective capacitance can be changed [37]–[39]; the variation of total capacitance with respect to reverse voltage across varactor diode is tabulated in Figure 4(b) [40]. Skywork's varactor diode SMV1281 series, is a surface mount, hyperabrupt varicap diodes which are made for high capacitance tuning ratios and low series resistance for wideband applications [41]. When the applied DC voltage across the varactor diode varies from 0 to 20 volts, the total capacitance of the diode varies from 13.30 to 0.69 pF. Accordingly, the electrical length of the patch radiator changes and results into frequency agility.

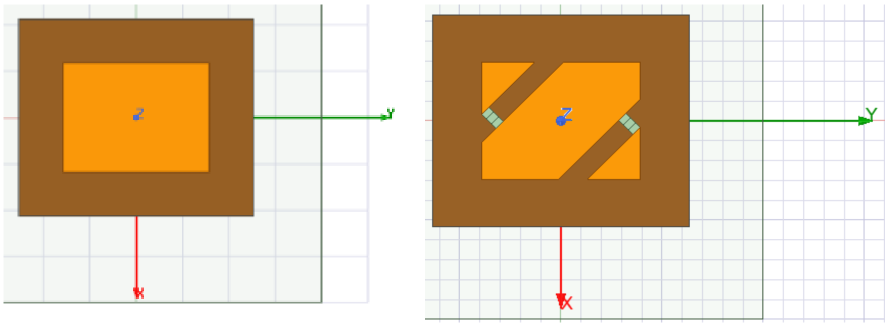


(a) (b)

Figure 4. Varactor diode (a) SPICE model and (b) variation of capacitance of varactor diode with applied reverse voltage [40]

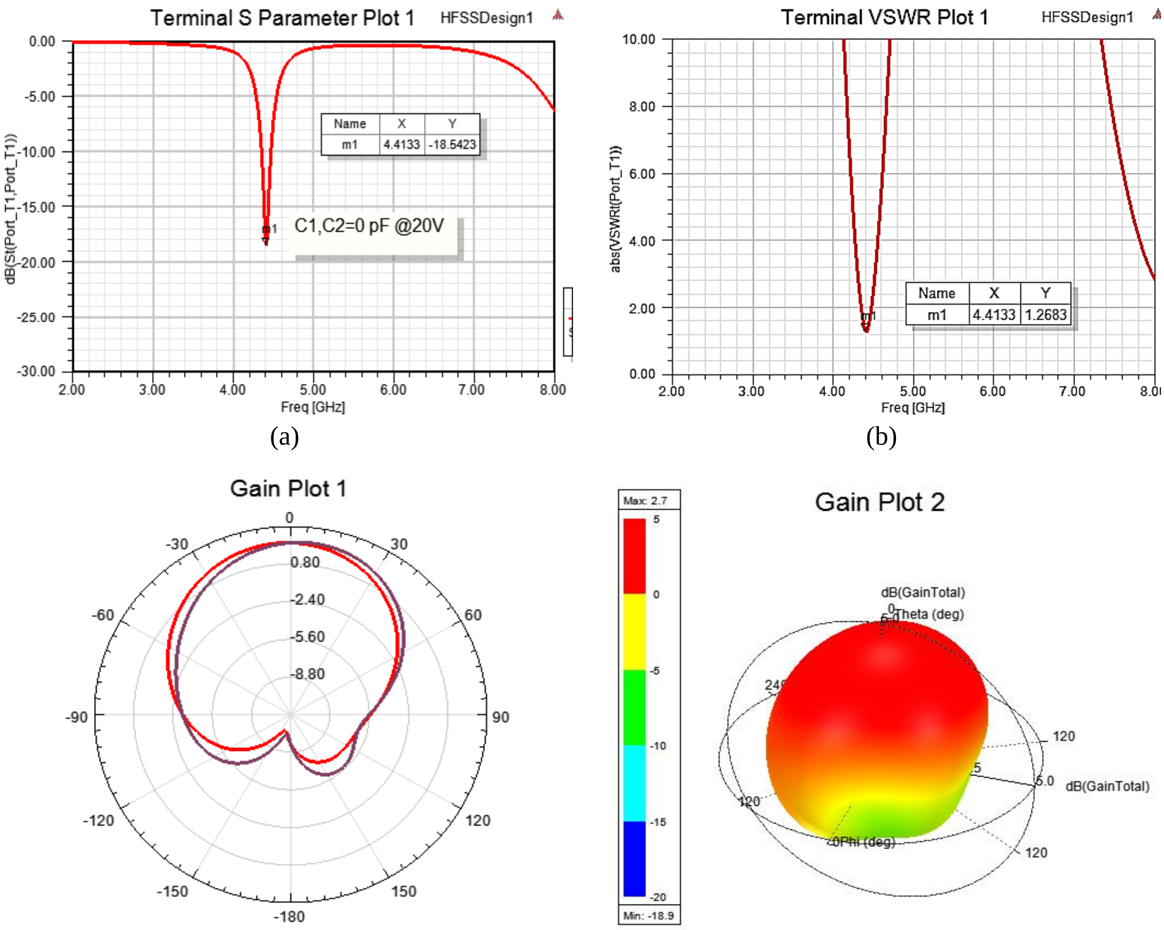
3. ANALYSIS OF RESULTS TO DETERMINE BIASING VOLTAGES

HFSS electromagnetic tool is used for simulating the designed patch antenna. Figure 5 presents the implementation of the proposed rectangular patch antenna in Figure 5(a) and incorporating varactor diodes in the slots in Figure 5(b) using HFSS. The substrate used is FR4 which is cheaply available in the market. The standard thickness of FR4 substrate is h=1.6 mm. The thickness of patch and ground plane is considered to be negligible because the material assignment is pec-perfect electrical conductor. The simulation is carried first with the two slots without the varactors. The return loss S_{11} in Figure 6(a), VSWR in Figure 6(b), two-dimensional radiation pattern in Figure 6(c), and three-dimensional radiation pattern in Figure 6(d) are presented. The return loss is lowest at 4.4133 GHz frequency for the capacitance values of 0 pF both, at which the VSWR is the lowest ρ=1.2683. Therefore, we can obtain very good radiation from the antenna with high efficiency. At this frequency the maximum gain obtained is 2.7 dB. A broad side radiation pattern is achieved, which is suitable for cognitive radio applications.



(a) (b)

Figure 5. The suggested patch antenna implemented in HFSS (a) top view, and (b) with varactor diodes in the slots



(a) (b)

(c) (d)

Figure 6. HFSS executed results for the proposed patch antenna with capacitance values of 0 pF: (a) return loss, (b) VSWR, (c) two-dimensional radiation pattern, and (d) three-dimensional radiation pattern

Following that, simulation is performed with parametric sweep for various combinations of capacitances for the two varactor diodes with values ranging from 0.69 to 13.3 pF as a result of biasing voltages ranging from 20 to 0 V. Figure 7 depicts the obtained return loss. There are four bands obtained: one at 3 GHz, one at 4.2 GHz, one at 4.6 GHz, and one at 5.2 GHz. These are the communication bands with channel occupancy very less as identified earlier. The DC bias voltage across the varactors to obtain these operating bands for the proposed antenna are listed in Table 2.

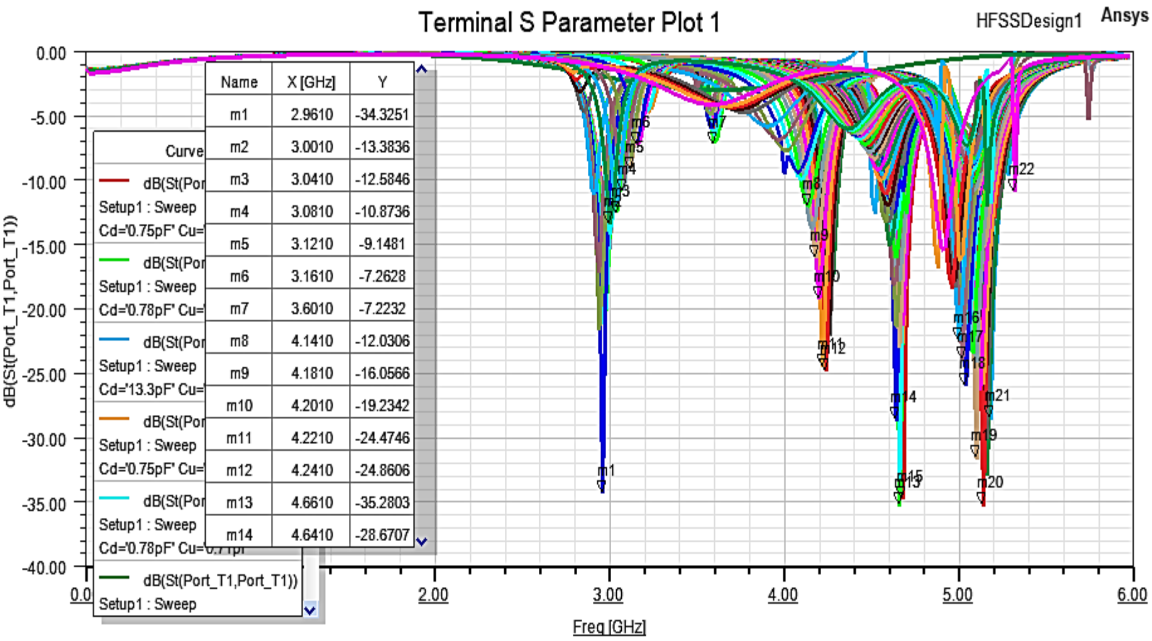


Figure 7. Return loss obtained by tuning the capacitance of varactor diodes at various values as mentioned

Figure 8 depicts the two-dimensional radiation patterns for the E-plane and H-plane in the four bands mentioned. For all of the resonant frequencies stated above, the radiation patterns have similar forms. The direction of maximal gain radiation is around 0 degrees. As a result, the suggested antenna is unidirectional, with a steady emission pattern over a large frequency range. The maximum gain obtained is 4.79 dB at 5.733 GHz resonant frequency. Gains at other tunable resonant frequencies are maintained above 2.59 dB. The proposed antenna can be tuned to these frequencies for transmission.

Table 2. The required biasing voltages for various frequencies

Band-1			Band-2			Band-3			Band-4		
Frequency (MHz)	C1, C2 (pF)	V1, V2 (volts)	Frequency (MHz)	C1, C2 (pF)	V1, V2 (volts)	Frequency (MHz)	C1, C2 (pF)	V1, V2 (volts)	Frequency (MHz)	C1, C2 (pF)	V1, V2 (volts)
2.901	13.3, 2	0, 6	4.141	13.3, 1	0, 11	4.521	0.78, 0.81	16, 15	4.881	13.3, 8.6	0, 1
2.941	13.3, 1.4	0, 8	4.161	13.3, 0.94	0, 12	4.581	0.75, 0.94	17, 12	4.901	13.3, 13.3	0, 0
2.961	13.3, 1.2	0, 9	4.181	13.3, 0.89	0, 13	4.601	0.78, 0.85	16, 14	4.961	13.3, 6.3	0, 2
2.981	13.3, 1.1	0, 10	4.201	13.3, 0.85	0, 14	4.641	0.78, 0.73	16, 18	5.101	13.3, 1.2	0, 9
3.001	13.3, 1.0	0, 11	4.221	13.3, 0.81	0, 15	4.661	0.78, 0.69	16, 20	5.141	13.3, 0.78	0, 16
3.021	13.3, 0.94	0, 12	4.241	13.3, 0.78	0, 16	4.681	0.75, 0.69	17, 20	5.161	13.3, 0.71	0, 19
3.041	0.75, 8.6	17, 1	4.261	13.3, 0.73	0, 18				5.181	13.3, 0.69	0, 20
2.901	13.3, 2	0, 6	4.141	13.3, 1	0, 11	4.521	0.78, 0.81	16, 15	4.881	13.3, 8.6	0, 1

The resonant frequency and radiation characteristics vary notably for varying DC biasing voltages. This is because of changing E-field distribution. By varying the DC bias voltages from 0 to 20 volts, the resonant frequency is altered between 2.901 to 5.321 GHz. With increasing bias voltage and decreasing capacitance, the resonant frequency shifts toward a higher value. The capacitance of varicap diodes decreases as the DC bias voltage rises, resulting in a shorter equivalent electrical length of antenna. As a result, the resonant frequency increases.

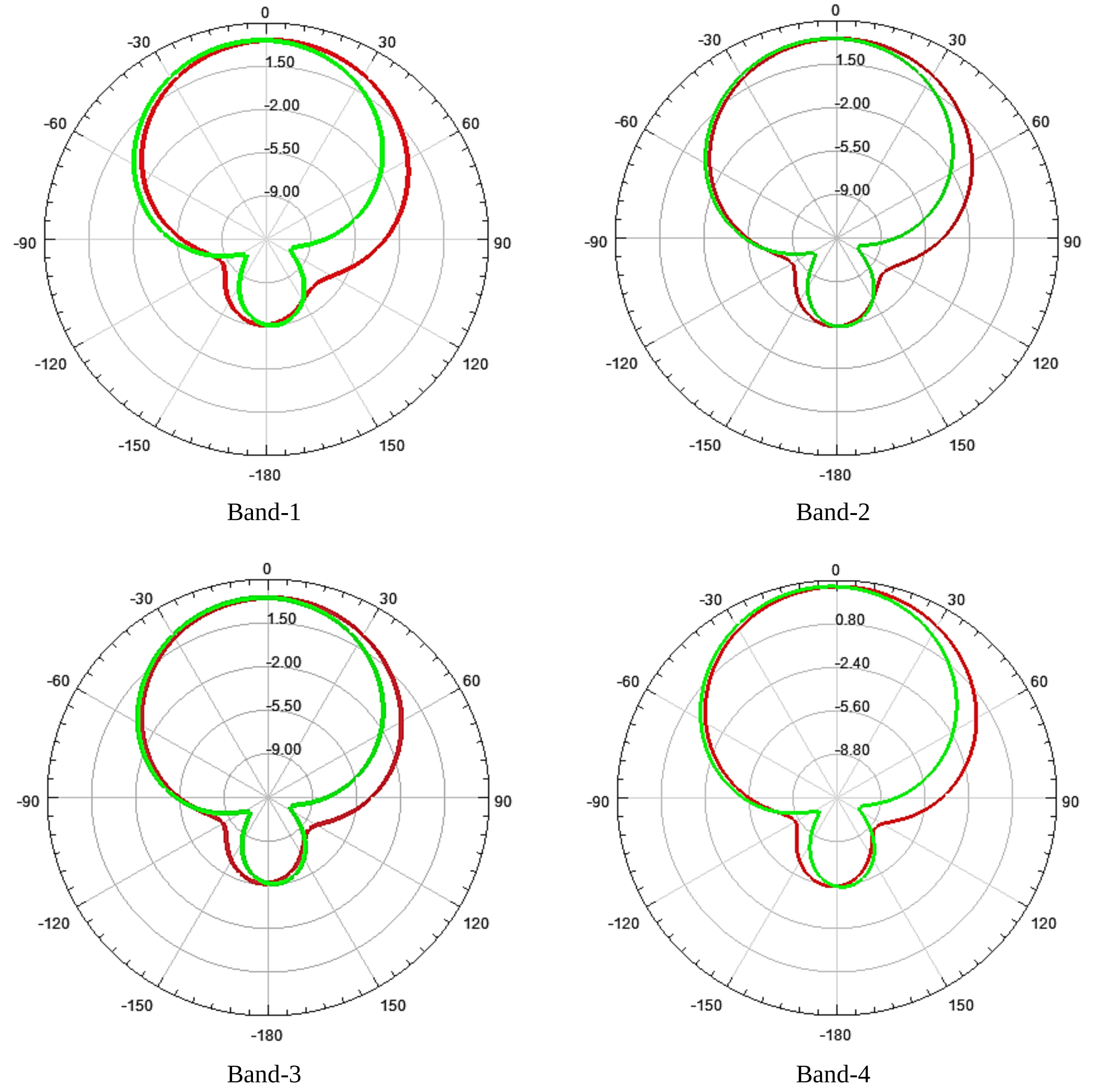


Figure 8. Two-dimensional radiation patterns obtained at the above mentioned frequencies with respect to the values of capacitances shown in Figure 7

Figure 9 depict E-field distribution obtained in the band-1 in Figure 9(a), in the band-2 in Figure 9(b), in the band-3 in Figure 9(c), and in the band-4 in Figure 9(d), of operation of the antenna. It is noted that the E-field distributions are different at different frequency bands. For the mentioned tunable frequencies, the return loss is below -10 dB. The comprehensive performance of the suggested antenna complacent the requirements of cognitive radios. Performance of the antenna is compared with similar previous work of other authors and is summarized in Table 3. The suggested antenna is compact in size, uses only two varicap diodes, quite uncomplicated to fabricate and display wide tunable ranges of frequencies between 2.901 and 5.321 GHz in four different bands.

Table 3. Comparison of performance of the suggested antenna with other works

Ref.	Size (mm^3)	No. of diodes	Range of frequencies	Gain (dB)
[42]	33.9x38x1.6	4	(5.35 to 7.00) GHz	4.50
[43]	80x80x2.4	2	(3.50 to 3.90) GHz	3.80 to 6.00
[44]	70x70x2.0	2	(2.45 to 3.55) GHz	4.25 to 8.49
[45]	50x50x3.04	5	(1.98 to 3.59) GHz	0.20 to 4.80
This work	25.34x25.33x1.6	2	(2.90 to 5.32) GHz	2.59 to 4.79

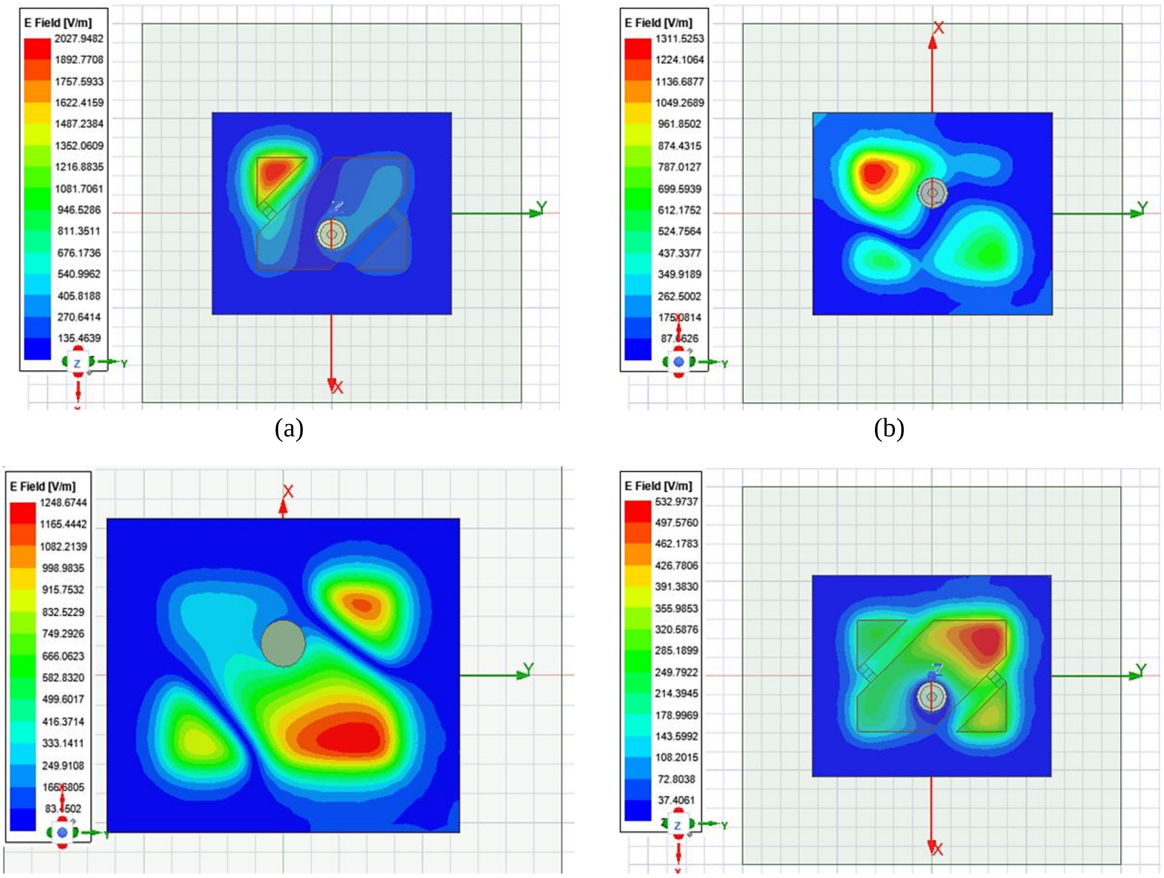


Figure 9. E-field distributions in (a) Band-1(b) Band-2 (c) Band-3, and (d) band-4

4. CONCLUSION

Sparse spectrum occupancy and spectrum holes are first investigated. This enables the SUs to utilize the opportunities and transmit or receive their signals without interference with the primary users. A frequency reconfigurable antenna is a need of the hour for wireless communication engineers. We have designed a compact rectangular patch antenna at resonant frequency 5.8 GHz with coaxial feed for transmission or reception in the spectrum holes. To realize the frequency agility function we have made two slots at the corners of the patch and introduced two variable capacitance functionalities in HFSS for varactors. This makes electrical length of the antenna to change. A stable unidirectional radiation pattern is observed. The proposed antenna is simple, compact, easy to fabricate, have good tunability ratio, and continuous frequency tuneable. There is a huge demand for such antennas in wireless communication and cognitive radio applications to reduce the number of antennas.

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