Design and characterization of frequency reconfigurable honey bee antenna for cognitive radio application

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ABSTRACT

In this article, a frequency reconfigurable honey-bee compact microstrip monopole antenna is proposed which is fed by a microstrip line (50 Ω) having the capability of providing dual-band as well as triple-band operation in eight distinct modes. By embedding three PIN diodes overs the honey bee arms, the effective current distribution is controlled hence resonant frequency is also changed in eight distinct modes in real-time. This is the reason the proposed antenna is portrayed as a frequency reconfigurable antenna in this paper which is suitable for cognitive radio application. This proposed antenna can be used for various wireless application such as Bluetooth, Wi-Fi, worldwide interoperability for microwave access (WiMAX), wireless local area network (WLAN), C-band, and X-band applications. The proposed antenna possesses a planner geometry of 39×34×0.87 mm^3 which is printed on a substrate as flexible FR-4 (lossy) (ε_r=4.4 and tanδ=0.019). The proposed antenna exhibits voltage standing wave ratio (VSWR)<2 for all 19 resonant frequencies of interest and perceptible radiation pattern over entire frequency bands with a positive gain. CST microwave studio is used to find out all simulated results of antenna parameters.

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1. INTRODUCTION

Nowadays, this modern era witnessed a rapid development of electronics and wireless communication and the reconfigurable antenna (RA) has gained a remarkable attraction among researchers. A single band antenna, for example in [1] can operate in single bands which can simultaneously transmit only one wireless signal. This single band antenna does not fulfill the customer demand and it is a suitable candidate for only one wireless application. On the other hand, frequency reconfigurable (FR) antenna provides multiple wireless applications and can utilize the available spectrum efficiently.

An FR antenna consists of a single radiator is designed in such a way that its nature of characteristics can be changed by switching in real-time such as bandwidth (BW), polarization, frequency, and pattern. Global positioning system (GPS), global system for mobile communications (GSM), wireless local area network (WLAN), and Bluetooth such kinds of devices draw significant attention [2], [3] in the designing of FR antenna. Reconfiguration of frequency can be achieved via diodes that are integrated within the radiating element and discuss various articles' techniques to achieve reconfiguration of microstrip antenna [4]. Apart from a RA can achieve compact size, stable radiation pattern, low cross-polarization and better tuning ability over a good range of spectrum submitted in [5], [6], and can switch between different narrowband modes [7]–[9]. To design a RA different type of switches can be used like PIN diodes [10]–[12], PIN diodes are very popular for their high handling competency, high switching speed, ease of packaging, low cost and it exhibits nearly pure resistance at microwave frequencies. using PIN diodes increase insertion loss as well as responsible to decrease the positive gain of an antenna for high biasing resistance of PIN diodes [10]. In [13], [14], by varying capacitance of varactor diodes, smooth frequency agility is achieved, but they are non-linearly dependent on applied voltage possessing limited tuning range capability [15]. Besides this, random forest (RF) micro-electro-mechanical system (MEMS) are integrated within the antenna for public safety bands [16], [17] and field-effect transistor (FET) switches are also used as switches presented in [18].

A FR antenna consists of two patches with a double ‘c’ slot is represented [19], in which both RF diodes, PIN diodes, and the capacitor is also used. PIN diodes are responsible for control the switching characteristics of the antenna. Using five PIN diodes a rectangular patch with a rectangular slot antenna is operated in nine distinct frequencies from 1.98 to 3.59 GHz [20]. By controlling shorting strips frequency reconfiguring is achieved using a thick substrate of 3.5 mm [21]. In [22] circular patch shape antenna with four PIN diodes is used and achieved ultra-wideband (UWB), narrowband, and dual-band characteristics by cutting slots in the ground. Three pairs of PIN diodes are amounted in [23] to achieve dual-band characteristics by simply changing the location and length of folded slots. A novel microstrip antenna is represented using varactor diodes with appropriate direct current (DC) bias circuit which can provide dual-band operation as a lumped capacitor is used in the middle of slot [24].

However above-mentioned articles have some drawback such as larger dimensions, limited usable BW, and design complexity in terms of numerous electronic switches and biasing circuit. As UWB technology is very popular in academic research as well as industrial application, to overcome bandwidth limitation and to achieve UWB characteristics many techniques have been published [25]–[27]. But using partial ground with microstrip feedline provides the simplest fabrication techniques to achieve UWB characteristics and many authors had proposed this [28]. Nowadays researchers paying heed to flexible antenna because of their lightweight, low profile, and low cost [29].

In this paper, a new approach to design a flexible and FR monopole antenna is proposed. This proposed design can show triple band, dual-band, narrowband, and UWB characteristics by switching its appropriate location. The proposed antenna exhibits combined UWB and narrowband characteristics in every distinct state respectively. Besides, it exhibits two wideband characteristics in states 6 and 8 respectively. Table 1 represents the switching configuration whereas antennas frequency band along with BW are listed in Table 2. This form of functionality made this antenna suitable for numerous military applications and cognitive radio applications as well. By switching appropriately, we can utilize this antenna for multitasking wireless application. A multi-band FR antenna can provide multiple excesses over a wide range of frequency and it uses the frequency spectrum efficiently. Besides this, they exhibit good positive gain and stable radiation pattern.

Table 1. Proposed antenna switching configurations with operating frequency

States	Switches			Operating Frequency (GHz)
	s1	s2	s3	
State 1	ON	ON	ON	2.39 & 4.9 & 8.0
State 2	OFF	ON	ON	2.58 & 8.0
State 3	ON	OFF	ON	2.42 & 7.5 & 6.0
State 4	ON	ON	OFF	2.47 & 8.02
State 5	OFF	OFF	ON	2.60 & 6.18 & 7.67
State 6	OFF	ON	OFF	3.10 & 8.0
State 7	ON	OFF	OFF	2.52 & 7.5
State 8	OFF	OFF	OFF	3.48 & 7.66

Table 2. Details of antenna frequency band and bandwidth in each state

States	Operating Frequency Bands (GHz)	Characteristics	Bandwidth
State 1	2.236-2.558; 4.712-5.09; 6.38-8.71	Triple Band	321 MHz & 375 MHz & 2330 MHz
State 2	2.41-2.76; 6.30-8.73	Dual Band	347 MHz & 2430 MHz
State 3	2.26-2.60; 5.33-8.80	Triple Band	332 MHz & 3450 MHz
State 4	2.32-2.63; 6.34-8.69	Dual Band	312 MHz & 2350 MHz
State 5	2.45-2.78; 5.84-8.75	Triple Band	326 MHz & 2910 MHz
State 6	2.83-3.44; 6.24-8.72	Dual Band	604 MHz & 2471 MHz
State 7	2.37-2.67; 6.0-8.74	Dual Band	299 MHz & 2743 MHz
State 8	3.12-3.94; 6.31-8.75	Dual Band	812 MHz & 2445 MHz

2. THE PROPOSED ANTENNA GEOMETRY

Figures 1(a)-(d) show the schematic diagram of the represented FR honey bee antenna with PIN diode equivalent circuit. A honey bee monopole antenna is proposed in Figure 1(a), it has three arms which are different in length in Figure 1(b). The main reason behind these different lengths is to obtain various electrical lengths for surface current. It can be operated through 2.26 to 8.86 GHz in the UWB range by switching in eight distinct states.

The antenna is printed on materials FR-4 (lossy) as its substrates (ε_r=4.4 and $tan\delta$=0.019) with a thickness of 0.8 mm. The size of the substrate is 39×34×0.8 mm^3. A 50 Ω transmission line is used to feed the main resonator having a dimensions *w*×*l* in Figure 1(a). The main resonator of shape that possesses a thickness of 0.035 mm occupies two '*I*' shape slots of having *a*×*k* dimensions to obtain good impedance matching. The widths of these slots contribute to controls the current intensity and minimize the return loss of the antenna. A squared shape hole has cut in the middle of the patch to make it a square ring resonator and to lengthen current path. Three honey bee arms with a circular ring are located at the uppermost of the main resonator which are connected to the main resonator via three PIN diodes. These three arms possess three different lengths which help to obtain various resonant frequency, as the resonant frequency of the antenna depends upon the electrical length of the antenna. On the uppermost side of the antenna, each honey bee arm is connected with three rings having equal outer radius '*R*' depicted in Figure 1(b). The surface current circulates in these rings and helps to lengthen surface current path further. On the bottom of the substrate, there exists a rectangle manner ground plane having dimensions of 11×34×0.035 mm^3. By integrating three PIN diodes in the honey bee arms, represented antenna frequency band switching is achieved thus helps to be a suitable candidate for cognitive radio application. By integrating three PIN diodes (s1, s2, s3) it performs eight different switching configurations as shown in Table 1 for frequency band switching in where each state shows dual-band operation of having both narrow and UWB characteristics. Here PIN diodes of model No. 'MBP-1036-B11' act as a variable resistor with two operating states (ON/OFF). Both states have resistor, inductor, and capacitor (RLC) equivalent circuit which is demonstrated in Figures 1(c) and 1(d). In forward bias (ON state) it acts as a short circuit as it offers small resistance, and reverse biased condition (OFF state) it blocks the current as it builds up a parallel combination of capacitor and large resistance where resistance, capacitance and inductance values are mentioned in the associated figure.

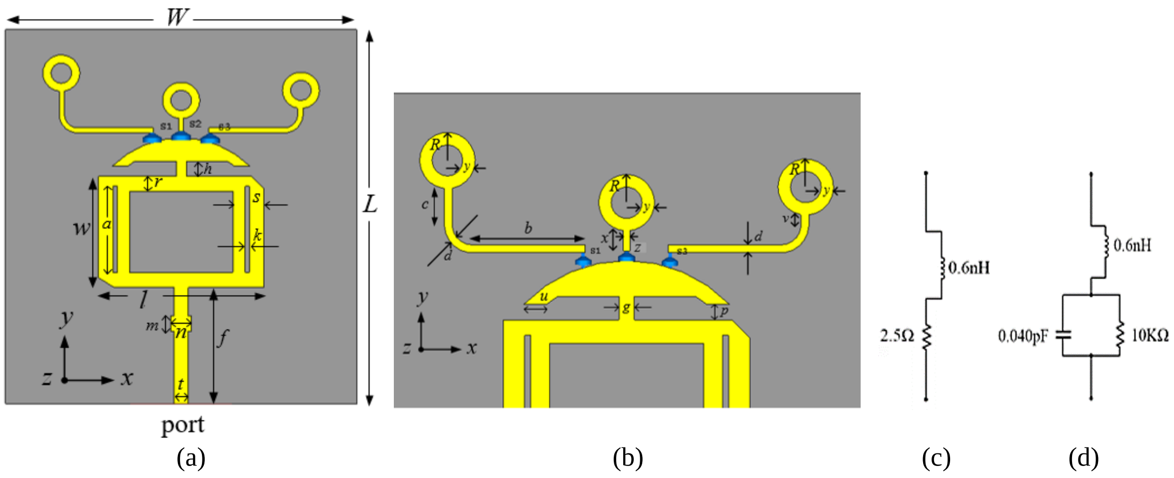

Figure 1. The antenna structure (a) front view, (b) magnified view of uppermost side of honey bee where *w*=14.8 mm, *l*=11 mm, *n*=2 mm, *t*=1.4 mm, *f*=11.50 mm, *m*=1.5 mm, *a*=8.50 mm, *k*=0.4 mm, *d*=0.5 mm, *W*=34 mm, g=1.0 mm, *L*=39 mm, *u*=1.49 mm, s=3.0 mm, *r*=1.8 mm, *c*=2.43 mm, *z*=0.4 mm, *b*=7.30 mm, *v*=0.73 mm, *y*=0.8 mm, *R*=1.8 mm, *p*=1.0 mm, *h*=1.50 mm and *x*=1.31 mm, RLC equivalent circuit of PIN diode at, (c) ON state, and (d) OFF state

To make the PIN diode in ON state a positive bias voltage is needed to provide across the PIN diode terminal hence extra circuitry is needed for switching purposes. A positive bias voltage of 0.7 V can make the PIN diode ON whereas a negative bias voltage will lead the diode in the OFF state. To get the above mention operation of PIN diode successful a biasing circuit is needed while fabricating the antenna and by biasing PIN diode suitably desired biasing state can be obtained easily. In the course of simulation, the lumped element condition of CST Microwave Studio (CST MWS) is used to model the PIN diode and to carry out simulation its equivalent ON and OFF state value has been put simultaneously and this way three PIN diodes act as a switch here.

3. SIMULATION RESULT ANALYSIS AND DISCUSSION

3.1. Reflection coefficient (RC) curve and voltage standing wave ratio (VSWR)

Frequency band switching is easily achieved in the represented antenna by simply changing current distributions among three honey bee arms, three PIN diodes act as electronic switches. With the help of three switches, eight different states of an antenna are achieved, that means antenna has the capability of performing operations in a various different frequency band which is listed in Table 2. The represented antenna has also band rejections characteristics and rejects Wi-Fi bands in states 8 as shown in Table 2 and Figure 1(b), otherwise in other states, it performs in the Wi-Fi band as shown in Table 2. Corresponding simulated RC curves and VSWR against frequency are presented in Figure 2. The RC curve (S11) achieved less than -10 dB gain at all frequencies of interest in Figures 2(a)-2(b). It can be clearly seen that the antenna operates from 2.26 to 8.80 GHz band and can be switched at desired bands by simply turning ON/OFF switches. All the states except states 1, 3 and 5 showed dual-band characteristics. The simulated VSWR curve for the proposed antenna is represented in Figures 2(c)-2(d). Every different state of the represented antenna shows VSWR<2 in operating frequency and VSWR>2 in every other frequency. At every operating frequency value of VSWR is just near to unity and indicates the existence of maximum impedance matching.

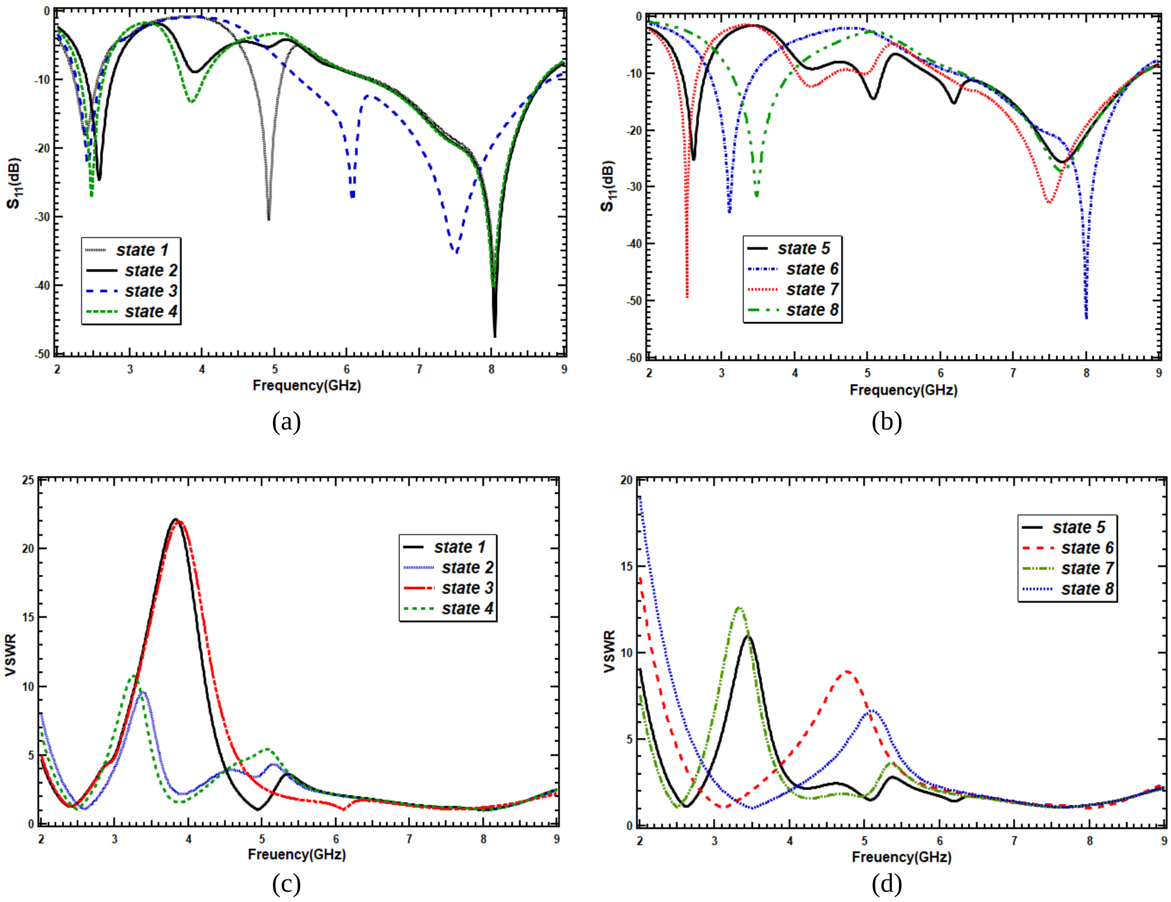

Figure 2. The simulated reflection coefficient (S_{11}) curve for (a) state 1 to 4, (b) state 5 to 8 and simulated VSWR curve, (c) for state 1-4, and (d) for state 5-8

3.2. Radiation pattern and surface current

The radiation characteristics of the proposed antenna are simulated using CST MWS and radiation characteristics for all 8-states of antenna are shown in Figures 3(a)-3(d). The proposed antenna shows a superior omnidirectional pattern in the x-z (E-plane) plane that is suitable for communication purposes and shows a bidirectional pattern in y-z (H-plane) plane at lower frequencies. But the ignominy of the x-z plane is noticed at some higher frequency due to asymmetric structure and feeding loss of antenna.

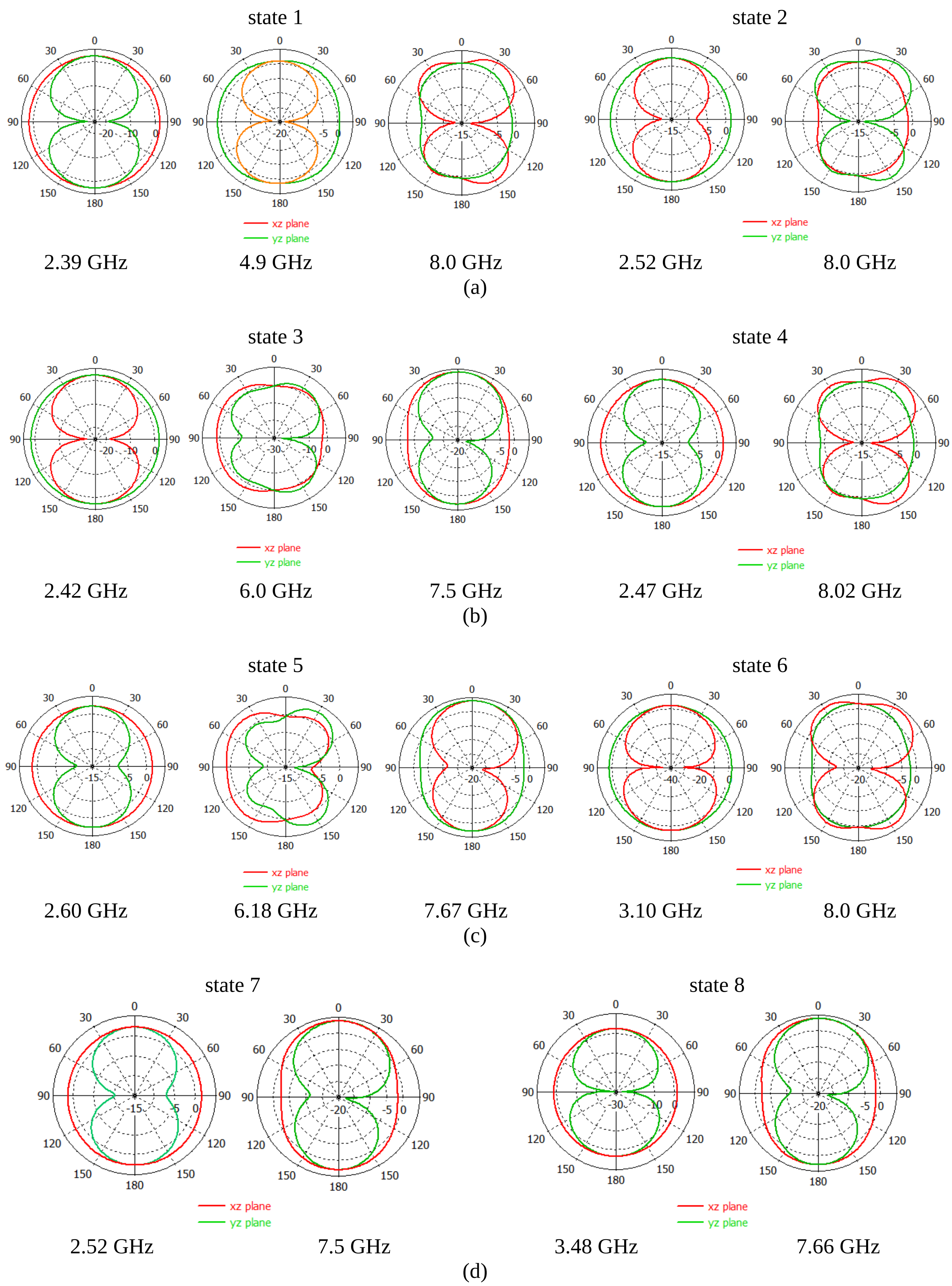

Figure 3. Simulated normalized radiation pattern in x-z plane and y-z plane for (a) state 1 and state 2, (b) state 3 and state 4, (c) state 5 and state 6, and (d) state 7 and state 8 of the proposed antenna

At higher frequency, the x-z plane behaves like a dipole radiation pattern when the y-z plane reveals omnidirectional characteristics. The simulated average current distribution for certain operating frequency is presented in Figure 4 and antennas performance is observed through current distribution. A color map is also attached which conveys the intensity of current flow at the different resonant frequency is different. From Figures 4(a)-4(f), it can be seen that different parts of the honey bee antenna act differently at different resonant frequencies. Depending upon diode condition different parts of the honey bee is responsible for different working frequency. Obviously higher current is flowing at a higher operating frequency.

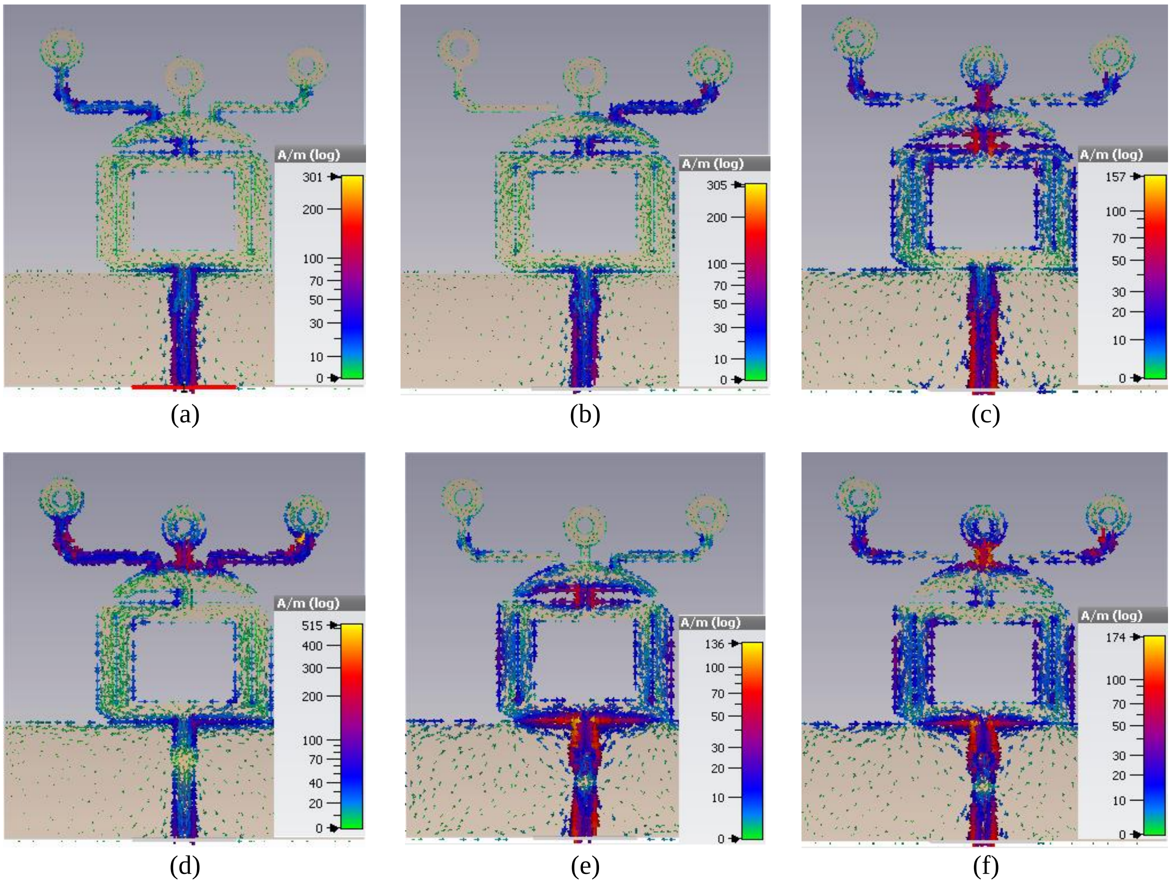

Figure 4. Surface current of proposed antenna at (a) 2.39 GHz, (b) 2.60 GHz, (c) 3.10 GHz, (d) 4.9 GHz, (e) 7.67 GHz, and (f) 8.0 GHz

3.3. Gain, realized gain, directivity and efficiency

The proposed antennas' other parameters such as gain, directivity, and efficiency for all eight states are defined in Table 3. The antenna gain is an important parameter and describes how much an antenna is transmitted power in specific direction compared to an ideal radiator or how much input power is converted to output by an antenna. The proposed antenna has a positive gain of all states of resonant frequencies and shows high gain at higher frequencies. Simulated realized gain has a value closer to gain, which indicates a small amount of power has been lost due to antenna mismatch or by antenna port. Apart from some frequencies gain and realized gain are almost equal to each other. Both radiation efficiency and total efficiency is depicted in Table 3. Antenna shows the highest radiation efficiency of 92.72% at 3.10 GHz in state 6 and the lowest radiation efficiency of 75.79% at 6.0 GHz in state 3.

3.4. Comparison with other work and discussion

The antenna size is a major issue during designing a microstrip antenna, in comparison to Table 4, [19] an antenna is proposed which is small in size but the substrate RO4350 is not accessible everywhere and shows narrowband characteristics. In [20], [24], [30] proposed antenna possesses large dimensions and suffers from narrow BW, apart from a usable substrate is not available at all. Larger BW characteristics are achieved in [16], [31] but antenna dimension and thickness are greater compared to the proposed work in this paper. The proposed antenna possesses a smaller size compared to other works except for [19] indexed in Table 4. The proposed antenna has a total of eight different states by embedding only three PIN diodes wherein every state is able to provide a different resonance point for wireless application indicates it is worthy of cognitive radio application. In every state, it shows a remarkable amount of BW, dispels the problem of having a narrow BW problem with meaningful omnidirectional radiation pattern.

Apart from 19 resonance point of this antenna per se reveals the ability to provide a multiwireless applications. Not because the antenna has a smaller size and a flexible substrate but because these above mention criteria set the proposed antenna stands out from another antenna. Here, the proposed antenna employed three PIN diodes which increases the complexity of the antenna as antenna does not have full plane ground and to make its operation successful practically, PIN diodes should be grounded by a via after drilling the substrate and a small diameters of copper wire should be concatenated with via to ground plane. A small diameters of copper wire will render a radiation which would be ineffectual to antennas main radiation not demeaning the radiation pattern.

Table 3. Parametric study of all eight states of proposed antenna

Antenna Parameter	Frequency (GHz)																		
		State1		State2			State3		State4			State5		State6		State7		State8	
	2.39	4.9	8.0	2.58	8.0	2.42	7.5	6.0	2.47	8.02	2.60	6.18	7.67	3.10	8.0	2.52	7.5	3.48	7.66
VSWR	1.28	1.10	1.01	1.12	1.02	1.30	1.10	1.13	1.12	1.01	1.13	1.42	1.09	1.03	1.0	1.10	1.09	1.05	1.09
RC (dB)	-18.15	-30.6	-38.5	-24.68	-47.5	-22.18	-35.4	-27.71	-27.09	-40.25	-25.28	-15.16	-25.55	-34.66	-53.24	-49.38	-32.69	-31.58	-27.16
Gain (dB)	2.09	2.03	3.78	2.54	3.78	2.09	3.51	1.38	2.11	3.79	2.16	3.38	3.39	2.4	3.72	2.08	3.42	2.50	3.45
Realized gain (dB)	2.04	2.01	3.78	2.17	3.78	2.03	3.51	1.38	2.08	3.79	2.13	2.01	3.38	2.4	3.72	2.02	3.41	2.50	3.44
Directivity (dBi)	2.5	2.78	4.4	2.18	4.35	2.44	3.97	2.58	2.46	4.38	2.53	2.99	3.85	2.73	4.29	2.44	3.87	2.86	3.93
E_{max} (dBV/m)	16.8	16.3	18.5	16.89	18.50	16.8	18.3	16.1	16.8	18.5	16.9	16.8	18.1	17.2	18.5	16.7	18.2	17.3	18.2
H_{max} (dBV/m)	-34.5	-35.3	-33	-34.6	-33.0	-34.7	-33.3	-35.4	-34.7	-33.0	-34.7	-34.7	-33.4	-34.4	-33.1	-34.8	-33.3	-34.2	-33.3
Radiation efficiency (%)	92.3	84.0	87.4	91.85	87.7	92.1	89.9	75.79	92.25	87.28	91.6	82.54	89.96	92.72	87.72	92.0	90.09	92.24	89.41
Total Efficiency (%)	91.1	83.7	87.3	91.60	87.6	90.92	89.8	75.75	91.61	87.27	91.28	79.73	89.79	92.66	87.1	90.6	89.98	92.14	89.19
HPBW (degree)	80.0	49.3	85.0	90.0	105	78.6	80.3	55.5	79.2	107	90.2	56.3	80.1	83.6	106.5	80.0	80.6	82.4	82.0

Table 4. Performance comparison with recently published work

Ref.	Characteristics			
	Size (mm^2)	Substrate and thickness	No. of Switches and resonant point	Bandwidth at different resonances bands (MHz)
[19]	675	RO4350B & 0.8 mm	3, 6	100; 120; 280; 220; 100; 320
[20]	1600	Taconic TLT & 1.0 mm	2, 6	220; 190; 170; 180; 250; 150
[30]	2300	Taconic RF35 & 1.52 mm	5, 6	250; 310; 300; 300; 260; 210
[16]	1600	FR4 & 1.6 mm	4, 7	8140; 940; 590; 550; 780; 810
[31]	1600	FR4 & 1.33 mm	5, 13	9170; 400; 60; 2000; 440; 230; 190; 300; 450
[24]	1829	PET & 0.1 mm	1, 3	160; 180; 270
This work	1326	FR4 & 0.8 mm	3, 19	321; 375; 2330; 347; 2430; 332; 3450; 312; 2350; 326; 812; 2910; 604; 2470; 299; 2740; 2440

4. CONCLUSION

The proposed compact honey bee antenna achieved frequency reconfigurability characteristics via PIN diodes. The antenna has 19 various operating frequencies with an omnidirectional positive gain. In every interest of frequency of eight states, it shows good radiation efficiencies, effective bandwidth, and appreciable RC gain, which made this antenna a suitable candidate for multiwireless communication. Effective length for surface current is enhanced by adding three honey bee arms over the main resonator. Besides, the antenna has a wide tuning range from 2.26 to 8.80 GHz and can be used for cognitive radio communication and ultra-wideband applications.

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