Design and Modeling of a Compact Reconfigurable Slot Antenna for WLAN Portable Devices

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Abstract: **This paper presents design and modeling of a compact reconfigurable quarter wavelength slot antenna compatible with the portable devices of the 5GHz wireless local area network (WLAN) applications. The concept of the transverse resonant method which is used for the transmission lines is utilized for modeling the proposed slot antenna. A PIN diode is used to switch the antenna operating band from the lower unlicensed indoor 5GHz WLAN band (5-5.3) GHz to the upper one (5.7-5.9) GHz and vice versa. Another PIN diode is attached to the feed line to provide suitable matching stub length for each operation mode. Furthermore, the shape of the radiating slot of the proposed antenna is modified to provide an omnidirectional radiation pattern in the H-plane suitable for the portable gadgets of the WLAN system. The measurements are in well agreement with the simulated results, and they verify the precision of the suggested model and the enhanced matching characteristics for the two operation modes of the proposed antenna.**

***Index Terms*: Slot Antenna, Transverse Resonant, Tuning Stub, Magnetic Current, PIN Diode.**

I. INTRODUCTION

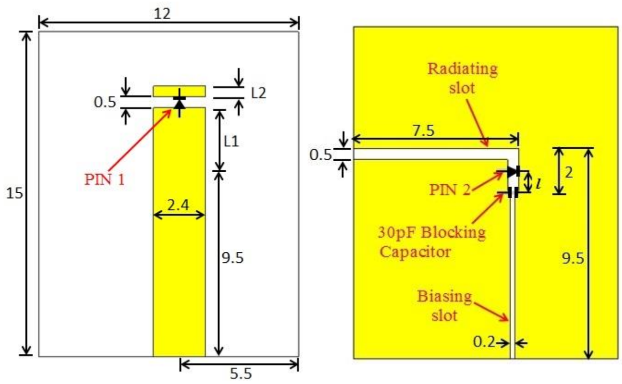
The advent of gadgets that are function for wireless communications has fueled the antenna researchers to develop miniaturization techniques that provide more compatible antennas with the emerging demand. Slot antennas are good candidate for this kind of technology due to its planar structure, low cost, and easy fabrication techniques. Unlike the other types of printed circuit antennas which have large electric near field, the magnetic field of the slot antennas dominates the near field region [1]. Therefore, these antennas have a reduced undesired coupling with the nearby electrical components [2]. To present more versatile slot antenna, researchers tend to design reconfigurable slot antennas whose resonant frequency, radiation pattern, or polarization can be modified as required.

Different radio frequency (RF) switches are used to reconfigure the resonant frequency of the slot antenna. PIN diodes are used to generate step variation in the half wavelength slot antenna resonant frequency [3], while the continuous variation in the resonant frequency is obtained by attaching varactor diodes to the slot antenna [4]. Some researchers utilize non-conventional RF switches, such as microfluidical switches, for the reconfiguration purposes [5]. Nowadays, reconfigurable half wavelength slot antennas are utilized for variety of applications such as wireless local area network (WLAN) [6] and smart phones [7]. Furthermore, their applications are extended to include cognitive radio systems [8].

In this paper, a compact quarter wavelength reconfigurable slot antenna for 5GHz unlicensed indoor WLAN applications is proposed. The antenna operation is modeled with the aid of transverse resonant method to predict the antenna resonant frequency for different PIN diode states. The antenna operating band is reconfigured between the two unlicensed indoor 5GHz WLAN band (5-5.3) GHz and (5.7-5.9) GHz, so it is convenient for unlicensed WLAN cognitive radio systems. The shape of the slot antenna is modified to provide an omnidirectional radiation pattern in the H-plane which is suitable for portable devices. The feed line of the proposed antenna is attached by another PIN diode to ensure an improved matching for both operating bands. The simulation and measured results are in good agreement, and they exhibit reasonable frequency domain and radiation characteristics. Moreover, the results verify the precision of the proposed model in predicting the antenna resonant frequency in spite of the stray effects of the PIN diode in the forward and the reverse biasing.

II. ANTENNA DESIGN

The general structure of the proposed antenna is illustrated in Figure 1. The dielectric substrate of the antenna is Rogers RT5880 with dielectric constant $\varepsilon_r = 2.2$, loss tangent of 9×10^{-4}, and height $h = 0.8mm$. Two



(a) (b)

Figure 1 Propose antenna structure (a) the front view and (b) the back view (all dimensions are in mm).

SMP1320-079LF PIN diodes are used to control the operating frequency of the proposed antenna. This PIN diode is selected due to its small values of reverse biasing capacitance ($C_r = 0.3pF$) and forward biasing resistance ($R_f = 0.9\Omega$ at $10mA$). PIN diode 1 is utilized for controlling the feeding line length to provide an improved matching for both operating bands, whereas PIN diode 2 is used for controlling the slot length to modify the resonant frequency of the proposed antenna. The antenna overall dimensions are ($12 \times 15 \times 0.8\ mm^3$).

The antenna back view shows two different slots. The first one is a radiating slot whose width is $0.5mm$, while the $0.2mm$ width slot is used for isolating the biasing lines of the PIN diode, so it is called a biasing slot. Since the slot antenna depend on the magnetic current for its electromagnetic radiation [1], the position of the biasing slot is selected based on the magnetic current distribution of the slot antenna. It is positioned where the magnetic current of the radiating slot is minimum in order not to affect the magnetic current distribution of the radiating slot as will be verified in Section 4. Figure 2(a) shows a sketch of the magnetic current distribution of a quarter wavelength slot antenna. In opposite to the electric current, the magnetic current is maximum at the open circuit terminal (positive x-direction) and zero at the short circuited terminal (negative x-direction). Therefore, the biasing slot is engraved starting from the short circuited terminal of the radiating slot. A blocking capacitor ($C_b = 30pF$) is placed at the interface of the radiating and biasing slots to provide a path for the RF current and block the DC biasing current. It is worth to mention that the antenna has no radiating power toward the short circuit terminal of the slot because of the zero magnetic current in that direction, so the H-plane (xz plane) radiation pattern of the antenna is directive and not suitable for portable devices. Consequently, the radiating slot is bent (see Figure 2(b)) in order to compose almost omnidirectional radiation pattern in the H-plane by producing non-zero magnetic current in the negative x-direction.

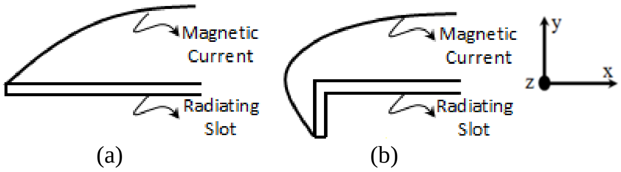


Figure 2 Simple representation of the magnetic current along a quarter wavelength (a) strait slot and (b) bent slot.

III. ANTENNA MODELING

The radiating slot of the proposed antenna can simply be modeled using Transverse Resonant Method which is originally specified for transmission lines [9]. This method imposes on the standing wave extending along a purely reactive loaded transmission line. It is known that the voltage and current standing waves are continuous signals, so their magnitudes to the left and the right of a certain point on the transmission line are equal. The voltage polarity to the left and right of the selected point are the same, while the current to the left of that point has an opposite direction to the current passing toward the right of it. Consequently, the voltages to the left and right of certain point are equal, whereas the current to the left of the selected point is the negative of the current to the right of that point. As a result, the impedance at the left (Z_L) and the right (Z_R) of certain point can be given by the following formula [10]:

$$Z_R = -Z_L \tag{1}$$

This method can be utilized for the radiating slot of the proposed antenna which is terminated by an open circuit in one side and a $30pF$ blocking capacitor (C_b) in the other. To enhance the precision of the proposed model, PIN diode 2 is modeled by its forward biasing resistance (R_{f2}) during its ON state and by its reverse biasing capacitor (C_{r2}) during its OFF state. For the OFF state of PIN diode 2, the radiating slot can simply be modeled by the microwave circuit shown in Figure 3(a). The impedance to the right of the selected reference point is given by:

$$Z_R = \frac{1}{j\omega C_{r2}} //[\lim_{Z\to\infty} Z_{os}\frac{Z + jZ_{os}\tan\beta l'}{Z_{os} + jZ\tan\beta l'}] \tag{2}$$

where $//$ denotes a parallel connection, Z_{os} denotes the characteristic impedance of the radiating slot, and β represents the propagation constant of the radiating slot.

$$Z_R = -\mathrm{j}\frac{Z_{os}}{\omega C_{r2} Z_{os} + \tan\beta l'} \tag{3}$$

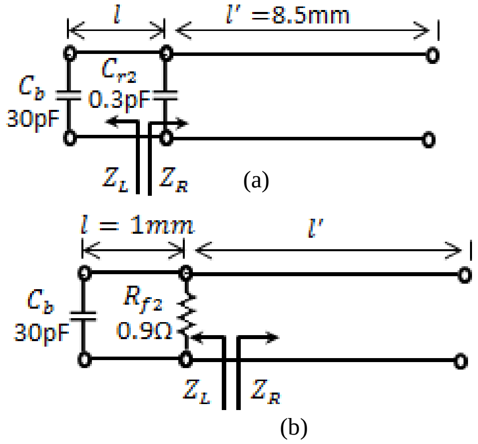


Figure 3 Model of the radiating slot with PIN diode 2 (a) OFF and (b) ON.

The impedance to the left of the reference point is given as:

$$Z_L = Z_{os}\frac{(1/j\omega C_b) + jZ_{os}\tan\beta l}{Z_{os} + j(1/j\omega C_b)\tan\beta l} \tag{4}$$

$$Z_L = -jZ_{os}\frac{1 - \omega C_b Z_{os}\tan\beta l}{\omega C_b Z_{os} + \tan\beta l} \tag{5}$$

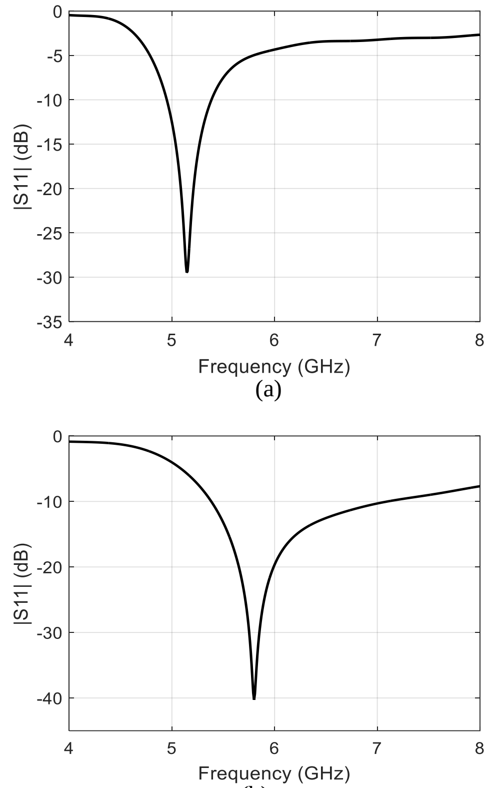
where $\omega = 2\pi f$ represents the angular frequency. If λ_s and λ denotes the slot wavelength (wavelength of the wave passing through the slot) and the wavelength in the free-space, respectively, then the values of β and Z_{os} can be calculated from the following formulas [11]:

$$\begin{aligned} \lambda_s/\lambda &= 1.05 - 0.04\varepsilon_r + 0.01411(\varepsilon_r - 1.421) \\ &\times \ln\left[\frac{W_s}{\mathrm{h}} - 2.012(1 - 0.146\varepsilon_r)\right] \\ &+ 0.111(1 - 0.366\varepsilon_r)\sqrt{W_s/\lambda} \\ &+ 0.139[1 + 0.52\varepsilon_r \times \ln(14.7 - \varepsilon_r)](h/\lambda) \\ &\times \ln(h/\lambda) \end{aligned} \tag{6}$$

$$\beta = \frac{2\pi}{\lambda_s} \tag{7}$$

$$\begin{aligned} Z_{os} &= 120.75 - 3.74\varepsilon_r + 50[\tan^{-1}(2\varepsilon_r) - 0.8] \\ &\times (W_s/h)^{[1.11+(0.132(\varepsilon_r-27.7)/(100h/\lambda+5))]} \\ &\times \ln\left[100h/\lambda + \sqrt{(100h/\lambda)^2 + 1}\right] + 14.21(1 - 0.458\varepsilon_r) \\ &\times (100h/\lambda + 5.1\ln(\varepsilon_r) - 13.1)(W_s/h + 0.33)^2 \end{aligned} \tag{8}$$

where W_s is the radiating slot width, h is the height of the dielectric substrate, and ε_r is the dielectric constant of the substrate. It should be noted that W_s, h, and λ are in mm in equations (7) and (8). Since it is required to cover the lower unlicensed indoor band of the 5GHz WLAN (5-5.3)GHz, the antenna resonant frequency is selected to be 5.15GHz. By substituting this value in (3) and (5) and $l' =$ 8.5mm and applying the transverse resonant method condition given in (1), the value of l is found to be about $1mm$. Figure 4(a)



(a)

(b)

Figure 4 Simulated reflection coefficient of the proposed antenna with $L_1 = 2mm$, $L_2 = 0.5mm$, $l = 1mm$, and $l' = 8.5mm$ for PIN diodes 1 and 2 are (a) OFF and (b) ON.

illustrate the CST microwave studio reflection coefficient of the proposed after setting $l = 1mm$ and the PIN diode 1 and 2 at their OFF state. The reflection coefficient shows that the antenna resonant frequency is at 5.16GHz which is too close to the required resonant frequency.

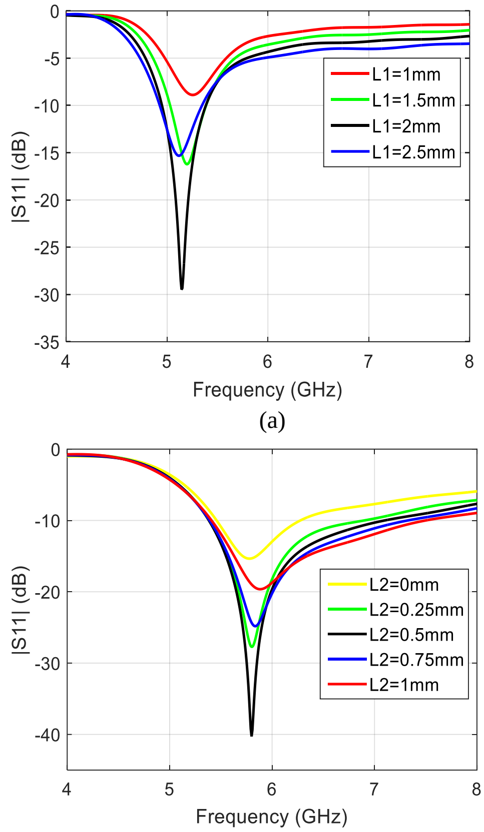
For the ON state of PIN diode 2, the microwave circuit model of the radiating slot of the proposed antenna is illustrated in Figure 3(b). The impedance to the left of the selected reference point is given below:

$$Z_L = R_{f2} // \left[Z_{os} \frac{(1/j\omega C_b) + jZ_{os} \tan \beta l}{Z_{os} + j(1/j\omega C_b) \tan \beta l} \right] \quad (9)$$

Since the value of R_{f2} is small (0.9Ω), the value of Z_L is close to the value of this resistance ($Z_L \approx R_{f2} \approx 0$). Meanwhile, the impedance to the right of the reference point is as follows:

$$Z_R = \lim_{Z \to \infty} Z_{os} \frac{Z + jZ_{os} \tan \beta l'}{Z_{os} + jZ \tan \beta l'} = -jZ_{os} \cot \beta l' \quad (10)$$

After applying the transverse resonant condition presented in (1) and setting the frequency to 5.8GHz (the center of upper unlicensed indoor 5GHz WLAN (5.7-5.9) GHz), the length l' is found to be about $8.5mm$. Figure 4(b) exhibits the simulated magnitude of the reflection coefficient using CST microwave studio simulation suite for PIN diode 1 and 2 at their ON state. The simulated resonant frequency is 5.83GHz which is almost equal to the center frequency of the upper unlicensed indoor 5GHz WLAN.



(a)

(b)

Figure 5 Simulated reflection coefficient of the proposed antenna with and $l' = 8.5mm$, $l = 1mm$ when (a) PIN diode 1 and 2 OFF, $L1 = 2mm$, and different values of $L2$, (b) PIN diode 1 and 2 ON, $L2 = 0.5mm$, and different values of $L1$.

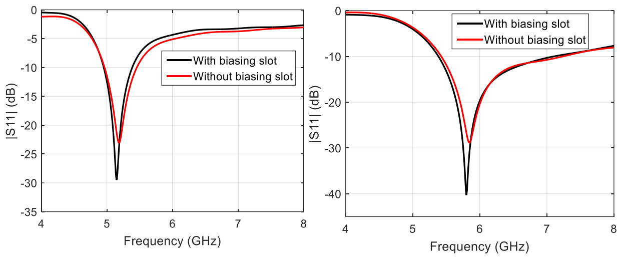
IV. Matching Improvement

The matching network of the slot antenna is accomplished by positioning the feed line at a certain position then optimizing the length of the matching stub. In fact, the matching stub is an extension of the feed line that is expanded beyond the radiating slot. The proposed antenna operates at two different resonant frequencies depending on the state of PIN diode 2, so each resonant frequency requires different stub length for its own matching process. PIN diode 1 (shown in Figure 1(a)) has been attached to the antenna feed line to introduce two different stub lengths for each state of PIN diode 2. When PIN diode 2 is at its OFF state, the antenna operating at resonant frequency of 5.16GHz. In this case, PIN diode 1 is at its OFF state too. Figure 5(a) illustrates the simulated magnitude of the antenna reflection coefficient under these conditions for ($L2 = 0.5mm$) and different values of stub length ($L1$). Recall that PIN diodes 1 and 2 are simulated by their reverse biasing capacitor during this mode of operation. It is clear that $L1 = 2mm$ gives the best matching with a reflection coefficient value at the resonant frequency equal to $-30dB$.

The ON state of PIN diodes 1 and 2 makes the antenna to be operating at 5.83GHz, so the optimization process involves varying the upper piece of the feed line ($L2$). After simulating the two PIN diodes by their forward biasing resistance, the simulated magnitude of the reflection coefficient for different values of $L2$ is shown in Figure

5(b). The superiority of $L2 = 0.5mm$ can clearly be observed from this figure where the reflection coefficient value reaches to $-40dB$ at the resonant frequency. The matching network of slot antennas is modeled and studied in detail in [12], but because it is not the main theme of this paper, the model is compensated by the aforementioned simple parametric study.

As mentioned in Section 2, the biasing slot is engraved starting from the short circuited terminal of the radiating slot because the magnetic current of the radiating slot is negligible at this point. Therefore, the antenna characteristics are not affected by the presence of this slot. Figure 6 reveals the influence of the biasing slot on the reflection coefficient of the proposed antenna for the two different modes. The resulted reflection coefficients with and without the biasing slot are almost similar to each other, so the minor effect of the presence of the biasing slot at the suggested position on the characteristics of the proposed antenna is verified successfully.

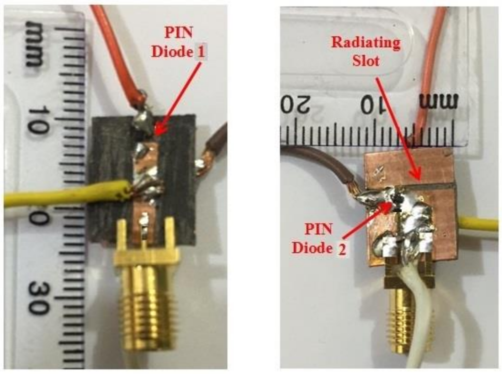


(a) (b)

Figure 6 Simulated reflection coefficient of the proposed antenna with and without the biasing slot when PIN diodes 1 and 2 are (a) OFF and (b) ON.

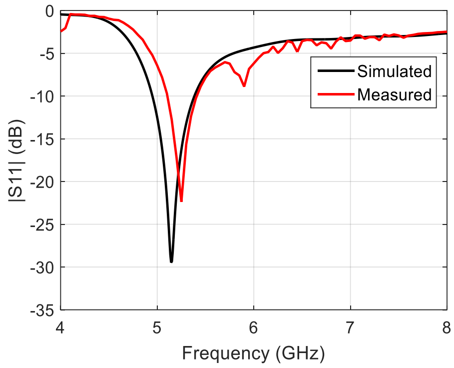
V. MEASURED RESULTS

Figure 7 shows the front and the back view of the prototype of the proposed antenna with the two SMP1320-079LF PIN diodes whose parameters are given in Section II. The measured results are acquired from AMITEC network analyzer package at University of Basrah/Department of Electrical Engineering. The simulated and measured reflection coefficients of the proposed antenna during the OFF state of diode 1 and 2 are illustrated in Figure 8(a), whereas Figure 8(b) illustrates the simulated and measured reflection coefficients when PIN diodes 1 and 2 are ON. The deviation between the simulated and measured reflection coefficients may be attributed to the imperfect soldering of the SMA connector, the fabrication tolerations, or the imperfect alignment of the PIN diodes. However, the measured reflection coefficients verify the successful operation of the reconfiguration as well as the improved matching characteristics of the proposed antenna.

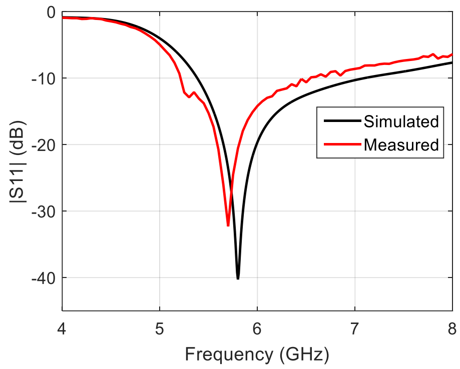


(a) (b)

Figure 7 Prototype of the proposed antenna (a) front view and (b) back view.



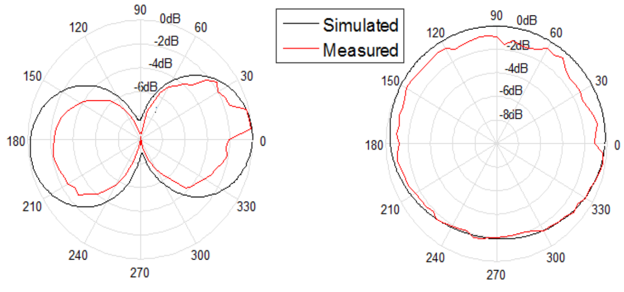
(a)



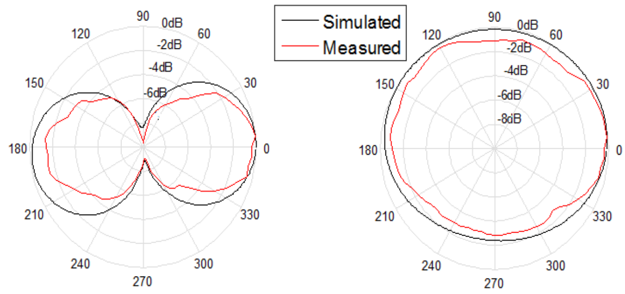
(b)

Figure 8 Simulated and measured reflection coefficients when PIN diodes 1 and 2 are in their (a) OFF state and (b) ON state.

The simulated and measured power patterns of the proposed antennas for the OFF and ON states of PIN diode 1 and 2 are exhibited in Figure 9. The distortion of the measured power pattern is caused by the reflections coming from the surrounding objects because the anechoic chamber is not perfectly covered by the absorbing material. As explained in Section 2, the radiating slot is bent to generate an omnidirectional radiation pattern in the H-plane which is convenience for portable devices. The radiated power toward the short circuited terminal of the radiating slot is about 2dB weaker than that toward the open circuited terminal, so the H-plane pattern can be considered as an omnidirectional. Furthermore, the power patterns for the two different cases of the PIN diodes are almost the same, and this is an important property for the frequency reconfigurable antenna design. The simulated and measured gains of the proposed antenna for the OFF state of the PIN diodes at 5.16GHz are 1.7dBi and 1.5dBi, respectively. On the other hand, for the ON state of the PIN diodes the simulated and measured gains of the proposed antenna at 5.83GHz are 2.2dBi and 1.9dBi, respectively.



(a) Both diodes are OFF, f=5.16GHz



(b) Both diodes are ON, f=5.83GHz

Figure 9 Simulated and measured power patterns of the proposed antenna for different states of PIN diodes.

VI. CONCLUSION

A compact quarter wavelength reconfigurable slot antenna for indoor unlicensed 5GHz WLAN applications is design and modeled in this paper. Transverse resonant method is utilized to model the radiating slot of the proposed antenna. The frequency reconfigurability is performed by a PIN diode to switch the antenna operating band from the lower unlicensed indoor WLAN (5-5.3)GHz to the upper unlicensed indoor WLAN (5.7-5.9)GHz and vice versa. The length of the stub is also controlled by a PIN diode to provide an improved matching for the two different modes of the proposed antenna. Moreover, the shape of the antenna radiating slot is modified to provide an omnidirectional radiation pattern in the H-plane which is suitable for portable devices. The simulated and measured results verify the precision of the proposed model because they reveal that the resonant frequencies of the proposed model are just 0.2% and 0.5% higher than the simulated values in both modes. In addition, the measured reflection coefficients of proposed antenna at the resonant frequencies of each mode are -22dB and -32dB, and the power pattern has a doughnut shape which is convenient for portable gadgets.

REFERENCES

[1] H. Schantz, “UWB Magnetic Antennas,” IEEE Antenna and Propagation Society International Symposium, vol. 3, pp. 604-607, June 2003.

[2] F. Alnahwi and N. Islam, “A Generalized Concept for Band Notch Generation in Ultra-Wide Band Antennas,” Progress in Electromagnetic Research C, vol. 54, pp. 179-185, 2014.

[3] L. Pazin and Y. Leviatan, “Reconfigurable Rotated-T Slot Antenna for Cognitive Radio Systems,” IEEE Transactions on Antennas and Propagation, vol. 62, no. 5, pp. 2382-2387, May 2014.

[4] A. Khidre, F. Yang, and A. Elsherbeni, “A Patch Antenna With a Varactor-Loaded Slot for Reconfigurable Dual-Band Operation,” IEEE Transactions on Antennas and Propagation, vol. 63, no. 2, pp. 755-760, Feb. 2014.

[5] A. Saghati, J. Batra, J. Kameoka, and K. Entesari, “A Microfluidically-Reconfigurable Dual-Band Slot Antenna with a Frequency Coverage Ratio of 3:1,” IEEE Antenna and Wireless Propagation Letters, vol. 15, pp. 122-125, 2016.

[6] L. Han, C. Wang, X. Chen, and W. Zhang, “Compact Frequency Reconfigurable Slot Antenna for Wireless Applications,” IEEE Antenna and Wireless Propagation Letters, vol. 15, pp. 1795-1798, 2016.

[7] M. Stanley, Y. Huang, H. Wang, H. Zhou, Z. Tian, and Q. Xu, “A Novel Reconfigurable Metal Rim Integrated Open Slot Antenna for Octa-band Smartphone Applications,” IEEE Transactions on Antennas and Propagation, vol. 65, no. 7, pp. 3352-3363, 2017.

[8] G. Srivastava, A. Mohan, and A. Chakrabarty, “Compact Reconfigurable UWB Slot Antenna for Cognitive Radio Applications,” IEEE Antenna and Wireless Propagation Letters, vol. 16, pp. 1139-1142, 2017.

[9] D. Pozar, Microwave Engineering, 4th Ed., John Wiley and Sons, 2012.

[10] N. Behdad and K. Sarabandi, “Dual-Band Reconfigurable Antenna With a Very Wide Tunability Range,” IEEE Transactions on Antennas and Propagation, vol. 54, no. 2, pp. 409-4016, Feb. 2006.

[11] K. Gupta, R. Garg, I. Bahl, P. Bhartia, Microstrip Lines and Slotlines, 2nd Ed., Artech House, 1996.

[12] J. Kim, and W. Park, “Network Modeling of an Inclined and Off-Center Microstrip-Fed Slot Antenna,” IEEE Transactions on Antennas and Propagation, vol. 46, no. 8, pp. 1182-1188, Aug. 1998.