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Design and Analysis of a Frequency Reconfigurable Microstrip Patch Antenna switching between Four Frequency Bands

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Abstract—An effective design of a novel, compact, single feed, dual patch frequency reconfigurable Microstrip Patch Antenna (MPA) for wireless communication systems is proposed and studied in this paper. Fundamental structure of the antenna consists of a rectangular patch and a U-shaped patch. This antenna occupies a compact volume of $86.3\,\text{mm} \times 50\,\text{mm} \times 1.5875\,\text{mm}$ ($6850.6\,\text{mm}^3$) including ground plane. Switching among four different frequencies is obtained by varying effective length of antenna. Effective length is changed by placing three PIN diodes at different positions in the slot present between two patches of the antenna. Variations in effective length perturb the surface current paths and hence change current density on the conducting patches. By changing states of PIN diodes, the proposed antenna could be switched to 1.87 GHz, 3.55 GHz, 3.67 GHz and 5.6 GHz frequencies. Antenna is simulated in High Frequency Structure Simulator (HFSS) Version 13.0, and a prototype of the simulated antenna with DC biasing circuit is fabricated on a flame retardant (FR-4) Epoxy substrate. The antenna is fed by an inset microstrip line which provides impedance matching. The prototype is tested for its performance analysis. A good agreement is obtained between measured and simulated results. Simulated and measured results show that the antenna provides return loss less than -10 dB assuring good match in absence of any matching network at all frequencies. Effect of changing the position of PIN diodes on resonance frequencies is also studied. The proposed antenna provides benefits such as multifunction operation and symmetry of radiation pattern upon switching between different frequencies.

1. INTRODUCTION

The rapid increase in wireless standards demands antennas with multifunctional abilities, i.e., antennas capable of changing their characteristics dynamically and in reversible manner. Reconfigurable antennas fulfill all these demands due to their ability to change any of their characteristics without affecting the others. Reconfigurable antennas can switch between different frequencies [1–3], different polarization modes [4–6] and different radiation patterns [7, 8] in order to adapt to the environment where they operate. The reconfiguration is not limited to switching of a single characteristic, but combination of more than one characteristic can be made to switch between different modes depending upon device antennas are used in [9, 10].

Three different types of antenna structures are preferred to obtain frequency reconfiguration in mobile devices: wire antennas, Planar Inverted F Antennas (PIFA) and Microstrip Patch Antennas (MPA). MPAs are mostly preferred over other two types for their advantages of low profile, low cost and light weight. Each type of antenna employs a different mechanism in order to reconfigure its frequency. MPAs detour the current paths on the patch to control the resonance of antenna. Change in resonance switches the operating frequency of antenna. Four different techniques are used to change the current path on patch: use of electronic switching devices such as PIN diodes, varactor diodes or Micro

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Electro Mechanical Switches (MEMS) in radiating element or microstrip feed line [11], employment of optical switches in structure of antenna, use of metamaterials to change frequency of antenna [12, 13] and through mechanical changes which are introduced by including different mechanically movable parts in structure of antenna [14]. Reconfigurable antennas containing multiple ports and multiple patches in a single structure have also been proposed [15–17]. Frequency reconfigurable fractal antennas have also attracted attention in past few years. These antennas contain self repeating geometries in their structures to increase length of the antenna which reconfigures frequency of antenna [18].

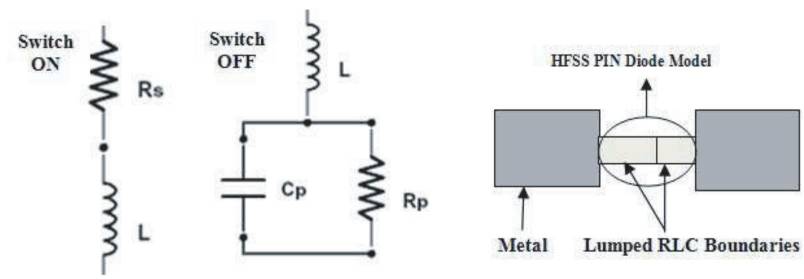
A large number of frequency reconfigurable antennas with slots in their structures have been reported in past few years. The slots are used to change the path of currents, and different types of switches are placed in slots to control length of slots in order to obtain different operating frequencies. Slot can have any shape depending upon the structure of antenna [19]. In many reconfigurable antennas reported in past few decades, slots are etched in their radiating structure, and different types of switches are placed between slots to change operating frequency of antenna. A microstrip patch antenna containing PIN diodes to switch between six frequency bands is presented in [20]. A dual-band antenna containing varactor diodes is presented. Change in capacitance of diodes makes antenna reconfigure between different frequencies [21]. Another antenna with annular slots is proposed in literature. This antenna consists of an RF MEMS based actuator placed between the antenna structure and the feed line. By controlling the actuator, frequency is reconfigured [22]. Varactor diodes are preferred for continuous tuning of frequencies and PIN diodes find their application in switchable frequency reconfigurable antennas. Two different prototypes of a quasi-Yagi dipole antenna are presented in [23]. One prototype contains varactor diodes in structure to provide continuous tuning within a range of frequencies, and the other is designed using PIN diodes to enable switching between two different frequency bands. Silicon made optical switches have been used by some researchers to construct frequency reconfigurable antennas [24]. Some compound reconfigurable antennas using PIN diodes [25] and optical switches [26] have also been reported in the past. RF MEMS and PIN diodes are mostly used as electronic switches in reconfigurable antenna design for wireless devices. PIN diodes are preferred over MEMS switches due to their high power handling abilities, fast switching, low cost and low driving voltage. PIN diodes require DC bias for their operation which demands insertion of DC bias lines in structure of antenna. Resonance characteristics of the antenna are greatly affected if bias lines are placed in near vicinity of radiating structure. In order to isolate DC lines from radiating structures, some lumped elements are placed in antenna structures, which causes distortion in radiation pattern of antenna.

In this paper, a single feed frequency reconfigurable MPA is proposed. The antenna contains two nested patches, i.e., a rectangular patch and an inverted U-shaped patch. Three PIN diodes are placed in the slot present between both patches to provide reconfiguration between four frequency bands of WiFi, WiMAX and GPS. Inset microstrip feed is used to excite the antenna. This type of feed introduces a junction capacitance by introducing a physical notch. By changing the length and width of notch junction capacitance can be changed in order to match impedance of feed line to the patch. This feeding technique has eliminated the need of extra matching network for our antenna. DC bias circuitry is designed by splitting the U-shaped patch into three different parts in order to excite all three diodes independent of each other. $\lambda/4$ high impedance lines are used to connect diodes to the DC bias which is provided from ground plane through via holes. Bias circuitry is designed without using any lumped element on radiating side of MPA.

Section 2 gives an overview and procedure of using PIN diode in antennas. In Section 3, the design of our proposed antenna including parameter details is discussed. Simulated and measured results are presented in Section 4. Section 5 explains the effect of changing the positions of diodes on the resonance frequency of MPA. The paper is concluded in Section 6.

2. PIN DIODE MODEL

At RF frequencies PIN diodes behave as a variable resistor, with some more complicated circuit model for ON/OFF states, as shown in Figure 1(a). Both the ON and OFF states have a package inductance L. The equivalent circuit for the ON state (forward biased) has a low resistance Rs which contributes to insertion loss. The equivalent circuit for the OFF state (reverse biased) has parallel combination of reverse bias resistance R_P and total capacitance C_T, which contributes to the isolation. All values



(a) (b)

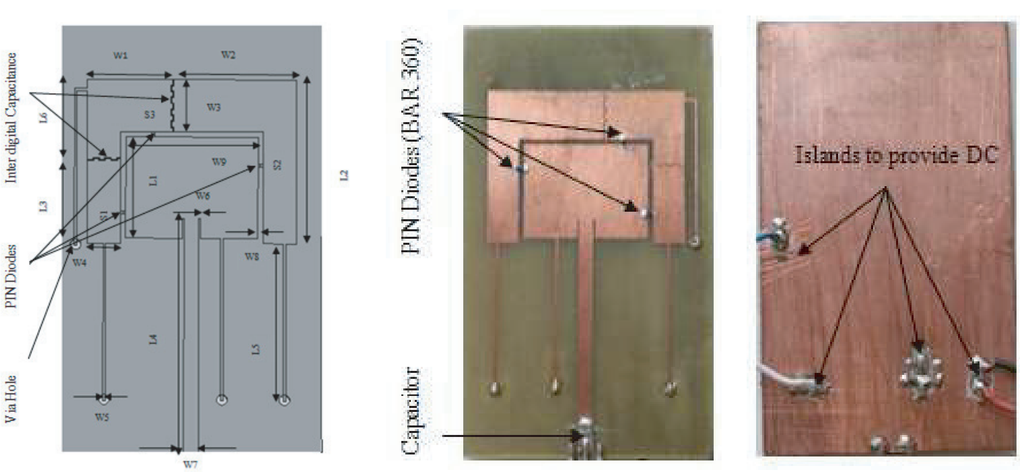
Figure 1. RF PIN diode. (a) Equivalent lumped element model. (b) HFSS model.

required for the circuit models are available in the data sheet of all PIN diodes provided by the manufacturers. In our design, the PIN diode is modeled in HFSS using two series lumped RLC boundary conditions, as shown in Figure 1(b), where the first part of RLC boundary is L and second is either R_s for the ON state or a parallel combination of R_p and C_T for the OFF state. These diodes are used to achieve robustness in terms of reconfiguration between different frequency bands.

The PIN diodes modeled in our design are BAR 360 provided by BARUM Electronics Corporation Limited. The HFSS RLC boundary values for the diodes in ON state are: $L = 0.6\,\text{nH}$ and $R_s = 1.33\,\Omega$ and for the OFF state the RLC boundary values are: $L = 0.6\,\text{nH}$, $R_p = 3\,\text{k}\Omega$, and $C_T = 0.17\,\text{pF}$ as listed in the data sheet of diode provided by manufacturers.

3. ANTENNA DESIGN

This section describes the design and geometry of the antenna. The schematic of frequency reconfigurable MPA and fabricated prototype is shown in Figure 2. The antenna is printed on an FR-4 Epoxy substrate having a practically measured permittivity value of 4.5 and dielectric loss tangent of 0.02. The antenna has dimensions ($L \times W \times h$) of $87.3\,\text{mm} \times 50\,\text{mm} \times 1.5875\,\text{mm}$. Thickness of the substrate is chosen to be 1.5875 mm for our design as it is standard thickness of an FR-4 epoxy substrate available in the market. All the lengths and widths of patches are calculated for this value of substrate thickness. HFSS V 13.0 is used to simulate the designed antenna. Top layer of the substrate consists of two nested patches, i.e., a rectangular and a U-shaped patches separated by a U-shaped slot having a width of 1 mm. A $50\,\Omega$ inset feed line is connected to the rectangular patch to provide the



(a) (b) (c)

Figure 2. (a) Structure of proposed antenna. (b) Top view of fabricated antenna prototype. (c) Ground plane of fabricated antenna prototype.

Table 1. Dimensions of antenna.

Parameter	**L1**	**L2**	**L3**	**L4**	**L5**	**L6**
Value (mm)	21.456	38.478	15.978	49.3	31.25	22.292
Parameter	**W1**	**W2**	**W3**	**W4**	**W5**	**W6**
Value (mm)	16.018	23.536	15.022	6.3395	0.5	0.3
Parameter	**W7**	**W8**	**W9**	**Height**	**Ground plane**	**Area of patches**
Value (mm)	2.86	1	25.357	1.5875	86.3× 50	31.478× 40.03

RF signal. Inset feed is used to match impedance of patch to the transmission line. Proper impedance matching results in a good return loss ($S_{11} \leq -10\,\mathrm{dB}$) of antenna at desired frequency. Width of the notch of inset feed, represented by W_6 in Figure 2(a), is optimized to get the best impedance match without affecting the resonance frequency. An optimal position of inset feed is also selected to improve impedance matching further. For our design, we have simulated antenna for different values of notch width, and an optimized value of 0.5 mm is used to provide the best impedance matching at our desired frequency bands. Bottom side of the substrate contains a ground plane, which has dimensions ($L \times W$) of 87.3 mm × 50 mm. Presence of ground plane on the bottom side of substrate allows just the top layer of substrate to radiate. Radiating patches and ground plane are made of cooper. Other dimensions of our antenna, such as lengths of patches, widths of patches, length of substrate, width of substrate, separation between patches, length and width of feed line and length and width of notch of antenna, are stated in Table 1.

Both patches are electrically connected in order to obtain reconfiguration between different frequency bands. Three RF PIN diode switches, which can be reconfigured in two operating states (ON and OFF), are positioned at different locations in slot to connect both patches as illustrated in Figure 2(a). PIN diodes are placed in slot on the locations where currents are concentrated. Points where PIN diodes are connected to U-shaped patch act as feeding points of U-shaped patch. Change in position of diode changes the mode excited in U-shaped patch and hence changes the frequency of antenna. In order to bias PIN diodes, a biasing network is required. Design of a biasing network demands great attention because interference of DC signal with RF signal affects antenna performance.

In our proposed design, the U-shaped patch is cut into three pieces to provide DC bias to diode, and these pieces are connected for RF signal using interdigital capacitor. The effectiveness of the interdigital capacitor is obvious from the surface current plots (shown in Figure 5) as there is no change in the RF currents (no color change) across these capacitances. Cathode of one of three diodes is connected to one piece of U-shaped antenna as shown in Figure 2(a). Anode of each diode is connected to the central rectangular patch. DC voltage of 5 V is provided to each part of U-shaped patch separately so that each diode can be turned ON/OFF independently. DC bias is provided from the ground plane of antenna. Each part of U-shaped patch is connected to the $\lambda/4$ high impedance lines of 0.5 mm thickness. These lines have very high impedance hence isolate DC signals from the RF signals which is provided to the U-shaped patch by the rectangular patch. These high impedance lines are terminated by a via hole drilled from top of the substrate to the ground plane as shown in Figure 2(a). Ground plane consists of four islands, three for providing DC bias to the PIN diodes and one for providing common ground to the DC through a resistor. Copper is removed from the area surrounding these islands, and chip capacitors are placed between these islands and ground plane to isolate DC from the rest of ground as shown in Figure 2(c).

4. SIMULATED AND MEASURED RESULTS

Three diodes provide eight possible switching states, i.e., ON-ON-ON, ON-ON-OFF, ON-OFF-ON, OFF-ON-ON, ON-OFF-OFF, OFF-ON-OFF, OFF-OFF-ON and OFF-OFF-OFF. Out of these eight states, four are useful for our design because these states provide S_{11} parameter value of $-10\,\mathrm{dB}$ or less. So, our designed antenna operates in four different modes given in Table 2 to resonate at four different frequencies.

Table 2. Modes of operation of antenna.

Modes of operation	**Number of diodes in ON state**	**State of diodes**		
		S1	**S2**	**S3**
1	1	OFF	ON	OFF
2	2	OFF	ON	ON
3	2	ON	ON	OFF
4	3	ON	ON	ON

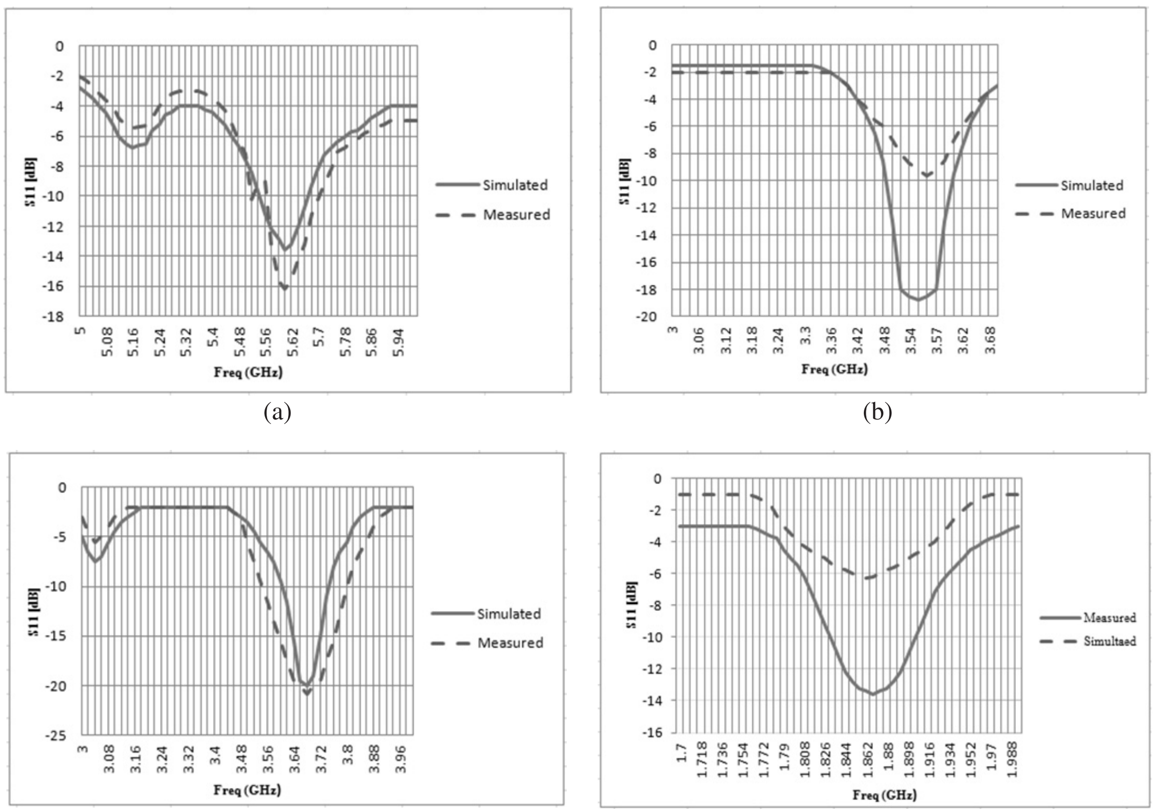
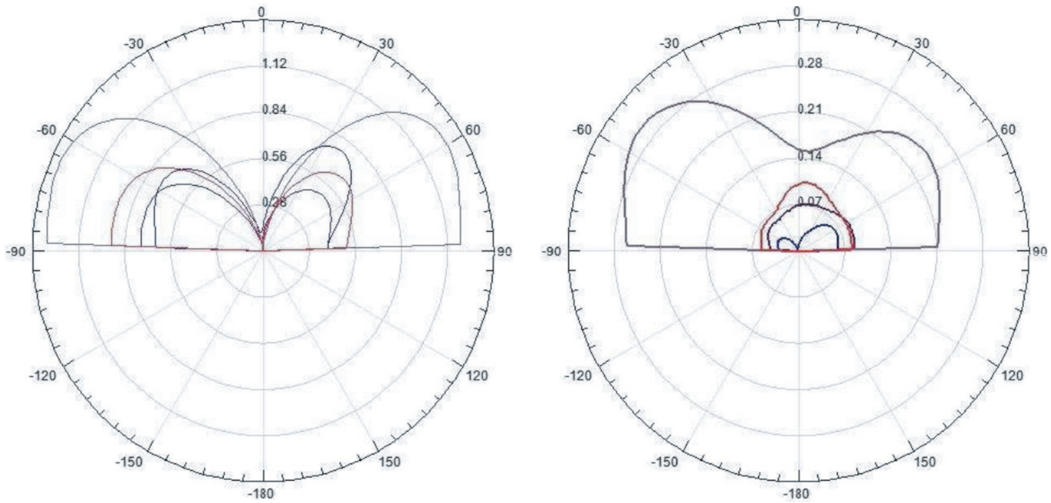


Figure 3. Simulated and measured S_{11} plots. (a) For mode 1. (b) For mode 2. (c) For mode 3. (d) For mode 4.

The designed antenna is simulated using HFSS, and simulated and measured results are presented here.

Simulated and measured S_{11} parameter plots for all four modes of operation are given in Figure 3. It is clear from the plots of Figure 3 that the value of S_{11} parameter for all modes is less than -10 dB for three modes and a little bit greater than -10 dB for the fourth mode of operation because of impedance matching issues. These values of return loss assure its usage for practical applications. In the first mode, only switch S2 is ON. Only one part of the U-shaped patch is connected to the rectangular patch and hence to the RF signal. In this mode of operation, the antenna resonates at 5.6 GHz frequency as shown in Figure 3(a). For mode 2, switches S2 and S3 are ON. So, two parts of the U-shaped patch, which are connected to switches S2 and S3, get the RF feed, and the antenna resonates at 3.55 GHz as shown in Figure 3(b). In the case of third mode, the antenna resonates at 3.67 GHz as shown in Figure 3(c). Switches S1 and S2 are ON for this mode, and two parts of the U-shaped patch, which are connected



(a) (b)

Figure 4. (a) E plane radiation pattern (blue line: for mode 1, black line: for mode 2, red line: for mode 3, brown line (with least gain): for mode 4.) (b) H plane radiation pattern (black line (with maximum gain): for mode 1, blue line: for mode 2, red line: for mode 3, brown line: for mode 4.).

to switches S1 and S2, are connected to the RF excitation. For the fourth mode, all the switches are ON, and thus all three parts of U-shaped patch are connected to the inner rectangular patch. For this case, size of the patch increases, and the frequency decreases to 1.87 GHz as shown in Figure 3(d). The effective length and width of the radiating patch become equal to length and width of the U-shaped patch. For this length and width, the resonance frequency can be calculated by using Equation (1).

$$f_r = \frac{c}{2L\sqrt{\epsilon_{eff}}} \tag{1}$$

where c is the speed of light in vacuum, L the effective length of patch, and ϵ_{eff} can be calculated by using Equation (2). Equation (1) gives resonance frequency value of 1.89 GHz that is very close to 1.87 GHz.

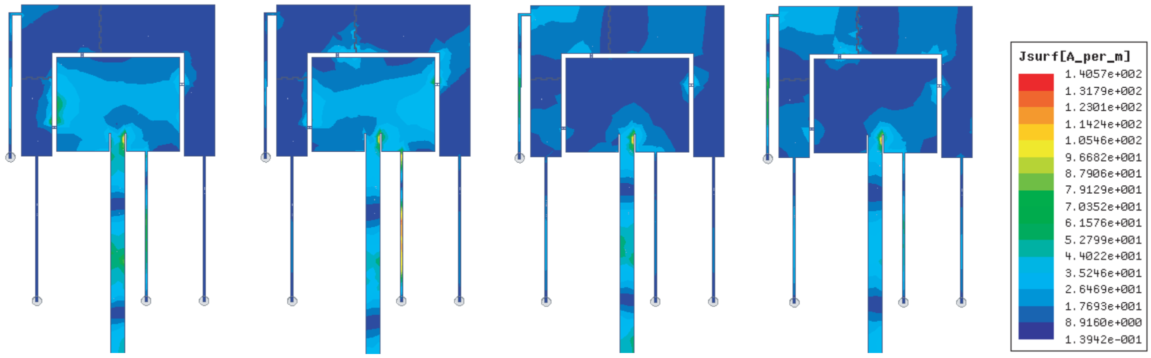
$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\left[1 + \frac{12h}{W}\right]^{-0.5} \tag{2}$$

E and H plane radiation patterns for four cases of simulations, i.e., switch S2 ON, switches S2 and S3 ON, switches S1 and S2 ON and all switches ON are shown in Figure 4. It is clearly perceived that gain of the antenna in E plane varies from 0 dBi to 0.6 dBi for mode 1. For mode 2, gain varies between 0 dBi and 1.12 dBi. For case 3, gain varies from 0 dBi to 0.56 dBi, and for case 4 it lies between 0 dBi and 0.8 dBi. For H plane radiation plots, a maximum gain of 0.28 dBi is achieved for mode 1. For the second mode of operation, maximum gain of 0.05 dBi is obtained. For mode 3 and mode 4, the antenna provides maximum gain of 0.12 dBi. Low gain of the antenna is due to the high on state resistance of PIN diodes.

Current distributions over the radiating patches for all four simulation runs are plotted in Figure 5. It is clear that the surface current distributions are very strong on the rectangular patch for all the frequencies. As for the U-shaped patch, current distributions change for different modes because the number of switching devices that are ON in some particular mode is different at each frequency. Due to the changed current paths or distributions on the patches, electrical characteristics of antenna are changed. Change in electrical characteristics makes an antenna to reconfigure at different frequencies of operation.

5. EFFECT OF POSITION OF EACH DIODE ON FREQUENCY

In order to study the effect of position of diode on resonance frequency of antenna, the antenna is simulated for three different configurations discussed in Table 3. While simulating antenna for three



(a) (b) (c) (d) (e)

Figure 5. Current distributions on antenna. (a) For mode 1. (b) For mode 2. (c) For mode 3. (d) For mode 4. (e) Detail of colors.

Table 3. Different configurations of antenna to find an optimal position for each diode.

Configuration	**Position of diode**		
	S1	**S2**	**S3**
I	Changed	Fixed	Fixed
II	Fixed	Changed	Fixed
III	Fixed	Fixed	Changed

Table 4. Simulation results for Configuration I.

Position of S1 X_1 (mm)	**Resonance Frequency (GHz)**			
	Mode 1	**Mode 2**	**Mode 3**	**Mode 4**
30.587	5.46	3.538	3.22	1.69
36.587	5.34	3.49	3.24	1.67
38.587	5.30	3.46	3.25	1.66
42.587	5.26	3.37	3.32	1.64

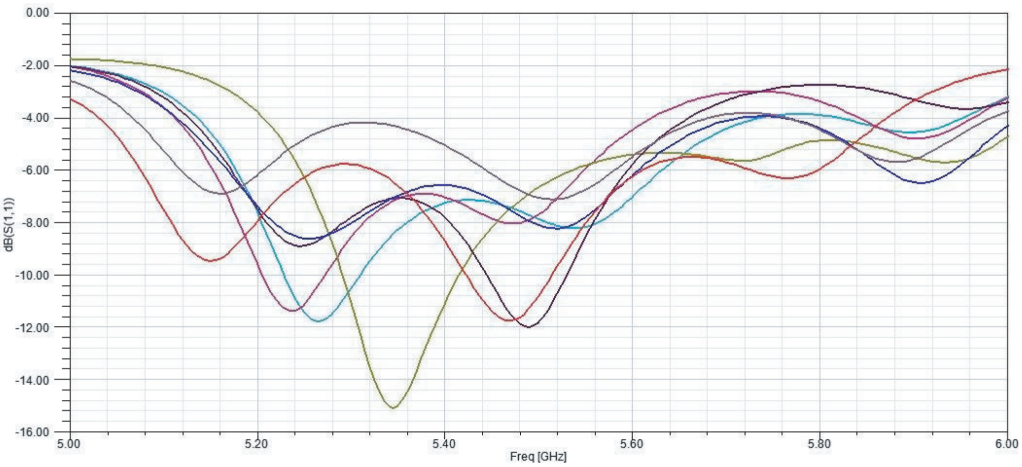
Table 5. Simulation results for Configuration II.

Position of S2 X_2 (mm)	**Resonance Frequency (GHz)**			
	Mode 1	**Mode 2**	**Mode 3**	**Mode 4**
21.587	5.6	3.26	3.36	1.79
27.587	5.48	3.44	3.489	1.78
29.587	5.478	3.49	3.46	1.77
33.587	5.47	3.51	3.485	1.76

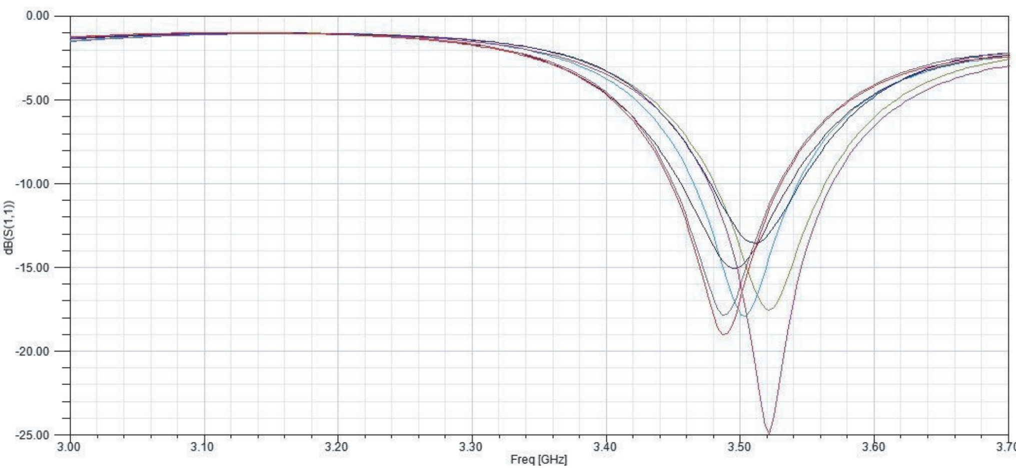
configurations stated in Table 3, all parameters of the antenna are kept same, as mentioned in Table 1, but position of one of three diodes is changed in order to find an optimal position for each diode. When each diode is placed at this optimal position, the antenna provides desired frequency of operation.

For the first configuration mentioned in Table 3, simulation results of reflection coefficient in terms of scattering matrix S_{11} are shown in Figure 6 for all four modes of operation. Simulation is run for four different positions of diode S1 varying between $(X_1, Y_1) = (30.587\,\text{mm}, 11.3215\,\text{mm})$ and $(X_1, Y_1) = (42.587\,\text{mm}, 11.3215\,\text{mm})$. Resonance frequencies obtained at each position are listed in Table 4.

For the second configuration, S_{11} plots for all four modes of operation of antenna are shown



(a)



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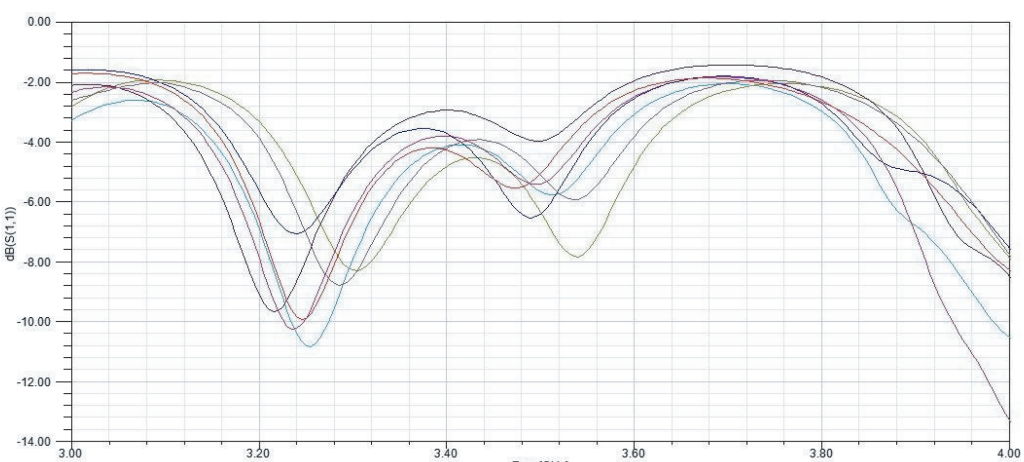
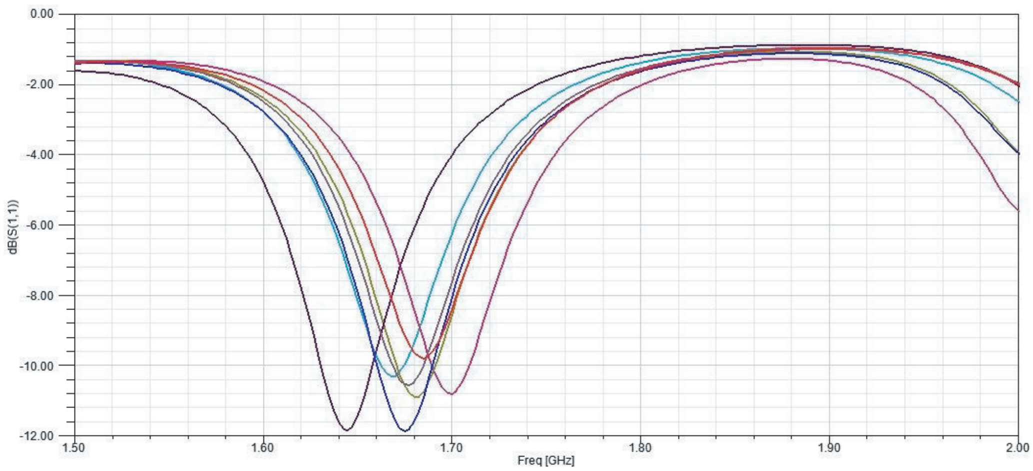
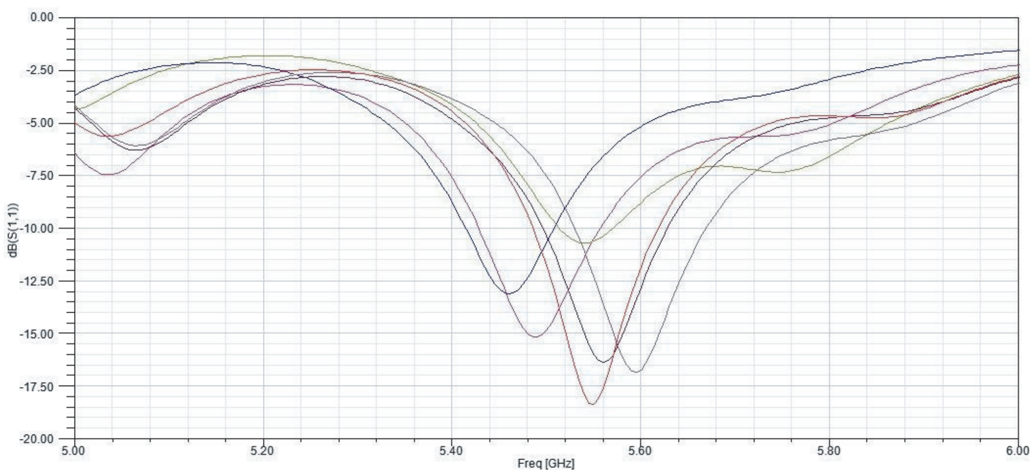


(c)

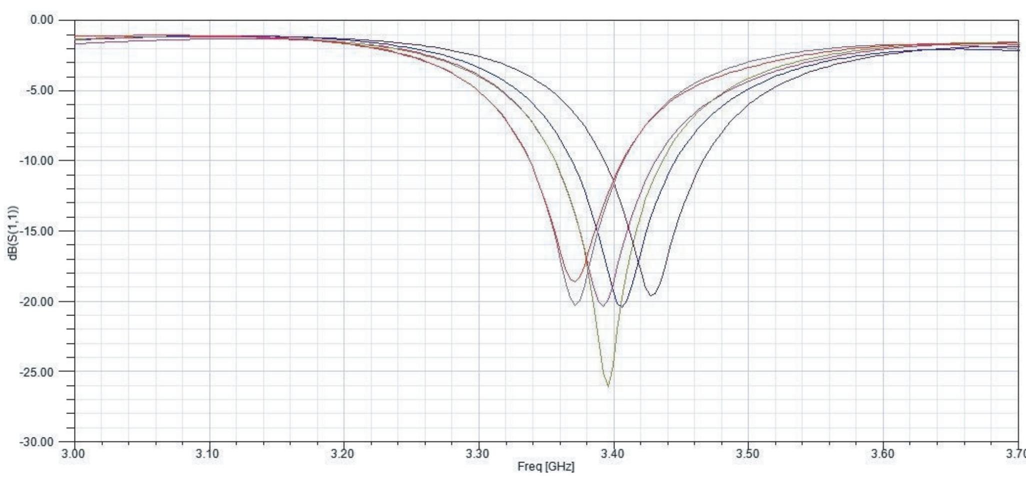


(d)

Figure 6. S_{11} plots for configuration I. (a) For mode 1. (b) For mode 2. (c) For mode 3. (d) For mode 4.



(a)



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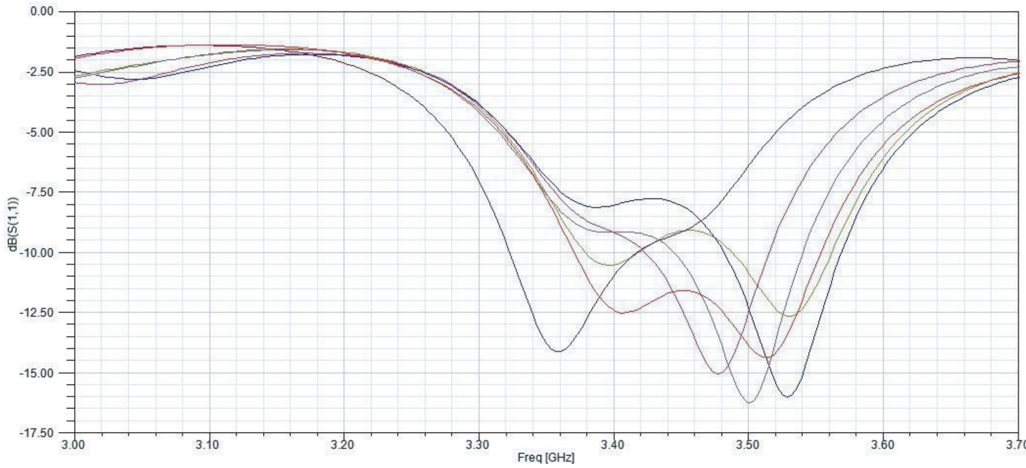

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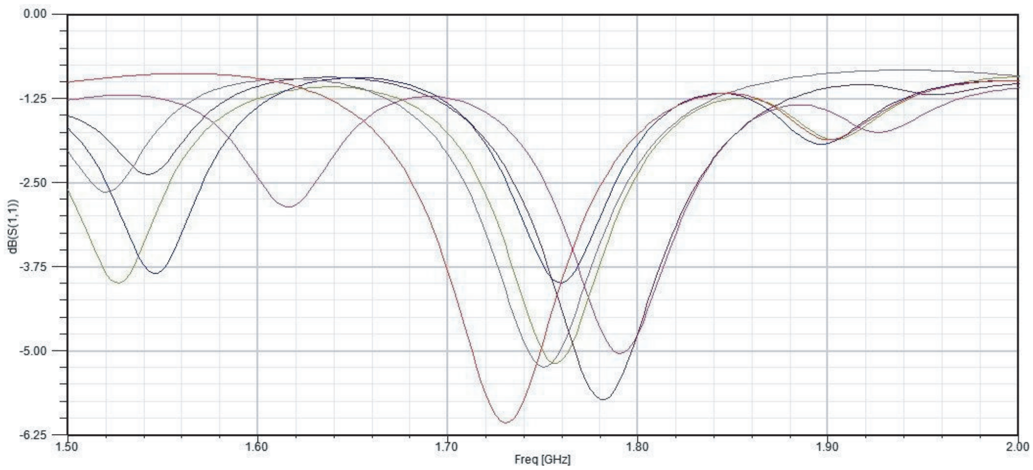


(d)

Figure 7. S_{11} plots for configuration II. (a) For mode 1. (b) For mode 2. (c) For mode 3. (d) For mode 4.

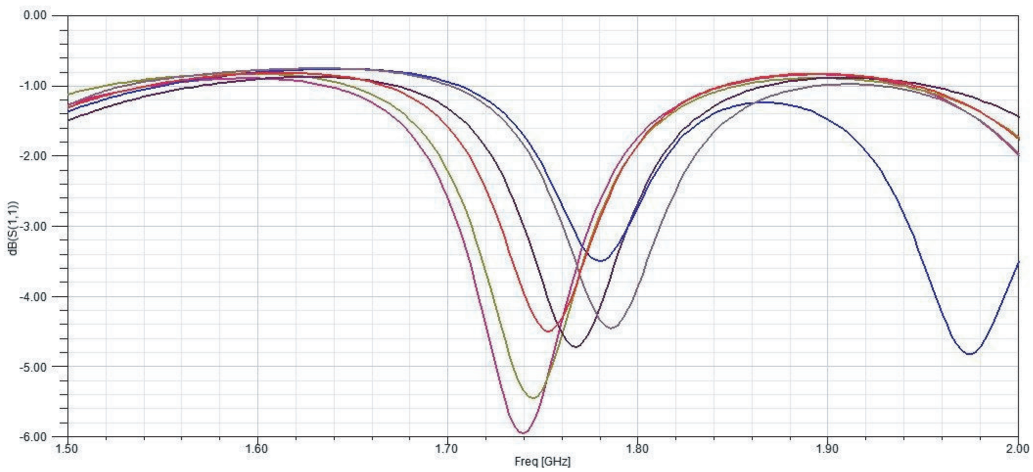
Table 6. Simulation results for Configuration III.

Position of S3 X (mm)	**Resonance Frequency (GHz)**			
	Mode 1	**Mode 2**	**Mode 3**	**Mode 4**
13.3215	5.64	3.3	3.64	1.74
17.3215	5.58	3.29	3.55	1.75
19.3215	5.49	3.28	3.54	1.765
23.3215	5.40	3.27	3.53	1.78

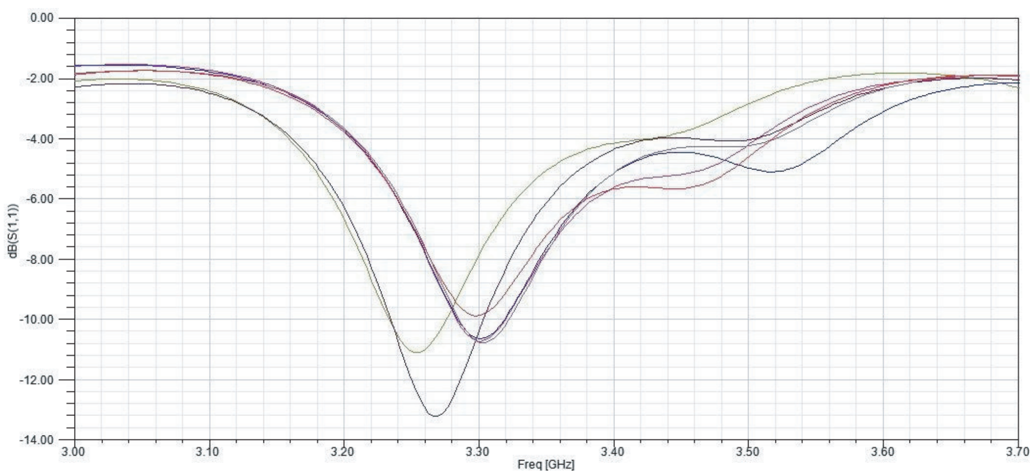
in Figure 7. Simulation is run for four different positions of diode S2 between $(X_2, Y_2) = (21.587\,\text{mm}, 37.6785\,\text{mm})$ and $(X_2, Y_2) = (33.587\,\text{mm}, 37.6785\,\text{mm})$. Table 5 contains the details of frequencies corresponding to each position of S2.

For the third configuration, S_{11} plots for all four modes of operation of antenna are shown in Figure 8. Simulation is run for four different positions of S3 between $(X3, Y3) = (23.359\,\text{mm}, 13.3215\,\text{mm})$ and $(X3, Y3) = (23.359\,\text{mm}, 23.3215\,\text{mm})$. Table 6 contains the details of frequencies corresponding to each position of S3.

When switch S1 is moved from the top end to the bottom end of the U-shaped patch, frequency decreases for all modes except for mode 3. For the second configuration, when S2 is moved from the top end of U-shaped patch to the bottom end, resonance frequency increases for mode 2 and mode 3 and decreases for mode 1 and mode 4.



(a)



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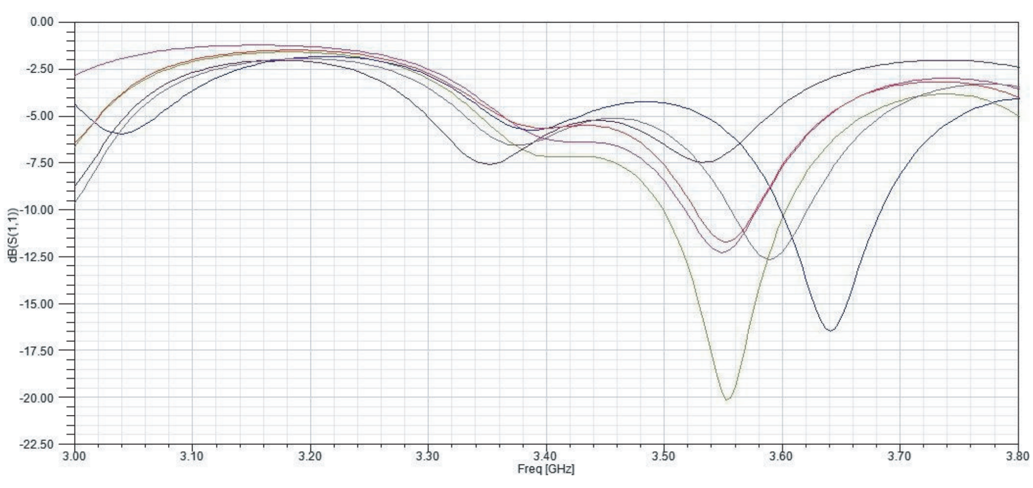

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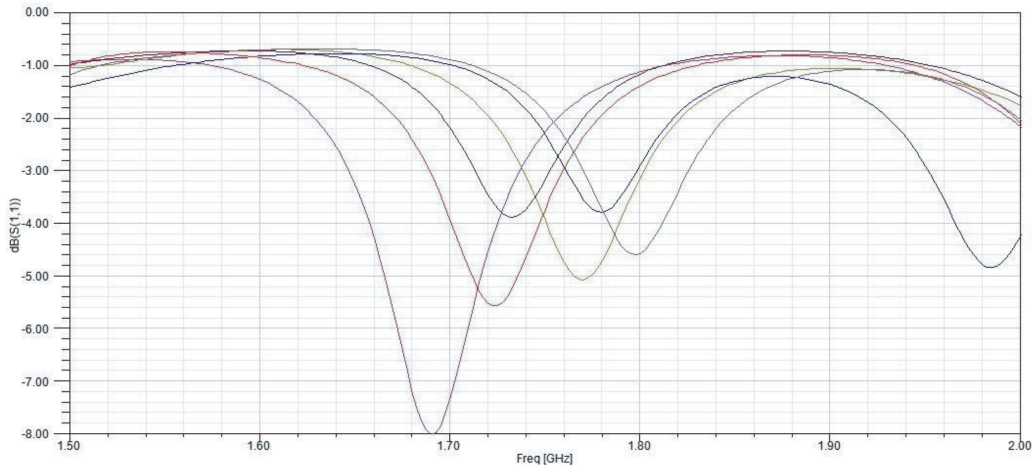

(d)

Figure 8. S_{11} plots for configuration III. (a) For mode 1. (b) For mode 2. (c) For mode 3. (d) For mode 4.

6. CONCLUSIONS

This paper presents a frequency reconfigurable microstrip-fed antenna that can be operated at 5.6 GHz, 3.55 GHz, 3.67 GHz and 1.87 GHz frequencies. The PIN diodes present in structure of antenna reconfigure the frequency by changing electrical lengths of the antenna. Simulation results demonstrate that the system provides S_{11} parameter value less than -10 dB at the three frequencies of operation and slightly greater for 1.87 GHz frequency, and radiation pattern remains the same for all modes. An antenna is required to have an S_{11} parameter value less than -10 dB for practical applications because it indicates that there is an acceptable matching among feed line, transmission lines and antenna. The antenna is then realized, and capacitors are used in the biasing network on ground plane to block the DC currents. Diodes are biased through high impedance lines. Measured results of the fabricated antenna show that the obtained S_{11} parameter value is less than -10 dB for all four frequencies of operation. Simulated and measured results are compared, and a good match is obtained for all four configurations of antenna. The antenna is also simulated for different positions of PIN diodes. Change in position of diodes causes change in resonance frequencies.

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