An Electronically Reconfigurable Patch Antenna Design for Polarization Diversity with Fixed Resonant Frequency

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Abstract. *In this paper, an electronically polarization re-configurable circular patch antenna, with fixed resonant frequency and operating at Wireless Local Area Network (WLAN) frequency band (2.4–2.48 GHz,) is presented. The structure of the proposed design consists of a circular patch as a radiating element fed by a coaxial probe, coop-erated with four equal-length slits etched on the edge along the x-axis and y-axis. A total of four switches were used and embedded across the slits at specific locations, thus controlling the length of the slits. By activating and deacti-vating the switches (ON and OFF) across the slits, the cur-rent on the patch is changed, thus modifying the electric field and polarization of the antenna. Consequently, the polarization excited by the proposed antenna can be switched into three types; linear polarization, left-hand circular polarization or right-hand circular polarization. This paper proposes a simple approach that enables switching the polarizations and excites at the same oper-ating frequency. Simulated and measured results of the ideal case (using copper strip switches) and the real case (using PIN diode switches) are compared and presented to demonstrate the performance of the antenna.*

Keywords

Polarization reconfigurable antenna, circular patch, slit perturbations

1. Introduction

Antenna is a key and critical component in wireless telecommunication systems. The evolution of the antenna has rapidly grown and been extensively investigated. It leads to a change of system requirements, hence making it more complex. Adjustments of the operating system sce-nario are needed in order to meet current trends and de-mands from end users - such as light weight and compacted devices with enhanced performance. Conventional antenna may face restrictions and limitations to adapt to the new adjustments, due to their characteristics of being fixed and inflexible. One solution to overcome this restriction is the use of reconfigurable antenna.

Reconfigurable antennas, or multi-functional anten-nas, have recently become quite an active and important topic of research all over the globe. This is due to the fact that the characteristics and properties of the reconfigurable antenna - such as operating frequency/bandwidth, far-field radiation pattern and polarization [1] - can be altered dynamically using external control, hence providing addi-tional functionality and versatility to the systems. Flexibil-ity and reconfigurability features could result in the adapta-bility of the antenna to address complex system require-ments and new specifications. Furthermore, through this concept, the number of components, sizes and hardware complexities could be reduced [2] - hence the cost would be more economically efficient. These benefits would ren-der reconfigurable antennas to become a highly desired feature in modern radio-frequency (RF) systems for wire-less and satellite communications.

Reconfigurability can be achieved in different ways, such as through deliberate modification of the antenna physical structure, radiating edge and feeding network. These changes will alter the current flows and distributions on the antenna structure, hence modifying the performance characteristics. To achieve this reconfigurability feature, mechanical [3], optical (photoconducting switches) [4] or electronic (RF switching devices) [5] switches can be used. Among these types of switches, RF PIN diodes and RF MEMS are typical components used in designing the re-configurable antenna. The PIN diode needs less compli-cated biasing components, and the lower cost results in it becoming a more popular choice amongst researchers. Even though PIN diodes also have a few drawbacks, such as high insertion loss and lower efficiency, the simplicity in biasing is a key criterion for the selection. The equivalent circuit of the PIN diode for forward bias and reverse bias is shown in Fig. 1.
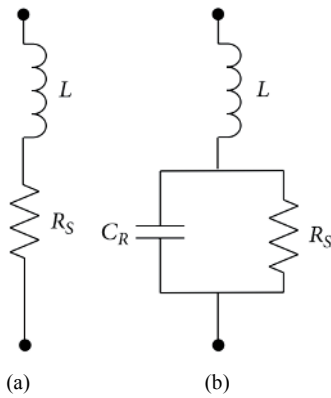
Fig. 1. PIN diode equivalent circuit. (a) forward bias; (b) reverse bias.

Recently, polarization reconfigurable antennas, which can incorporate and offer various polarizations from a single antenna, have attracted considerable attention. This is because the antenna has the ability to reduce the multipath fading [7], and the realization of frequency re-use [8]. In addition, this type of antenna is experimentally proven to improve the capacity offered in the multiple-input-multiple-output (MIMO) systems [9], [10]. For instance, the polarization reconfigurable antenna might take place between linear polarization (LP) and circular polarization (CP), between orthogonal LPs [11], [12], or between left-hand (LHCP) and right-hand circular polarization (RHCP) [13], [14]. Ideally, the main goals in designing reconfigurable antennas are to have the characteristics to be separable and independent. This is because the major challenge to achieve this kind of reconfigurability is to accomplish, without significant changes, on the frequency response and impedance matching. Therefore, careful design approaches are required in order to achieve this feature.

A few papers on the polarization reconfigurable antenna between LP and CP are reported in the literature. Reconfigurable polarization is achieved in [15], through the control of two crossing diagonal slots on the square patch. A similar technique is also used in [16]. In [17], the authors incorporated PIN diodes on the inset of the U-shaped slot-line. However, the design required switchable matching stubs in order to obtain good reflection coefficient, which adds more size and complexity to the structure. Furthermore, reference [18] proposed an interesting design approach to achieve polarization reconfigurability features by creating loop slots in the ground plane. The switches were embedded on every slot of the ground plane, which altered the desired polarization sense. Even though the proposed solutions [16-18] managed to obtain a polarization reconfigurable antenna, however the changes of the polarization sense were excited at a different resonant frequency.

Hence, this paper proposes polarization reconfigurable antenna with fixed operating frequency. Details of the design, development and analysis of the polarization reconfigurable circular patch antenna with switchable slit length are presented. Two pairs of slits were located at the edge of the circular radiating patch, positioned on the x-axis and y-axis. The polarization reconfigurability feature of the an-

tenna was executed by placing four switches at specific positions across the slits. The change of the state of the switches consequently alters the length of the slit, hence creating a length difference between the slit in the x-axis and the y-axis. This, accordingly, will determine the types of polarization excited by the antenna - either LHCP, RHCP or LP. Interestingly, all types of polarization senses produced are operated at the same resonant frequency.

Work done in [19] proposed quite a similar approach. However, the polarization was only able to be reconfigured between LHCP and RHCP, without consideration made for the LP. Despite that, the biasing technique applied in this paper is much simpler and requires smaller dimensions.

This manuscript is divided into two main sections based on the type of switch adopted: "Design A" (ideal diode) and "Design B" (PIN diode). The simulated and measured results for both designs are presented, compared and analyzed.

2. Stage 1: Proof of Concept (Copper Strips)

In this section, the initial stage of the design started with the employment of ideal switch. The ideal switch is represented by copper strips or metal pins, with dimensions of 1 mm × 1 mm. The presence of the copper strips indicates the switch in the 'ON' state, meanwhile the absence denotes the 'OFF' state condition.

2.1 Antenna Geometry and Operation

The schematic geometry of the proposed antenna is illustrated in Fig. 2. This consists of a circular patch with radius of r on the finite fully grounded Taconic RF-35 substrate (dimensions of $L \times W$ in mm) with a dielectric constant, ε_r of 3.52, thickness, h of 1.52 mm and tangent loss, $\tan\delta$ of 0.0018. Four slits, which have a length of L_s mm and width of W_s mm are etched at the corner of the circular patch, located along the x-axis and y-axis of the structure with 90º apart from each other. Each slit will have a switch located across it, thus altering the length of the slits. As shown in Fig. 2, the switches are placed at the distance of L_p from the center of the patch. The location of the switch is crucial as it determines the optimum result for the axial ratio. The feed location is positioned diagonally and is fed from the back of the structure through subminiature (SMA) probe. Parameter d is optimized to achieve good impedance matching.

The design procedure generally started with determining the value of unloaded Q_o of the patch, which depends on the radius r, thickness of the substrate h, and the dielectric constant ε_r. By using (1), the value of slit perturbation is determined [20].

$$\left|\frac{\Delta S}{S}\right| = \frac{1}{1.841Q_0} \qquad (1)$$

where S is area of patch and ΔS is the area of slit perturbation. Then, the dimension of the slit is optimized using parameter sweep in order to obtain good circular polarization.

The approach and mechanism of the proposed antenna can be explained using the cavity model method. Due to the diagonal feeding on the structure and perturbation segments, the two near degenerated orthogonal resonant modes TM_{01} and TM_{10} are excited simultaneously. The existence of the perturbation slits will drive the surface current at the edge of the structure to move along it. The lengthened path is only affected to the current travel in the perpendicular direction to the L_s. However, from the parallel direction, the small width, W_s of the perturbation slits will slightly affect the current that is coming from that route. For example, when the pair of slits is cut on the x-axis of the patch, only TM_{01} mode will be affected without giving much effect on the TM_{10} mode, and vice versa.

Due to the presence of the copper strips, the slit length will be shortened, thereby causing an effective surface current to flow across it (shortest distance) instead of travelling around the slits. Consequently, the length difference between the slit on the x-axis and on the y-axis will provide the phase delay between both orthogonal resonant modes. At a specific length difference, the two orthogonal degenerated resonant modes will have the same amplitude and in-phase quadrature, which the CP is excited. Meanwhile, LP is excited when two switches on the x-axis and y-axis are ON, which means no phase difference between both orthogonal resonant modes.

Overall, this proposed antenna works in three polarization modes; namely LHCP, RHCP and LP. The type of excited polarization depends on the configurations of four switches. The switching conditions of all switches, with the respected modes, are tabulated in Tab. 1. The other configurations are not presented, as they provide the same response and redundancy results due to the geometry symmetry. Fig. 3 shows the physical structure used in the simulation, and the photograph of the prototype is shown in Fig. 4.
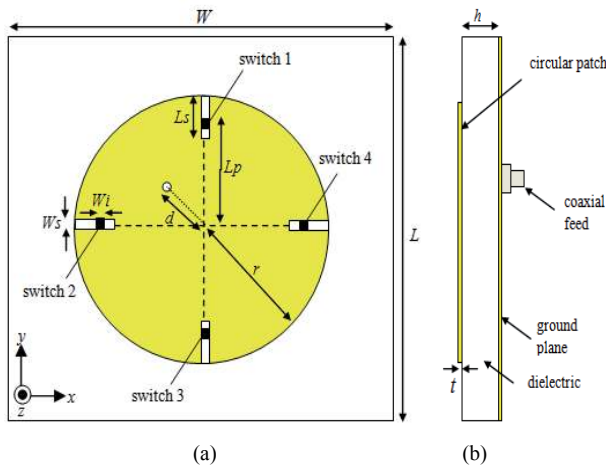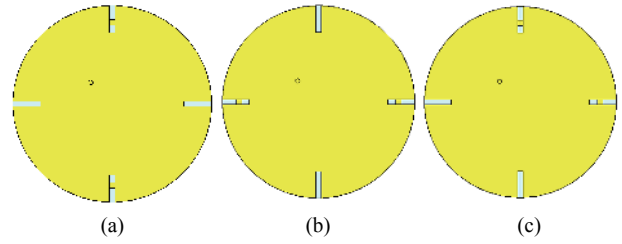

Fig. 3. The physical structure of the proposed antenna used in the simulation: (a) C1-LHCP; (b) C2-RHCP; (c) C3-LP.

Configuration	State of switch				Polarization mode
	SW1	SW2	SW3	SW4	
C1-LHCP	ON	OFF	ON	OFF	LHCP
C2-RHCP	OFF	ON	OFF	ON	RHCP
C3-LP	ON	ON	OFF	OFF	LP

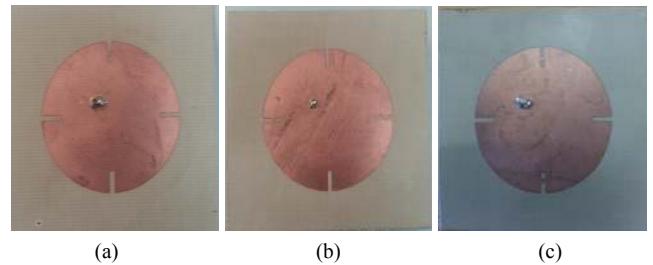**Tab. 1.** Switching configurations of the proposed antenna.

Fig. 4. Front view photograph of fabricated antenna prototypes. (a) C1-LHCP. (b) C2-RHCP. (c) C3-LP.

2.2 Result and Analysis of the Proposed Antenna

The prototype of the antenna is tested and analyzed. S-parameters and far-field test is measured using a Rohde & Schwartz ZVL network analyzer and in an anechoic chamber, respectively. The simulation is carried out using Computer Simulation Technology (CST) Microwave Studio full wave simulator.

Figure 5 shows the comparison between simulated and measured reflection coefficient of the proposed antenna for all switch configurations. It can clearly be seen that for C1-LHCP and C2-RHCP, the two degenerated resonant modes (TM_{01} and TM_{10}) are excited with close frequency at 2.45 GHz/2.49 GHz and 2.45 GHz/2.50 GHz, respectively. Meanwhile, the resonant frequency for C3-LP is 2.48 GHz. The measured -10 dB bandwidths (BW) of S_{11} are 71 MHz (2.438 ÷ 2.509 GHz), 84 MHz (2.437 GHz to 2.521 GHz) and 43 MHz (2.462 ÷ 2.505 GHz) for C1-LHCP, C2-RHCP and C3-LP, respectively. A good impedance matching is achieved for all configurations. It is observed that the measured center frequency is slightly higher than the simulated one. This frequency shift may be due to fabrication uncertainty.

The simulated and measured result of the axial ratio of two CP operations is shown in Fig. 6. For C1-LHCP, the
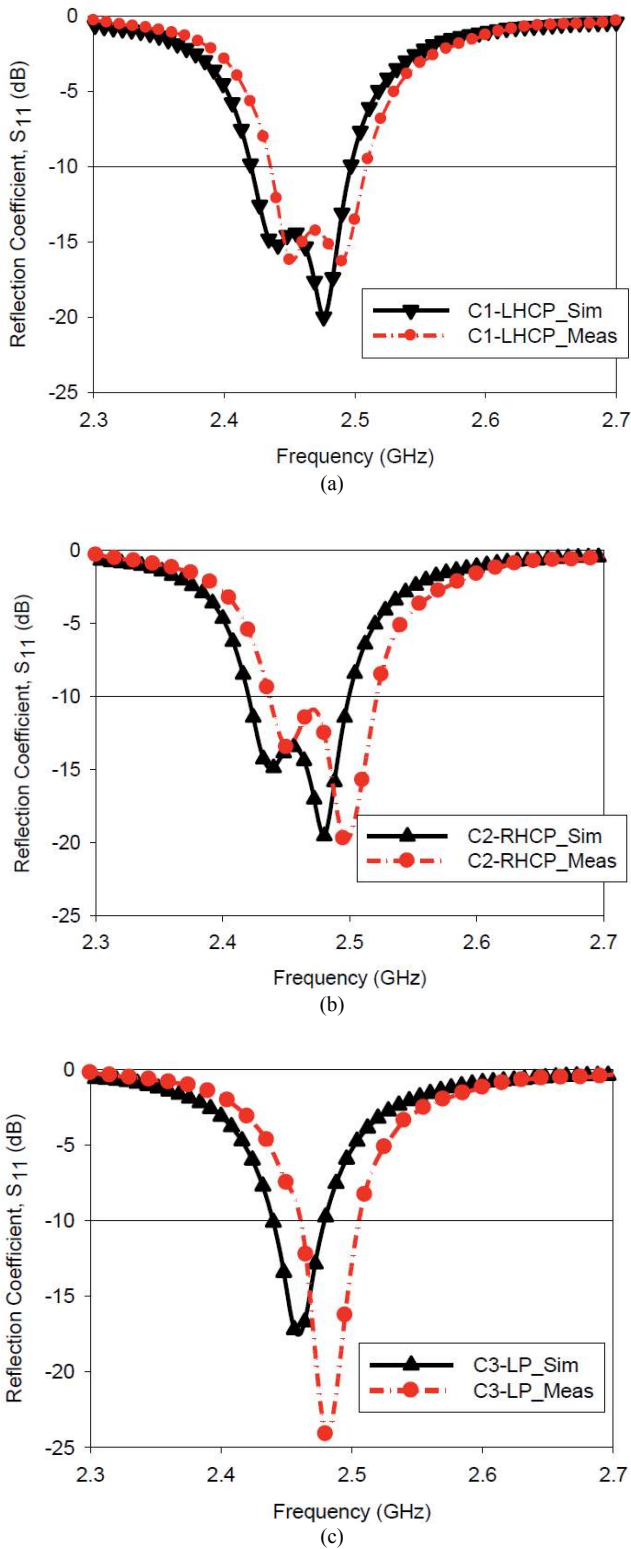

Fig. 2. Geometry of the proposed antenna: (a) front view; (b) side view.

(a)

(b)

(c)

Fig. 5. Comparison of simulated and measured reflection coefficient of the proposed antenna: (a) C1-LHCP; (b) C2-RHCP; (c) C3-LP.

measured 3dB axial ratio bandwidth is 19 MHz (2.456 ÷ 2.475 GHz), or 0.77% with respect to the center frequency of 2.468 GHz. In addition, the BWCP for C2-RHCP is 18 MHz (2.463 ÷ 2.481 GHz), or 0.73% with respect to frequency of 2.472 GHz. The phenomenon variance of the reflection coefficient result leads to the axial
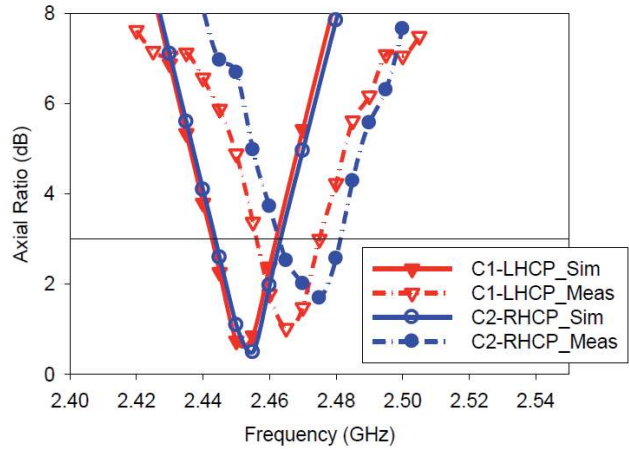

Fig. 6. Simulated and measured axial ratio.
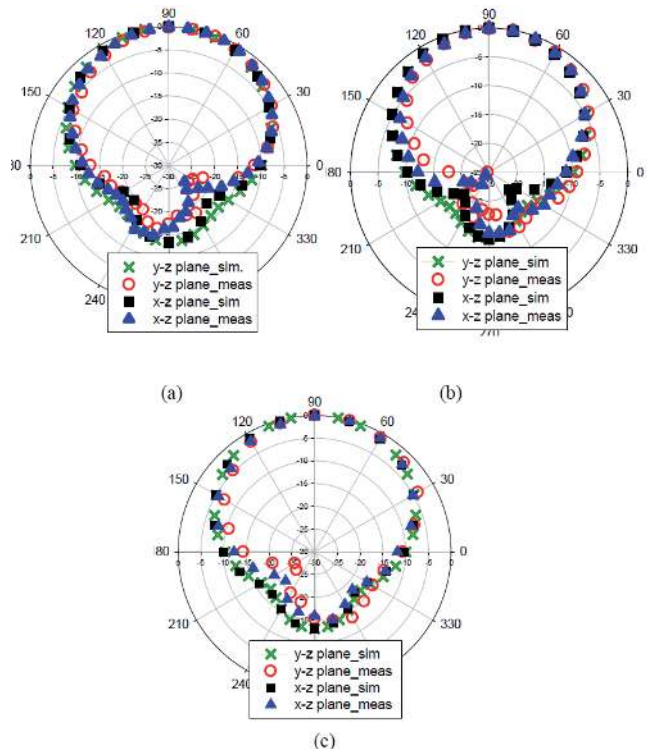

(a)   (b)

(c)

Fig. 7. Simulated and measured normalized far-field radiation pattern at frequency of 2.47 GHz: (a) C1-LHCP; (b) C2-RHCP; (c) C3-LP.

ratio to be shifted as well. The far-field radiation of the proposed antenna is investigated. Figure 7 presents the simulated and measured normalized radiation pattern (*y-z* plane and *x-z* plane) at 2.47 GHz. Good radiation pattern performance, with broadside form, is achieved for all types of polarization modes at the respective center frequency.

3. Stage 2: Antenna Design and Operation; Realization of Active Switches (PIN Diodes)

In this section, the copper strips are replaced by RF PIN diode. In this design, the RF PIN diode being used is

Infineon BAR 50-02L. For activating and deactivating the diodes, the antenna structure is modified by integrating a biasing circuit into the structure. To activate the diode, forward bias current is supplied to the ON-state, and the diode is left unbiased for the OFF state condition.

3.1 Modified Structure of the Antenna with Integrated Biasing Circuit

Figure 8 illustrates the antenna structure with modifications, including biased line and lump elements for the purpose of DC biasing. To accommodate the biasing network, minor adjustment was made on the design and re-simulation was done using the CST software in order to obtain the optimum results. The comparison of the dimension dissimilarity, between without biasing network (design A) and with consideration of biasing network (design B), is tabulated in Tab. 2.

In this structure, L-shape narrow slots with width of $W_b = 0.3$ mm and a length of 9 mm ($L_{b1} + L_{b2}$) are created to separate between the positive and negative areas of the DC voltage supply. Additional lump elements, RF capacitors and RF inductors are introduced into the design for a specific purpose. Five RF chokes inductors are placed between the radiator and biased wire to improve the isolation between RF current and DC supply [7]. The value of all inductors is 27 nH. Furthermore, considering the effect of the narrow slots, twelve DC block capacitors of 100 pF are mounted across it in order to preserve the continuity of the RF current across the radiator.

The cathodes of the diodes are connected to the four small copper areas and supplied with negative DC voltage. Meanwhile, the anodes of the diodes, which are soldered to the remaining copper region on the circular patch, are connected to the positive terminal of the positive DC battery. The DC is directly supplied using copper wire to the radiator through a via-hole and small circle slots created on the ground plane. The circle slots, with a diameter of L_c are introduced to provide separation of DC voltage. This technique is taken to avoid the presence of the biased wire from

(a)

Enlargement

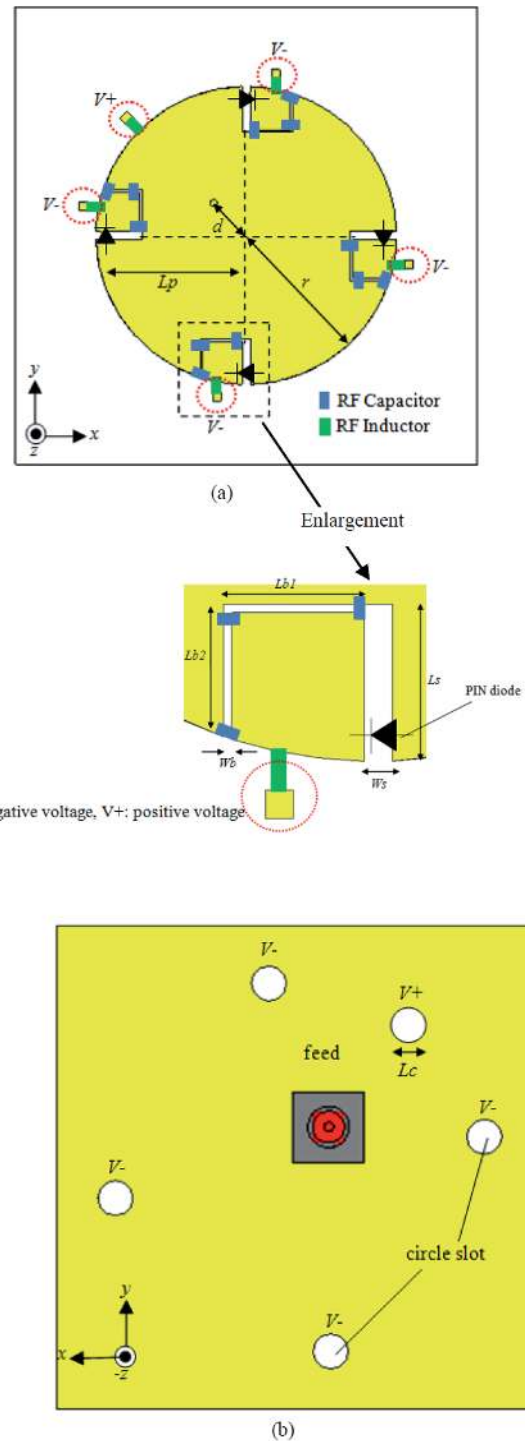* V-: negative voltage, V+: positive voltage

(b)

Fig. 8. Geometry of the proposed antenna with the integration of biasing mechanism: (a) front view, (b) back view.

interrupting the antennas far-field radiation pattern. In the meantime, the wire is terminated at the small square copper located outside the circular patch. For the activation of the diodes, the external switching control board is constructed. The switching board is composed of copper wire, 9V DC battery, a dip switch to control the biasing and the resistor for current limitation. The resistors with a value of $100\,\Omega$ are chosen so that the forward biased current 90 mA is obtained (ON-state) and left unbiased in the OFF-state condition. The photograph of the fabricated antenna is shown in Fig. 9.
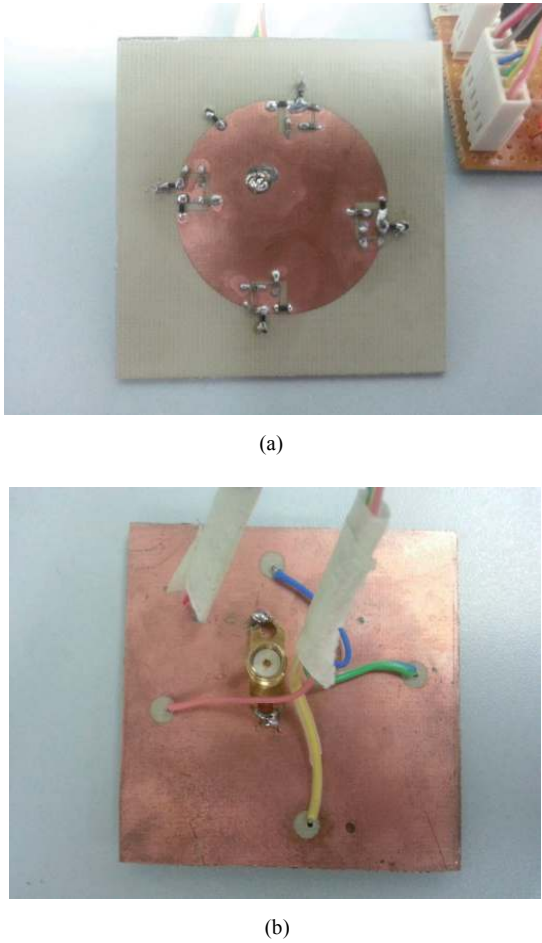
Parameter	Value (mm)		Parameter	Value (mm)	
	A	B		A	B
L	55	55	W_b	-	0.3
W	55	55	W_i	1	-
h	1.524	1.524	L_s	5	5
t	0.035	0.035	L_p	15.3	17
d	5.5	5.5	L_{b1}	-	5
r	17.9	17.9	L_{b2}	-	4
W_s	1	1	L_c	-	4

Tab. 2. Dimension of the designed antennas (Design A and Design B).

(a)

(b)

Fig. 9. Photograph of fabricated antenna prototypes: (a) front view, (b) back view.

(a)

(b)

Fig. 10. Comparison between the simulated and measured reflection coefficient result of the modified structure. (a) Circular polarization. (b) C3-LP.

3.2 Results and Analysis of the Modified Antenna

For accurate simulation results, the PIN diode (Infineon BAR 50-02L) was included in the design and simulated using CST. This step was done by the utilization of touchstone block that contains s2p file which can be obtained from the manufacturer. The touchstone file consists of the information s-parameter of the diode for the ON and OFF state condition.

The optimized antenna was measured using the similar equipment and set up used for the measurement of the ideal diode. The simulated and measured reflection coefficients of the modified structure for all switch configurations are presented in Fig. 10. Good measured impedance matching was achieved for C3-LP, with -10 dB reflection coefficient bandwidth is in the frequency range of 2.469 to 2.515 GHz, or 46 MHz.

However, the reflection coefficient for CP operations is slightly above -10 dB. The impedance bandwidths, based on -10 dB reflection coefficient is 40 MHz (2.494 GHz to 2.534 GHz) and 48 MHz (2.5÷2.548 GHz) for C1-LHCP and C2-RHCP, respectively.
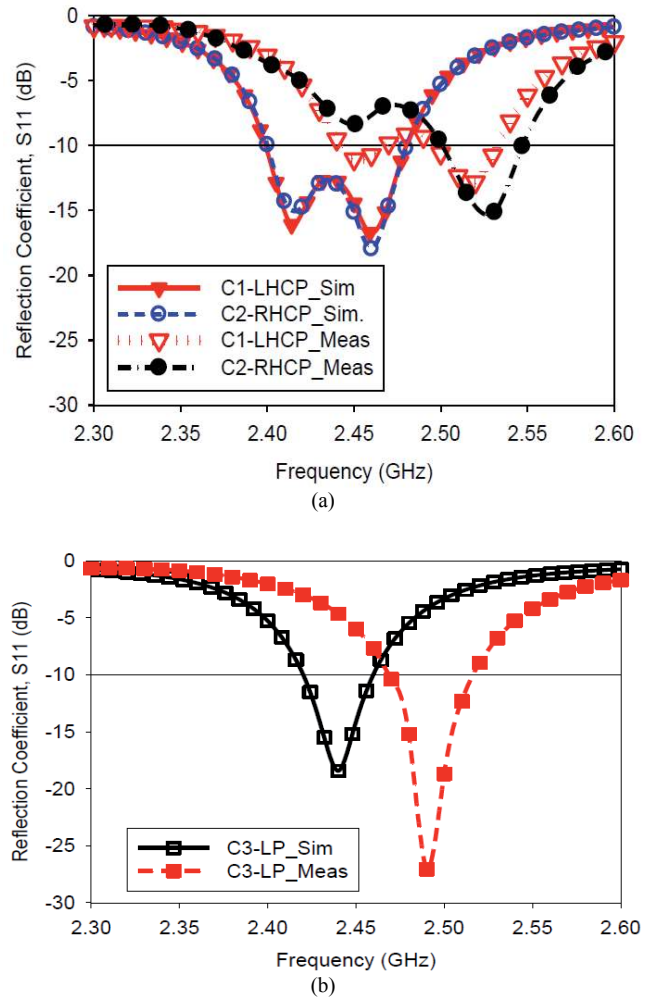
It can be seen that measurement is shifted to the higher frequency. It is also observed that the good impedance matching was obtained except for C2-RHCP configuration. The lowest value of the magnitude of S_{11} for C2-RHCP is -6.7 dB obtained at a frequency of 2.473 GHz. The slight discrepancies between simulation and measurement results could be due to fabrication tolerance, SMA port or parasitic effects from the PIN diode. As mentioned before, the position of the diode in the slits is highly crucial as it determines the axial ratio result and could affect the impedance of the antenna.

Figure 11 shows the simulated and measured results for axial ratio. The measured BW_{CP}, as referred to 3 dB axial ratio bandwidth, is 31 MHz (2.483 ÷ 2.452 GHz) and 22 MHz (2.474 ÷ 2.452 GHz) for C1-LHCP and C2-RHCP, respectively. It has to be noted that the BW_{CP} is totally covered by the BW for linear polarization. Since the proposed antenna performs polarization reconfiguration at a single operating frequency, thus the available working bandwidth is mainly determined by BW_{CP}. Due to symmetry structure, the performances for the both CP operations

are almost identical for reflection coefficient and axial ratio result, like the case of ideal diode. The frequency shifted of the reflection coefficient cause the variance between simulated and measured result for the axial ratio. This is due to the shift of the two degenerated orthogonal modes which will consequently shift the frequency of the excited CP mode.

The measured far-field radiation patterns in the y-z plane and x-z plane for all operation modes are plotted in Fig. 12. Measured results show that the antenna has a broadside radiation pattern at the resonant frequency and 3-dB beamwidth of more than 90º is obtained. In addition, the graph depicts that the proposed antenna has almost the same pattern in both planes. It is also noticed that the gain for C3-LP is higher than the CP modes. The comparison of results between design A and design B is summarized in Tab. 3.
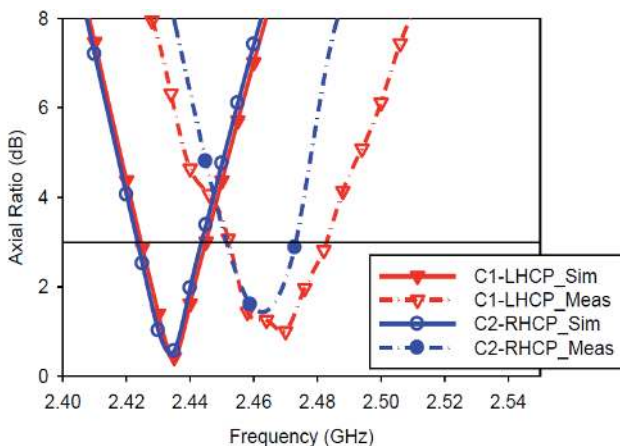

Fig. 11. Simulated and measured axial ratio of the modified structure.

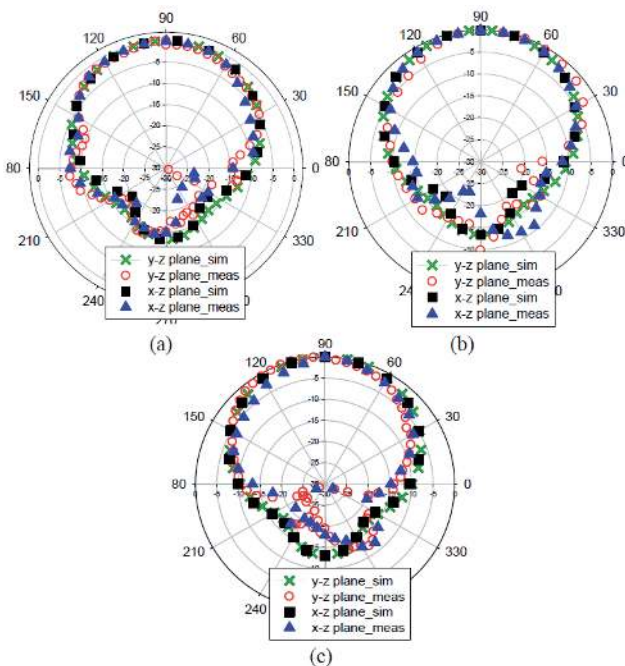**Fig. 12.** Measured normalized radiation pattern of the modified structure: (a) C1-LHCP at 2.47 GHz; (b) C2-RHCP at 2.47 GHz; (c) C3-LP at 2.49 GHz.

Conf.	Polar.	Meas. S_{11} (dB)		Meas. Bandwidth (MHz)			
		Design A	Design B	-10dB BW		3-dB BW (Axial Ratio)	
				A	B	A	B
C1-LHCP	LHCP	-16.48	-12.60	71	40	19	31
C2-RHCP	RHCP	-19.83	-15.25	84	48	18	22
C3-LP	LP	-24.06	-26.62	43	46	NA	

*A: Design A (Ideal diode) *B: Design B (PIN diode) *NA: Not applicable

Tab. 3. Comparison between Design A and Design B.

4. Conclusions

This paper presents a simple technique to achieve polarization reconfigurable antenna, with a fixed resonant frequency, that operates within WLAN frequency band. The study begins with the use of copper strips as a switch for proof of the concept. Then, minor modifications were made on the structure in order to accommodate the employment of real switches (RF PIN diode) and switching network. Using four switches embedded across the slits, the slit length is altered, hence producing a phase difference between two degenerated orthogonal resonant modes. Consequently, depending on the switching state, the polarization excited by the proposed antenna is capable to be reconfigured between three types - LHCP, RHCP or LP - that functioned at the same operating frequency. The results of reflection coefficient, axial ratio and radiation pattern are presented and comparisons are made between all different bias conditions. The results demonstrate good impedance matching, and broadside radiation pattern. The discrepancies of the results might be due to parasitic effects of the PIN diode, or fabrication tolerance. Small in dimension, and with unique features, the proposed antenna is potentially suitable in wireless applications for limited space and multipath rich environments; such as to serve as an access point in an indoor scenario for WIFI application.

Acknowledgements

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