Frequency Reconfigurable Patch Antenna with Bias Tee for Wireless LAN Applications

Hassan Tariq Chattha[1,2*], Noman Aftab[2], Muhammad Akram[2], Nathirulla Sheriff[1], Yi Huang[3], Qammer H. Abbasi[4],

[1]Department of Electrical Engineering, Faculty of Engineering, Islamic University of Madinah, Al Madinah, Kingdom of Saudi Arabia,
[2]Department of Electrical Engineering, University of Engineering & Technology (Lahore), Faisalabad Campus, Pakistan,
[3] Department of Electrical Engineering and Electronics, University of Liverpool, Liverpool, UK, L69 3GJ

[4] School of Engineering, University of Glasgow, Glasgow, UK, G12 8QQ
[*]chattha43@hotmail.com

Abstract: A frequency reconfigurable printed microstrip-fed patch antenna is proposed in this paper. The antenna consists of a microstrip feed connected to a circular radiating element divided into three patches which are connected through silicon PIN diodes used as switches for achieving reconfigurability as being cheap and easy to implement having high switching capabilities. The slots of different shapes are etched out in all the three patches to cover all used WLAN frequency bands including 2.4 GHz, 3.6 GHz, 4.9 GHz, 5.1 GHz, and 5.9 GHz. A bias tee is designed and connected to provide a DC bias to the PIN diodes. A prototype of the reconfigurable antenna is fabricated and measured along with the bias tee. The measured and simulated results are found in good agreement.

1. Introduction

Over the last two decades, the communication systems have grown exponentially, and the increasing demand for frequencies has led to a perceived shortage in the RF spectrum. This is partly because of the inadequate and inefficient use of the RF spectrum rather than the physical scarcity of RF spectrum. The Federal Communications Commission (FCC) has highlighted this inefficient utilization of overall spectrum and stated that the licensed spectrum allocated for different services remains 70% vacant at any instant of time [1]. A cognitive radio solves this problem by continuously interacting with the environment and can change its transmission parameters as per requirements [2]. The main reasons for using the cognitive radio are making efficient use of the available RF spectrum while ensuring reliable communication.

A reconfigurable antenna is an antenna capable of modifying dynamically its frequency, polarization and/or radiation patterns in a controlled and reversible manner. A lot of effort and focus have been put into the design of reconfigurable antennas [3-5]. There are different techniques used for making the antennas reconfigurable. One of the techniques used is the addition of electrical devices such as RF-MEMS, PIN diodes and the varactors. Other techniques include photoconductive (optical), physical structure alteration and use of materials like liquid crystal and ferrites [3]. Numerous reconfigurable antennas are found in the literature using these different techniques. In [6], PIN diodes were used to cover the 5.25 and 5.75 GHz portion of the Wireless LAN bands, but they did not cover lower WLAN bands. The authors in [7] incorporated three PIN diodes to cover Wi-Fi and WiMAX portion of the electromagnetic spectrum, but the system was not tested for 2.4 and 5.9 GHz. In [8], they designed a reconfigurable microstrip patch antenna with RF PIN diodes as switches for the frequency bands of 2.4 GHz and 5.6 GHz while other WLAN bands are not covered. [9] presented patch antennas for 3.5, 4.9 and 5.1 GHz using two techniques including the rotational motion of the radiating patch, whereas the second is based on optical switching. However, these techniques are either complex or not integrally having high manufacturing cost [9]. In [10], the authors designed a reconfigurable UWB antenna and incorporated it with RF-MEMS which made it capable of on-demand WLAN rejection. An antenna aware of its surroundings, incorporating IR sensors was presented in [11]. A miniaturized antenna for multi-radio wireless communication was presented in [12] which used PIN diodes for achieving reconfigurability. [13] showed a reconfigurable antenna which can be used for wireless temperature sensing. In [14], the authors introduced an antenna for 2.4-2.57 GHz only, capable of switching its polarization from left-hand circular polarization to right-hand circular polarization and vice versa. A frequency reconfigurable antenna covering LTE bands with MIMO implementation was presented in [15]. Antenna presented in [16] working between 2-3.2 GHz achieved reconfigurability by using RF-MEMS switches. The design and analysis of an RF-MEMS based reconfigurable antenna for use in the United States public safety bands were presented in [17]. A reconfigurable patch antenna possessing an E-shaped structure is presented in [18] where operation frequency is changed by integrating switches. Ali et al developed four reconfigurable antenna elements, including the reconfigurable Yagi, the reconfigurable corner-fed triangular loop antenna, the reconfigurable center-fed equilateral triangular loop antenna and the reconfigurable rectangular spiral antenna to work at 2.45 GHz and 5.78 GHz bands but the other WLAN bands were con covered [19]. A frequency reconfigurable patch antenna, proposed and analyzed using Finite-Difference Time-Domain method (FTDT), was presented in [20]. [21] used PIN diodes to reconfigure the impedance match and modify the radiation pattern of an annular slot antenna. Optically tuned/controlled frequency-reconfigurable microstrip antennas were presented in [22-23]. A microstrip patch antenna operating in the 5 GHz band was presented in [24] obtaining tuning using liquid crystal. However, this technique has a high manufacturing cost and does not cover lower WLAN bands. [25] presented a circular beam-steering reconfigurable antenna with liquid metal parasitics. The variation in the height and the angular position of the ground plane was used to tune the frequency response of a wideband reconfigurable antenna presented in [26].

In this paper, we have proposed a microstrip-fed patch antenna capable of communication with other RF devices over all the available/used Wireless LAN channels including 2.4, 3.6, 4.9, 5.0 and 5.9 GHz bands. The reconfigurability in this patch antenna is achieved by using RF PIN diodes as switches. A PIN diode is a versatile device having high switching capabilities and can be biased to behave like a short-circuit, an open circuit or exhibit any desired reflection coefficient in between [27]. It is a low-cost device being easy to implement thus reduces the overall antenna manufacturing cost. The DC (direct current) biasing of PIN diodes is achieved using a bias tee working in the frequency range 2-6 GHz. The paper is organized as follows: Antenna configuration is described in detail in section 2 whereas the results and current distribution and related discussion is done in sections 3 and 4 respectively.

2. Antenna configuration

2.1 Operation principle

For the proposed antenna to work for all the frequencies covering the Wi-Fi bands, we need to change the current densities and the electrical length of the antenna. For this purpose, two RF silicon PIN diodes to work as switches were initially embedded in the antenna structure. The use of two RF PIN diodes as switches gave four possible configurations. Two configurations were found obsolete as they didn't perform well enough in the Wi-Fi bands. These two configurations are conditions when PIN diode used as switch 1 is 'OFF'. Therefore, the switch 1 connecting the patches 1 & 2 is always 'ON'. This has reduced the configurations to only two where switch S_1 is always 'ON', and the switch S_2 is turned 'ON' and 'OFF' to switch between different Wi-Fi bands. As switch 1 is always 'ON', therefore, it is replaced with a short copper patch to connect the two patches. This not only has reduced the losses but also made the antenna less complicated as DC biasing is now only required for one diode to switch its state between 'ON' and 'OFF'. The silicon PIN diode used as the switch has the model BAR 64 by the Infineon Technologies having a working frequency range from 1 MHz to 6 GHz [28]. For simulation purposes, we need to see the equivalent circuits of Bar 64 PIN diode in its 'ON' and 'OFF' states. Fig. 1 shows the equivalent circuits of BAR 64 PIN diode in forward and reverse bias conditions. It is seen that this diode has a meagre forward resistance of 2.0 Ω and a parallel combination of 3 KΩ resistance and 0.17 pF capacitance in forward and reverse bias conditions respectively. These values are used for the simulation purposes to get 'ON' and 'OFF' states of the PIN diode used as a switch. Since there is only one switch to be DC biased; a bias tee is used where RF (AC) and DC inputs are connected to apply both AC and DC signals through the same feed line to the antenna.

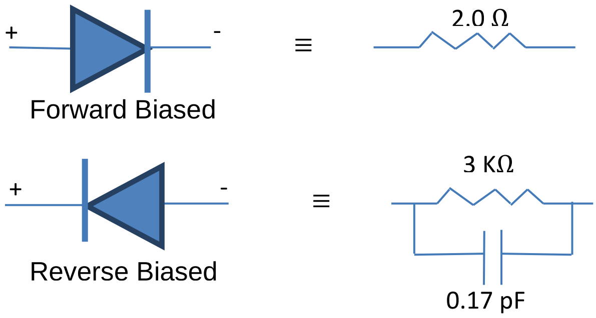


Fig. 1. *Equivalent circuits of BAR 64 PIN diode in forward and reverse bias conditions*

2.2 Antenna design

A circular radiating patch constitutes the main portion of the reconfigurable antenna having a radius R_1. The circular radiating elements with microstrip feeds are found in the literature for UWB applications [29-30]. For this antenna to be reconfigurable and to cover all the Wireless LAN bands, it is divided into three segments/patches named as Patch 1, Patch 2 and Patch 3. A step by step design approach is used to get the desired results of covering all the required WLAN bands. Fig. 2 shows all the intermediate design steps which were applied in design to get the required results. As shown in the Fig. 2, a microstrip-fed circular patch is initially divided into three patches, which are further modified by introducing a triangular-shaped slot in Patch 1 and a rectangular-shaped slot in Patch 2. In the third step, another rectangular-shaped slot is etched out in Patch 3. The patches are connected through switches (PIN diodes) as shown in figure. Fig. 3 shows the reflection coefficients S_{11} [dB] of all the six design steps shown in Fig. 2 when the switch S_2 is in its 'ON' and 'OFF' states. From Fig. 3, it is obvious that the result of these modifications is that the first resonance is shifted from around 2 GHz to a slightly higher frequency when the switch S_2 is 'ON' and no resonance is produced yet in the 5 GHz band when the switch S_2 is 'OFF'. In the next step, the rectangular slot in Patch 2 is modified to increase the electrical length by splitting it into two slots which have shown improved performance when the switch S_2 is 'OFF' but no significant change occurred when it is 'ON'. In step 5, the rectangular-shaped groove in Patch 3 is modified by adding a triangular-shaped slot in it.

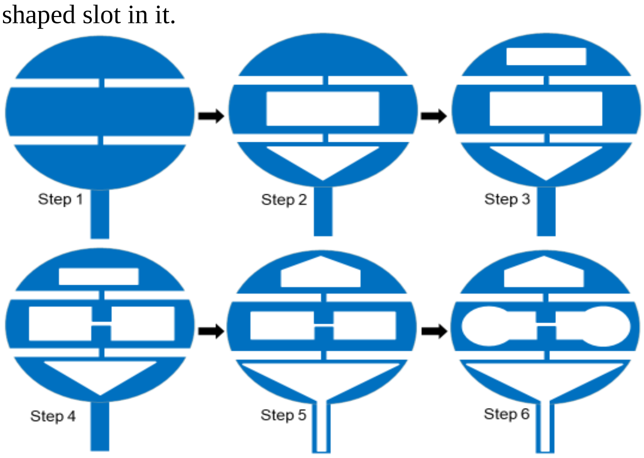
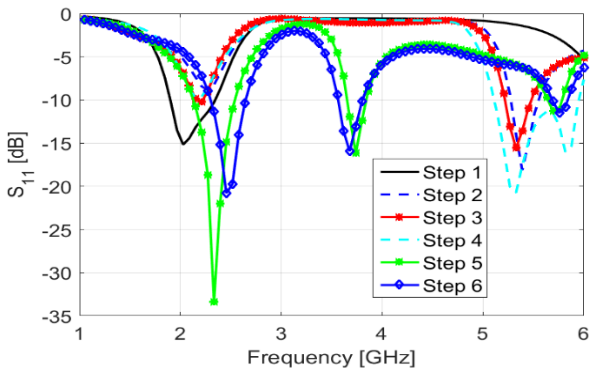
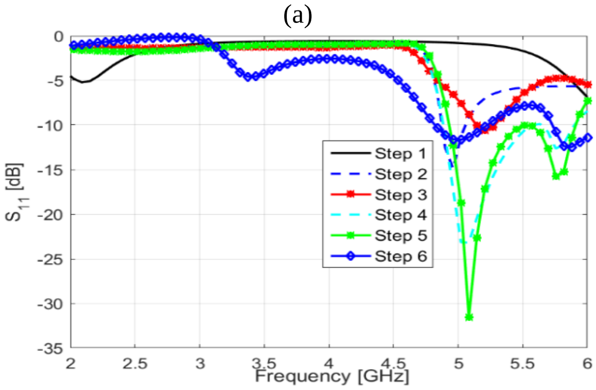


Fig. 2. *Step by step design approach, including all intermediate steps*



(a)



(b)

Fig. 3. *Reflection coefficients S_{11} [dB] of all the six design steps when the switch S_2 is (a) 'ON' (b) 'OFF'*

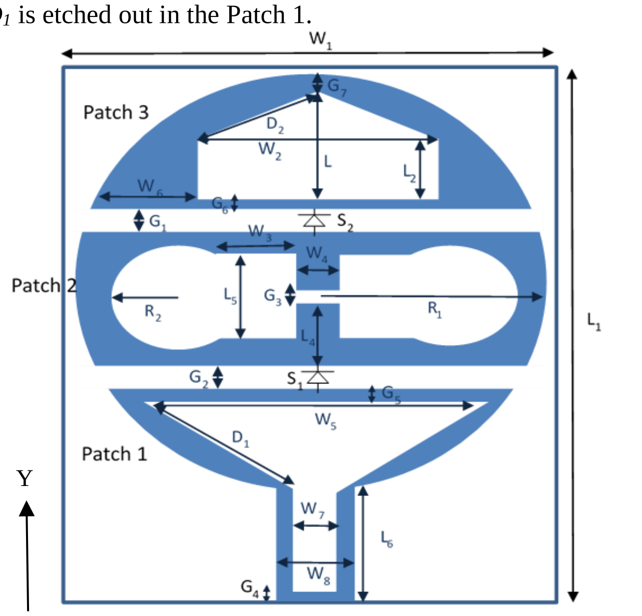
This step has shown a significant improvement as compared to the previous step as a resonance at around 2.2 GHz as well as a second resonance at around 3.8 GHz is produced when the switch S_2 is 'ON' and it covers the full 5-6 GHz band when S_2 is 'OFF'. Now, there are little modifications and optimizations required to cover the required bands of 2.45 GHz and 3.6 GHz when the switch S_2 is 'ON'. For this purpose, in the final step, two circular slots are merged with the two existing rectangular slots in Patch 2 whereas the parameters of the other slots etched out in Patches 1 & 3 are just optimized to get the required results of reflection coefficients as shown in Fig. 3.

Fig. 4 shows the top and bottom view of the final design highlighting its main structure. As shown in Fig. 4 (a), the slots, having different specific shapes, are etched out in each radiating patch as well as in the microstrip feed to control the current path to get the required electrical length for producing resonance in the required frequency bands. A slot of width W_7

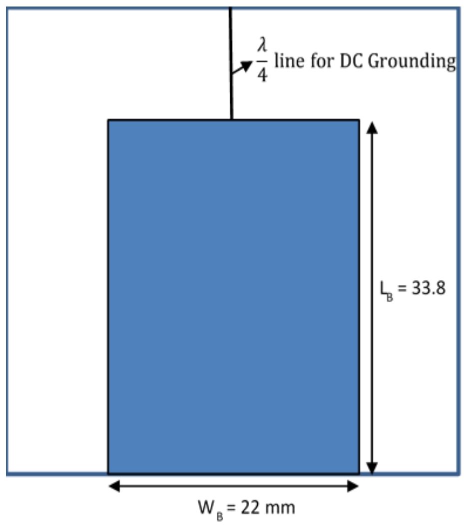
Table 1 Dimensions of the proposed antenna (Units in mm)

L_1	L_2	L_3	L_4	L_5	L_6	W_1
47.25	4.6	7.9	3.96	6.95	11.05	35
W_2	W_3	W_4	W_5	W_6	W_6	W_7
18.12	4.96	3.19	26.23	6.77	6.77	2.94
W_8	G_1	G_2	G_3	G_4	G_5	G_6
5.18	2.0	2.0	1.11	0.75	1.89	1.75
G_7	R_1	R_2	D_1	D_2		
1.52	17.5	4.5	14.56	6.6		

is etched out in the microstrip feedline having a width W_8 and length L_6. A triangular-shaped slot having dimensions W_5 and D_1 is etched out in the Patch 1.



(a)



(b)

Fig. 4. *Antenna dimensions (a) Top view (b) Back view*

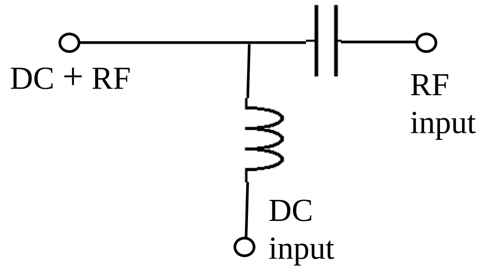
The size of the gap between Patches 1 & 2 and Patches 2 & 3 is the same and is equal to $G_1 = G_2 = 2$ *mm*, i.e. the size of the PIN diodes used as switches S_1 and S_2. There are two slots of equal dimensions etched out in Patch 2. Each slot is a combination of a rectangular-slot of dimensions $L_5 \times W_3$ and a circular-slot of a radius R_2. The slot introduced in Patch 3 is a combination of a rectangular-slot of dimensions $L_2 \times W_2$ and a triangular-slot having a size of $D_2 \times W_2$. Table 1 describes all the dimensions in mm of different antenna parameters/variables as shown in the top view of the antenna. The silicon PIN diodes are used to connect the three radiating patches named as switches S_1 and S_2. To operate the diodes, an external biasing circuitry known as bias tee is used as explained in the next section. The result of using the bias tee is that the signal applied to the antenna consists of both DC and RF signals. For design simplification of the DC bias setup, the diode S_1 is always set 'ON' and by turning the switch S_2 'ON' and 'OFF', the reconfigurability is achieved. The two-sided PCB substrate used is Rogers RT/duroid 5880 with a thickness of 1.575 mm and a relative permittivity $\varepsilon_r = 2.20$.

This antenna has a ground plane on the other side of the PCB. The ground plane has a smaller size as compared to the size of the main radiating structure with dimensions $L_B \times W_B$ (33.8×22 mm^2) as shown in Fig. 4 (b). For completing the DC path, i.e. DC grounding, a λ/4 line known as a quarter-wave transformer is inserted on the back side and is shorted with the ground plane as shown in Fig. 4 (b). The reason of using a λ/4 line is to minimize its effect on the AC performance of the antenna while providing a DC grounding. The λ/4 section is used to isolate the AC signal from flowing into the DC path. The AC signal should see a high impedance (current always takes the least resistance path) towards DC connection. By short-circuiting the λ/4 line, i.e. connecting with the ground plane, its input impedance will be too high to look like an open-circuit for AC signal [31]. The λ/4 line is shorted with the front radiating Patch 3 through the substrate. The value of λ = 53 mm is chosen which corresponds to the frequency f = 6 GHz approximately. The higher of the working frequencies is chosen to calculate λ, as from the theory of quarter-wave transformers, it can effectively stop the flow of RF signal into the DC path at higher as well as lower frequencies [31].

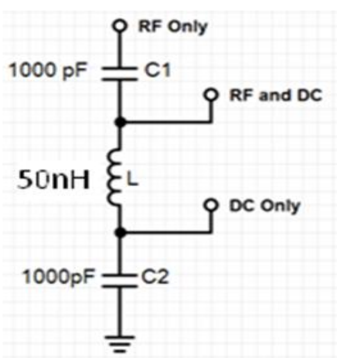
2.3 Biasing Circuit Design

For the proposed antenna to be reconfigurable, the silicon PIN diodes are used as switches. However, the PIN diode needs a DC input for activation, whereas the antenna works on an AC input.

The technique applied to bias the PIN diode is the use of a bias tee. Fig. 5 (a) shows the configuration of a bias tee. By using the bias tee, the signal applied to the antenna is a combination of DC and RF signals. When DC is applied, it turns 'ON' both the switches S_1 and S_2 which is then simplified by assuming the switch S_1 always 'ON' and reconfigurability is achieved by turning switching S_2'ON' and 'OFF'.



(a)



(b)

Fig. 5 *(a) Configuration of a bias tee (b) The circuit schematic of the bias tee*

As shown in Fig. 5 (a), the design of a bias tee involves capacitors and inductors to act as open-ended for DC and AC inputs respectively. A capacitor provides a high impedance to the DC signal and an electrical short to the AC signal. An impedance ratio of 1:100 is selected which means a 0.5 Ω impedance of the capacitor at the minimum operating frequency. As the frequency range of interest is 2-6 GHz, we can safely assume that the minimum frequency (f_{min}) is 2.0 GHz.

$$X_C = \frac{1}{2\pi f C}$$

$$C = \frac{1}{2\,\pi f X_C}$$

$$C = \left(\frac{1}{2 \times 3.14 \times 2 \times 10^9 \times 0.5}\right)$$

$$= 0.1\, nF$$

The inductor acts as an open-circuit for ACRF signal, therefore, an impedance ratio of 100:1 to the PIN diodes is chosen, which means that the inductor needed to have an impedance of approximately 2000 Ω at 2.4 GHz.

$$X_L = 2\,\pi f L$$

$$L = \frac{X_L}{2\,\pi\, f}$$

$$L = \frac{2000}{2 \times \pi \times 2.4 \times 10^9}$$

$$= 133\, nH$$

Eventually, the stray capacitance in the inductor will begin to look like a short-circuit. Smaller the inductor size, lesser RF power will go to the PIN diode, so an optimized inductance value of 50 nH is chosen for an inductor. We overcome this problem of selecting a lower value of inductance by increasing the power, but at the expense of efficiency. Fig. 5 (b) shows the circuit schematic of the bias tee.

3. Results

A prototype of the reconfigurable patch antenna along with the bias tee is fabricated as shown in Fig. 6. The significant parts of this prototype are highlighted and shown separately which include a hole made in the Patch 3 for shorting it with λ/4 line on the back side, a bias tee circuit for applying both RF and DC signals, the PIN diode used as switch S_2 and the back side of the antenna containing ground plane and a λ/4 line. As explained above, the Switch S_1 is replaced with a thin copper wire in the fabricated prototype as the switch S_1 always remains 'ON'.

The measurement setup used for the measurement of reflection coefficient S_{11} of the antenna consists of a Vector Network Analyzer (VNA) and a DC source as shown in Fig. 7 along with the antenna prototype and the bias tee. The RF

Table 2 Comparison of the proposed design with the reconfigurable antennas found in literature for WLAN applications

Reference	Reconfig. Technique / Type	Bands Covered [GHz]	Antenna Dimensions (mm^2)	Complexity / Ease of Manufacturing	DC Biasing Integrated / Included
Ref. [6]	PIN Diodes	5.1, 5.9	30 x 30	Simple	No
Ref. [7]	PIN Diodes	3.5, 5.2	50 x 55	Simple	No
Ref. [8]	PIN Diodes	2.4, 5.6	90 x 40	Complex	No
Ref. [9]	Physical Rotation, Optical Switching	3.6, 4.9, 5.1	50 x 46	Complex /Costly	Not Needed
Ref. [14]	PIN Diodes	2.4	200 x 100	Complex	Yes
Ref. [16]	RF-MEMS	2.4	120 x 100	Complex /Costly	Yes
Ref. [24]	Liquid Crystal	5.3-5.7	20 x 15 excluding microstrip feed	Complex /Costly	Yes
Proposed Design	PIN Diodes	2.4, 3.6, 4.9, 5.1, 5.9	35 x 47	Simple	Yes

signal is applied through an SMA connector to the bias tee whereas a DC source supplies DC signal to the bias tee.

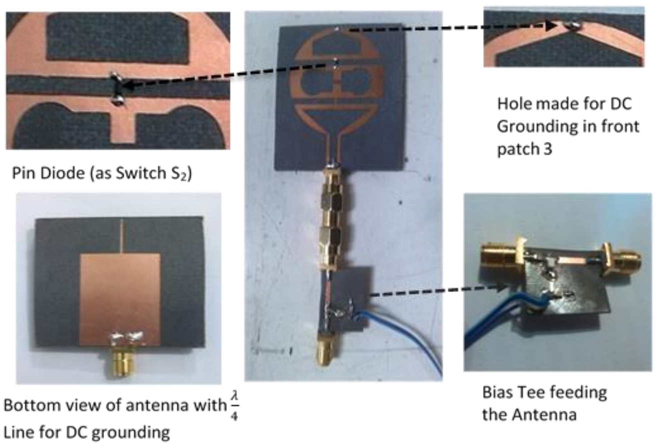
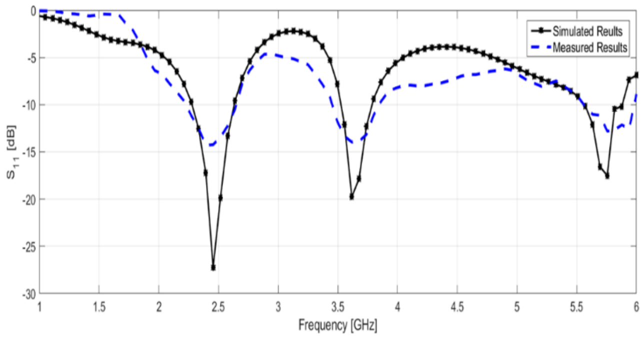


Fig. 6. *A fabricated prototype of the proposed patch antenna with significant parts highlighted separately*

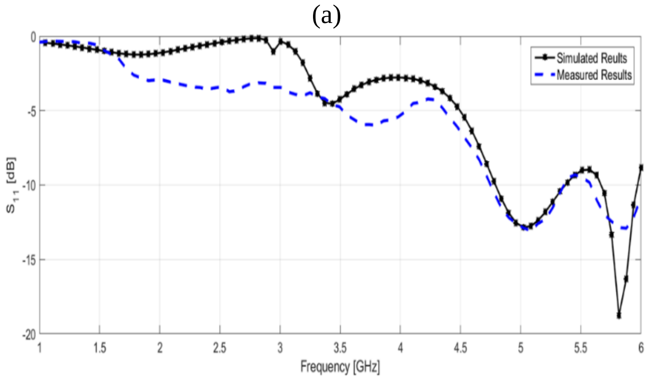
The measured and simulated results of the reflection coefficient S_{11} [dB] versus frequency [GHz] are shown in Fig. 8, which are found generally in good agreement with each other. The results show that while the switch S_2 in its 'ON' state, it covers mainly the 2.4 GHz and 3.6 GHz bands and the antenna is reconfigured to cover the Wireless LAN band in the 5-6 GHz range including 4.9 GHz, 5.1 GHz, and 5.9 GHz when the switch S_2 is turned to its 'OFF' state. The measured two-dimensional radiation pattern of this patch antenna at 2.45 GHz and 3.6 GHz, when the switch S_2 is 'ON', is shown in Fig. 9 (a) whereas Fig. 9 (b) contains the two-dimensional radiation patterns at 5.1 GHz and 5.9 GHz, when the switch S_2 is in its 'OFF' state. As this microstrip patch antenna is similar in shape to a printed monopole antenna structure, thus generally having omnidirectional radiation patterns.

A comparison of this proposed reconfigurable antenna design with the reconfigurable antennas found in the literature for WLAN applications is provided in Table 2. It is evident that the designs presented in [6-7] does not cover the lower WLAN bands and does not include/integrate the DC bias in the antenna whereas the antenna designs presented in [8-9] have complex structure with a high manufacturing cost and does not cover all WLAN bands. The antenna designs in [14,16] do not include higher WLAN bands whereas the antenna design in [24] does not include lower WLAN bands whereas all these structures are either complex or have high manufacturing cost. In contrast, our proposed reconfigurable antenna covers all the used WLAN bands, applies PIN diodes which are cheap and easy to implement, and has an integrated DC bias with a simple structure having a low manufacturing cost.

Fig. 7. *The measurement setup for measuring the reflection coefficient S_{11}*



(a)



(b)

Fig. 8. *Measured and simulated results of reflection coefficient S_{11} [dB] versus frequency [GHz] when the switch S_2 is (a) 'ON' (b) 'OFF'*

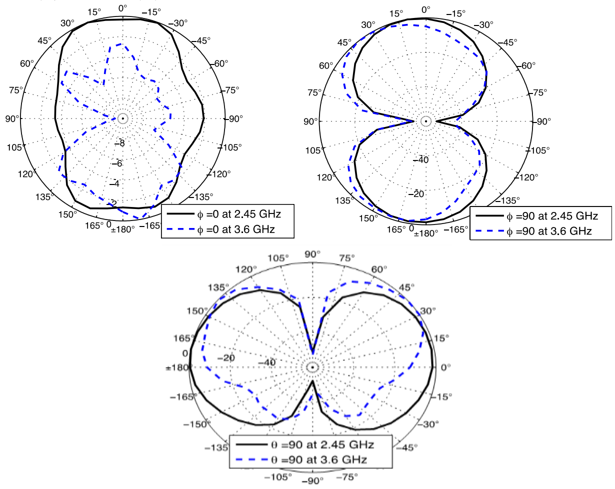


Fig. 9 (a). *Measured 2D radiation patterns at 2.45 and 3.6 GHz when switch S_2 is 'ON'*

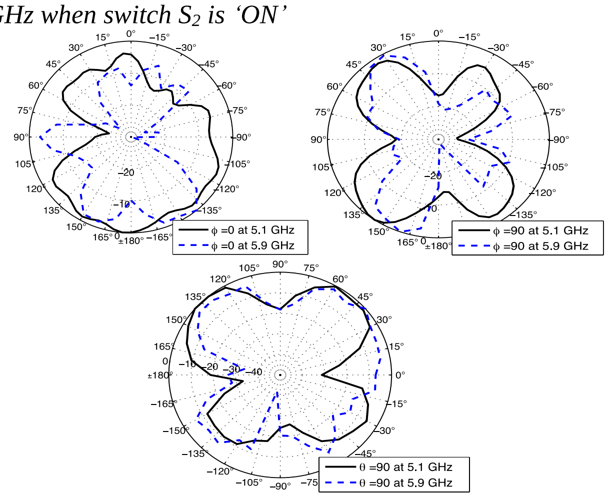


Fig. 9 (b). *Measured 2D radiation patterns at 5.1 and 5.9 GHz when switch S_2 is 'OFF'*

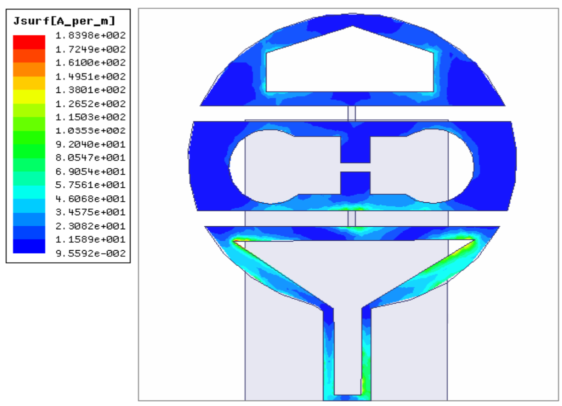
4. Current distributions and discussion

To understand the working mechanism of this patch antenna and reasoning of etching different specific shapes of slots in the three patches, the current distribution on the patch antenna for different working frequencies in the 'ON' and 'OFF' states of the switch S_2 would be helpful.

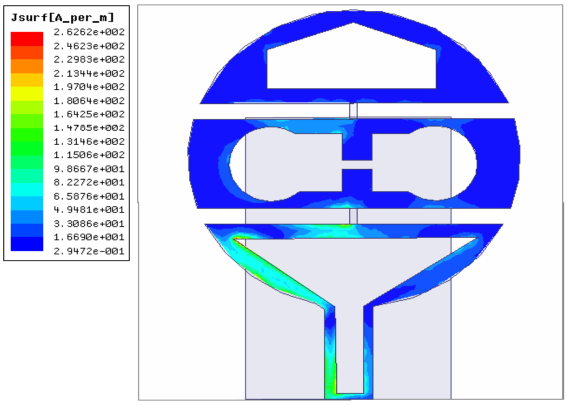
We start our discussion with the switch S_2 in its 'OFF' state. Fig. 10 (a) & (b) shows the surface current density at 5.1 GHz and 5.9 GHz, when S2 was in 'OFF' as shown in Fig. 8. High current density on patch 1 shows that it was acting as a radiating element at theses frequencies. Figure 10 also shows that Patch 1 act as a loop antenna at 5.1 GHz as current is distributed across the whole patch whereas At 5.9 GHz, the current is distributed only about half of the Patch 1. The triangular slot in Patch 1 helped in achieving the desired electrical length to get the resonance at our required frequency bands as patch 1 was the only active radiating element at this frequency. Majority part of the Patch 2 is etched out to limit the current on Patch 2 at higher frequencies such as 5.1 GHz and 5.9 GHz as we want to limit the current on the remaining patches especially when Patch 2 as being shorted to Patch 1 as switch S_1 is always 'ON';

Now we move our discussion to the condition when the switch S_2 is in its 'ON' state. As we need to cover the lower WLAN bands including 2.4 GHz and 3.6 GHz bands, we need to increase the electrical length of the patch antenna to get the resonance at these bands. Fig. 10 (c) & (d) show the surface current density on the patch antenna at 2.45 GHz and 3.6 GHz while the switch S_2 in its 'ON' state. It is clear from the Fig., that at 2.45 GHz, the current is distributed in all the three patches to get the required electrical length for producing the required resonance at 2.4 GHz band which also involves the etching out of a slot in the Patch 3 having a combination of a rectangle- and a triangular-shaped slot to limit the current to Patch 3 for obtaining the required electrical length. At 3.6 GHz, the current is mainly distributed on the Patch 2 where the partial current distribution is found in the Patches 1 & 3. In other words, the current distribution is found in the middle part of the patch antenna at 3.6 GHz in the 'ON' state of the switch S_2.

The above discussion explains and justifies the use of specific shapes of etched out slots to get our desired results which are obtained by performing extensive simulations through HFSS v. 15 while observing the current distribution and the results of each simulation.



(a)



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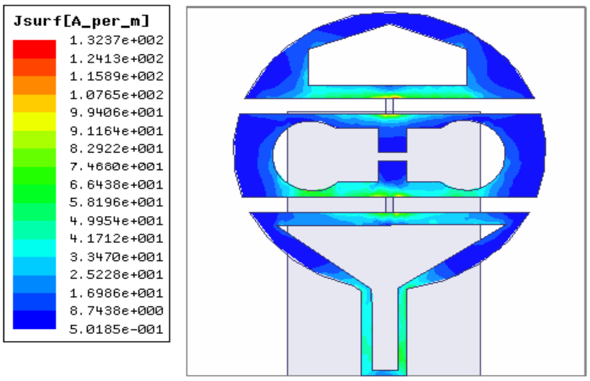

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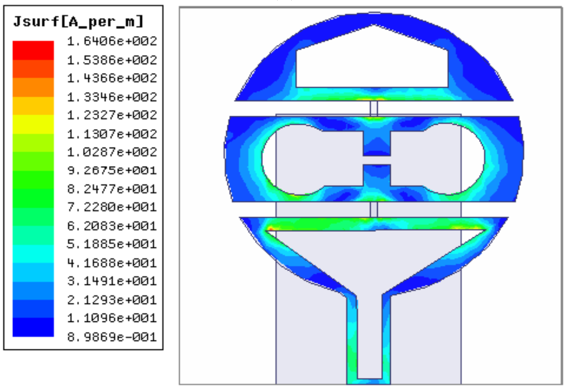

(d)

Fig. 10. *Current distribution on the patch antenna at (a) 5.1 GHz when S_2 is 'OFF' (b) 5.9 GHz when S_2 is 'OFF' (c) 2.45 GHz when S_2 is 'ON' (d) 3.6 GHz when S_2 is 'ON'*

5. Conclusion

In this paper, a new reconfigurable antenna design has been proposed covering all the frequency bands used for WLAN applications including 2.4, 3.6, 4.9, 5.1, and 5.9 GHz. This antenna uses PIN diodes for switching purposes between the three patches of the antenna. A bias tee is designed for activating the PIN diode used as a switch. A prototype of this reconfigurable patch antenna is fabricated and tested and all the measurement results are found in good agreement with the corresponding simulated ones. The current distributions on the patch antenna at the working frequencies are shown to get the insight and obtain reasons for using the specific shapes of the slots etched out in the three patches. A comparison is provided between the proposed antenna with the existing reconfigurable antennas found in the literature for WLAN applications to highlight the significance and novelty of the proposed reconfigurable antenna.

6. References

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