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## A Compact Single-Feed Patch Antenna with Frequency and Polarization Diversity

*Abstract-* A new compact single feed square ring patch antenna using meandered  $\lambda/4$  transformer is designed, for frequency and polarization diversity. The proposed antenna is constructed from a square ring patch antenna, and two orthogonal meandered cascaded  $\lambda/4$  transformer (OMCT), incorporated with six switches for frequency and polarization reconfiguration purposes. The OMCT with switches is necessary to get good impedance bandwidth (BW) and axial ratio bandwidth (ARBW) for circular polarization state. In addition, it utilized to excite the antenna at two orthogonal locations, with equal magnitude and quadratic in phase, for achieving circular polarization mode at resonant frequencies 2.44GHz, 4.7GHz, and 5.6GHz. Moreover, it can excite the antenna as non-orthogonal modes for various other frequency bands, such as 2.89 GHz, 3.49 GHz, 4.9 GHz, 5.2GHz, 5.49GHz, 6.16GHz and 3.1GHz as linear polarization (LP) state. The proposed antenna has a compact low profile planar structure with area equal to 23mm<sup>2</sup>. Simulation and measured results show that the proposed antenna demonstrates a reasonable impedance bandwidth, and axial ratio in the circularly polarized state. Simulation results have been obtained from commercial CST-2014 Microwave Studio. The proposed antenna is fabricated for simulation result verification, and the implemented antenna is tested using R&S ZVL13 Vector Network Analyzer. The experimental confirms the simulation results.

**Keywords-** Patch antenna, antenna reconfiguration, circular polarization, axial ratio.

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### 1. Introduction

Recently, reconfigurable antennas gained remarkable attention and extensively used in many wireless applications. The development of the multifunctional antenna, which can be incorporate and serve different frequency and polarization, has been a good candidate for the recent communication system, due to its competence to improve the overall system's capability. Application fields that avail from the evolution of reconfigurable antenna comprise multi-input multi-output (MIMO) system, ultra wideband system anti-jamming secure communication, to conform to the ever-demanding requirement of such system. However, the system capacity can be doubled by exploiting the advantages of frequency reconfigurable antenna. In addition, the circular polarized antenna has widespread usage in contemporary wireless communication systems, such as GPS, WLAN, RFID, and radars, due to their capability to suppress multipath fading and enhance signal strength [1].

The frequency and polarization reconfiguration can be accomplished by manipulating the path of surface current distribution in somehow, or equivalently, the electromagnetic fields on the antenna's effective aperture [2].

Various structures and shapes have been reported in the literature to generate frequency reconfigurable antenna, most of these antennas are based on empirical tests, and switch among only fixed different modes [3-5].

Another issue with these techniques is that they have been mostly created for reconfiguring the antenna with only one band of operation [6-7]. This is an issue in many communication terminal devices, as they usually need to work on in at least two operating bands simultaneously.

Recently, a number of frequencies and polarization reconfigurable antenna have been reported [8-13], but most of these designs have ability to switch between circular polarization and linear polarization for just one or two frequency bands, with complex feeding structure, such as using Wilkinson power divider with quadrature coupler [8], or using a pair of rectangular loops with parasitic elements and several PIN diodes to switch between them [9].

In this study, a new structure of a reconfigurable patch antenna using  $\lambda/4$  transformers for frequency and polarization diversity is proposed. This proposed antenna has the potentiality for reconfiguring among four groups of resonant operating frequency bands. One group of bands is circularly polarized, whereas, other groups of

bands are linearly polarized. The circular polarized group is obtained by exciting two opposite edges of square ring patch antenna, in order to stimulate two orthogonal modes of operation, using two orthogonal meandered cascaded  $\lambda/4$  transformers (OMCT). Six switches are placed between apexes of OMCT  $\lambda/4$  transformers and square ring patch at different locations, altering switches state will disturb orthogonal mode of operation, therefore generate distinct non-orthogonal operation modes. Hence, distinguishable groups of linearly polarized bands will be generated. Based on this concept, an outstanding reconfigurable SRP antenna is designed. The suggested antenna can operate on one group of frequency band as circular polarized mode (CP), and three other groups of frequency bands as linear polarized mode (LP). The complete simulation of the proposed antenna is performed using the CST-2014 microwave studio. Simulation results and measurement shows good matching performance for all cases.

**2. Design Strategy and Operation Mechanism**

*1. Design a compact frequency and polarization diversity antenna.*

The proposed antenna is based on a square microstrip antenna that is required to operate at 2.1 GHz resonant frequency. The dimension of the reference conventional square microstrip patch antenna  $W$  is calculated as a following [14].

$$W = \frac{c}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}}$$

(1)

Where  $c$  is the free space velocity of light ( $3 \times 10^8$  m/s),  $\epsilon_r$  is a dielectric constant of substrate 4.3, and  $f_r$  is required resonant frequency.

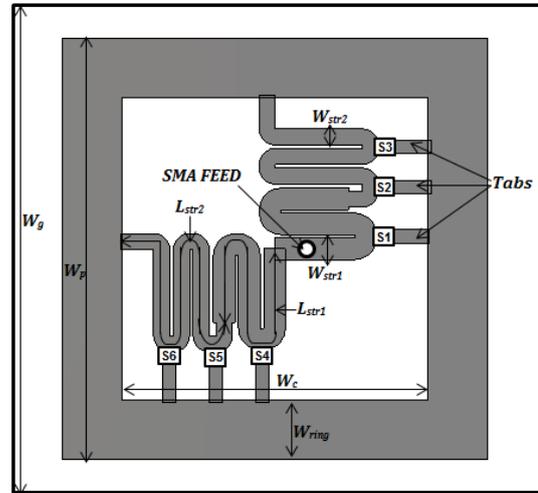
According to (1)  $W$  is selected to be equal to 43.89mm. The ground plane width is calculated according to the following formula [14].

$$W_g = 6h + W \tag{2}$$

Where  $h$  is substrate thickness 1.6mm, by using (2),  $W_g$  will be 53.45mm.

A square slot with maximum optimized dimensions  $Wc$  is embedded in the center of the patch, the microstrip square patch antenna (MSA) is then transformed to square ring, inserting slot in MSA has two main effects on size reduction. The first effect increases the path length of the surface current thereby reducing the resonance frequency [15]. The other effect is the slot can be exploited for implanting feeding network inside

the patch instead of built it outside. Consequently, realize a compact configuration. The final structure of the proposed antenna is depicted in Figure 1, and its dimensions are illustrated in Table 1.



**Figure1. Structure of the proposed antenna**

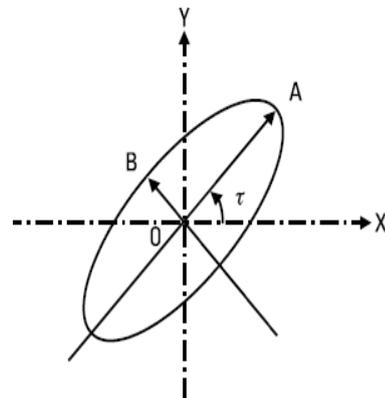
The performance of a circularly polarized antenna is characterized by its AR. The AR is defined as the ratio of the major axis to the minor axis; as shown in Figure2, in other words [15].

$$AR = \frac{\text{major axis}}{\text{minor axis}} = \frac{OA}{OB}$$

Where

$$OA = \left[ \frac{1}{2} \left\{ E_x^2 + E_y^2 + [E_x^4 + E_y^4 + 2E_x^2 E_y^2 \cos(2\Delta\phi)]^{1/2} \right\} \right]^{1/2} \tag{3}$$

$$OB = \left[ \frac{1}{2} \left\{ E_x^2 + E_y^2 - [E_x^4 + E_y^4 + 2E_x^2 E_y^2 \cos(2\Delta\phi)]^{1/2} \right\} \right]^{1/2} \tag{4}$$



**Figure 2: Elliptically polarized wave**

**Table 1: Dimension of the antenna depicted in Figure 1**

Antenna parameter	Dimension in mm	Antenna parameter	Dimension in mm	Antenna parameter	Dimension in mm
$W_g$	53.45	$W_{str1}$	1.64	$h$	1.6
$W_p$	32	$W_{str2}$	1.23	$\epsilon_r$	4.3
$W_c$	23	$L_{str1}$	18.59	<b>Total Antenna Volume</b>	23×23×1.6
$W_{ring}$	4.5	$L_{str2}$	21.5		

The tilt angle  $\tau$  of the ellipse is given by,

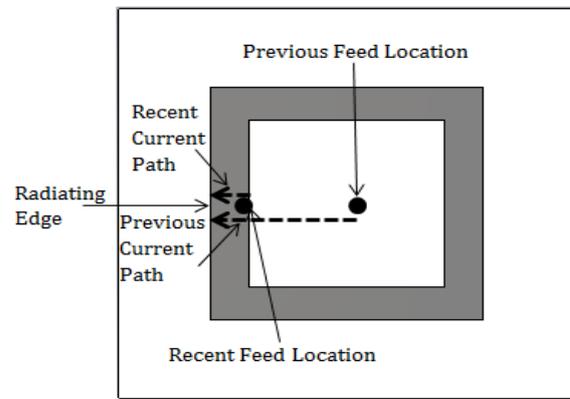
$$\tau = \frac{\pi}{2} - \frac{1}{2} \tan^{-1} \left[ \frac{2E_x E_y}{E_x^2 - E_y^2} \cos(\Delta\phi) \right] \quad (5)$$

For CP,  $OA = OB$  (i.e.,  $AR = 1$ ), whereas for linear polarization,  $AR \rightarrow \infty$ . Generally,  $AR = 3-6$  dB (numerical value 1.414 to 2) is acceptable for most of the practical applications [16]. A circularly polarized microstrip antenna (MSA) can be realized by exciting two orthogonal modes with equal magnitudes, which are in phase quadratic. The simplest way to obtain this by excites the antenna at an orthogonal position that is feed by  $1\angle 0^\circ$  and  $1\angle 90^\circ$  [16]. In this study, two orthogonal meandered cascaded  $\lambda/4$  transformers (OMCT) are used to excite the two orthogonal sides (modes) of square ring. The cascaded  $\lambda/4$  is necessary to get good impedance and axial ratio matching for circular polarized (CP). The meandered feed configuration is also exploited for connecting the feed line to ring patch at different locations, hence, generating four groups of reconfiguring bands corresponding to each feed location. The design steps can be described with the aid of Figure3 and 4 , as follows:

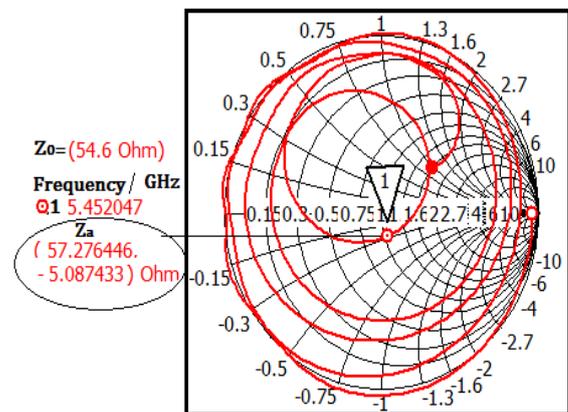
**Step1:** The  $\lambda/4$  transformer is used to provide matching between coaxial cable (SMA connector) and input impedance of square ring antenna [17]. However, primarily, the impedance of SMA connector  $Z_o$  and input impedance of square ring  $Z_a$  is determined from simulation results of smith chart for CST software package. Figure3a shows, direct connection SMA connector to the edge of square ring patch.

Figure 3b shows, that the  $Z_o$  and  $Z_a$  are equal to  $54.6\Omega$  and  $57.27\Omega$  respectively. The impedance is determined at resonant frequency 5.45GHz rather than 2.1GHz. This is because moving feed location from the center for conventional square patch antenna, toward the edge for square ring patch (Figure 3a); shorten the current path between feed location and radiating edges. Hence, shift the resonant frequency from 2.1GHz

to 5.45GHz, as shown in Figure3b. In addition, Figure3a shows the location of feed point is selected at the center of ringside because the antenna exhibits impedance almost with resistive part at the center of square ring patch as shown in Figure 3b.



(a)



(b)

**Figure 3: (a) Feed point at the ring edge without  $\lambda/4$  transformer (b) Smith chart for input impedance for Figure 3a**

**Step2:** After determining the  $Z_o$  and  $Z_a$  impedances, two stages of parallel OMCT is designed in order to accomplish matching between  $Z_o$  and  $Z_a$ . The characteristic impedance of each stage of the cascaded transformer shown in Figure 4 is calculated as a following [17].

$$\left(\frac{Z_0}{Z_{01}}\right)^2 = \frac{Z_{01}}{Z_{02}} = \left(\frac{Z_{02}}{Z_a}\right)^2$$

(5)

Where  $Z_{01}$  and  $Z_{02}$  are the impedances of the first and second stage of OMCT  $\lambda/4$  transformers.

From (5), the equations for  $Z_{01}$  and  $Z_{02}$  are simplified to [17]:

$$Z_{01\left(\frac{\lambda}{4}\right)} = Z_0^{\frac{3}{4}} Z_a^{\frac{1}{2}}$$

(6)

$$Z_{02\left(\frac{\lambda}{4}\right)} = \frac{Z_0}{Z_{01}} Z_a$$

(7)

Therefore, for  $Z_0=54.6\Omega$  and  $Z_a=57.27\Omega$ , using (6) and (7), yield  $Z_{01}=55.25\Omega$  and  $Z_{02}=56.57\Omega$ .

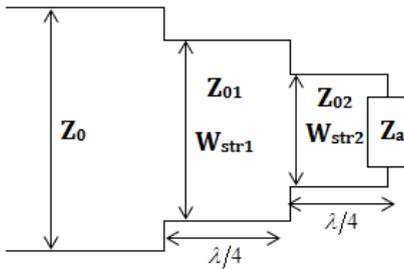


Figure 4: Cascaded quarter-wave transformer

**Step3:** In this step, the widths of cascaded quarter wave transformers  $W_{str1}$  and  $W_{str2}$  is calculated, depending on the results obtained from step2 for  $Z_{01}$  and  $Z_{02}$  respectively, according to the following formula [18].

$$Z_0 = \frac{87}{\sqrt{\epsilon_r + 1.41}} \ln\left(\frac{5.98 h}{0.8 W_{str1} + t}\right)$$

(8)

Where  $h$  is the substrate's thickness of 1.6 mm,  $t$  is the metallization thickness of 0.035 mm,  $\epsilon_r$  is a dielectric constant of substrate and for the FR4 substrate is 4.3, and  $W_{str1}$  is the microstrip line width. By using (8) and for  $Z_{01}=55.25\Omega$  and  $Z_{02}=56.57\Omega$ , the widths of first and second strip for the OMCT  $\lambda/4$  transformers are 2.57mm and 2.285mm, respectively. But since the two sides of the patch ring are feed with two parallel OMCT. Therefore, the width of each strip is divided into two. The  $W_{str1}$  and  $W_{str2}$  will be 1.28mm and 1.24mm, respectively. These values have been a little optimized using CST software for better return loss and axial ratio results,

therefore the final values for  $W_{str1}$  and  $W_{str2}$  will be 1.64mm and 1.23mm, respectively.

**Step 4:** Six collective switches S1, S2, S3, S4, S5, and S6 are implanted between taps and apex of the meandered feed line. A pair of switches S1-S4 are turned ON-OFF jointly also, S2-S5, and S3-S6, respectively. Initial results were obtained by using short and open circuits, to represent the switch ON and OFF respectively, instead of implanting PIN diode switch. Altering the switch states ON-OFF produce several distinct operating modes, therefore, several correspond distinguishable resonant frequencies as shown in Figure 5.

## II. Operational mechanism

Frequency and polarization diversity for the proposed antenna is feasible with dual feed to excite the antenna at two orthogonal feed points with an offset polarizer inside the ring, and implanting six switches between taps and apex of meandered feed line at a different location, to change the position of antenna's feed as shown in Figure 1.

The suggested antenna has two modes of operation in terms of polarization, which are; (1) circular polarized (CP) state, and (2) linear polarized (LP) state. In contrast, in terms of resonant frequency (return loss) has four operation modes.

The polarization mechanism of the proposed antenna is outlined with aid of Figure5, which depicts the surface current distribution for circular and linear polarization. The simulated surface current distribution for circular polarization (CP) case at resonant frequency 2.44 GHz, and for linear polarization (LP) case at 3.49 GHz, and for various current phases ( $\omega t = 45^\circ, 135^\circ, 225^\circ, \text{ and } 315^\circ$ ), is shown in Figure 5 a, and b, respectively. From Figure5 a, it is obviously seen that the surface current density rotating with phases ( $\omega t$ ), and comply the right hand rule, consequently, the antenna radiates right hand circular polarization (RHCP) signal. While in Figure 5.b, the current animates linearly through the antenna, hence the antenna radiates LP signal.

## 3. Result and Discussion

The proposed antenna's performance is analyzed and simulated using CST 2014 Microwave Studio, in term of return loss, axial ration, radiation pattern, and gain. Thereafter, for the simulation results validation, the suggested antenna has been fabricated, and the prototype is experimentally measured in terms of return loss,

radiation pattern, and gain using Rohde & Schwarz ZVA I3 vector network analyzer (VNA) (refer to Figure6).

### I. Return Loss ( $S_{11}$ )

The comparison between simulated and measured return loss for the four groups of resonant frequency is shown in Figure 7 (a-d). The suggested antenna with meandered configuration has potential to accomplish various multiband configurations correspond to various switch states shown in Figure6, rather than single frequency band at 2.1GHz with 32MHz impedance bandwidth, for direct feed line as shown in Figure 7e. With these frequency configurations the antenna is can operate on different sets of frequency bands in the range from 2.44GHz to 6.3 GHz, and is capable to meet the requirement of various wireless communication systems. Such as, LET 2300/2500, three operation bands in the IEEE 802.11WLAN standards, and three WiMAX operating bands 2.5/3.5/5.5.

A little discrepancy between simulated and measured results may be attributed to the cable and connectors were used in the measurement. Also, the antenna's manufacturing tolerance may be having an effect on measured results. However, the switch is modeled as metal pad with dimensions  $0.5 \times 0.5$ mm to represent ON-state in simulation measurement, while in fabrication process the switch is modeled as a lump solder.

The details of resonant frequencies and other frequency characteristics for the proposed antenna for various switch states are summarized in Table 2.

### II. Axial Ratio

Primarily, circular polarization can be realized by exciting two orthogonal modes with equal magnitude, which are quadratic in phase. The two feeds are positioned at center point of antenna's orthogonal edges, that are fed by  $1 \angle 0^\circ$  and  $1 \angle 90^\circ$ . Figure 8 shows, the axial ratio (AR) variation with frequency. The presented antenna exhibits CP for state 1, whereas LP for other rest states. The CP result is due to the effect of two feeds that are placed orthogonally to each other, specifically at the null location of the orthogonal modes; hence, a large isolation is obtained between feeds in this state. This concept does not work with other situations when any one of switches altered to ON state. For the circular

polarized state (state 1 in Figure 8), the axial ratio bandwidth (ARBW) remain below 6 dB with operating band of 750 MHz at 2.44GHz, 450 MHz at 4.7GHz and 440MHz at 5.5GHz. While the antenna with direct feed line and without OMCT, demonstrates circular polarization just for a single operating band at 2.4 GHz with ARBW 453MHz as shown in Figure 8 (CP DIRECT FEED), which is smaller than the ARBW for suggested antenna. The proposed antenna produces axial ratio bandwidth ARBW larger than return loss bandwidth RLBW in circular polarization state, so the antenna's operating band is limited by its RLBW, and not by ARBW.

### III. Radiation Pattern and Gain

The simulated and measured radiation pattern for Azimuth plane (XY-plane) and Elevation plane (XZ-Plane), for circular polarized configuration at two resonant frequencies 2.44GHz and 5.6 GHz. Furthermore, for linear polarized configuration at 3.4GHz and 5.6 GHz are plotted in Figure .9. It can be seen that the proposed antenna reveal broadside radiation pattern, with the degree of 3dB-beamwidth for both configurations (i.e., CP and LP configurations), and at the four corresponding resonant frequencies are shown in Table 3. The corresponding simulated and measured gain also declared in Table 3

## 4. Conclusion

A compact single feed frequency and polarization diversity antenna is proposed. The antenna is based on square microstrip patch antenna, a square slot with width  $W_c$  is embedded in the center of the proposed antenna to exploit it for miniaturizing purposes and implanting feeding network inside it. The feeding network consists of, two orthogonal meandered cascaded  $\lambda/4$  transformers (OMCT). Two orthogonal modes of operation are excited for realizing multiband circular polarization (CP) configuration. Six collective switches are implanted between square ring and apexes of OMCT  $\lambda/4$  transformers, for generating three non-orthogonal modes of operation, consequently generating three groups of multiband linear polarized resonant frequencies. The simulated and measured results verify the validity of suggested antenna.

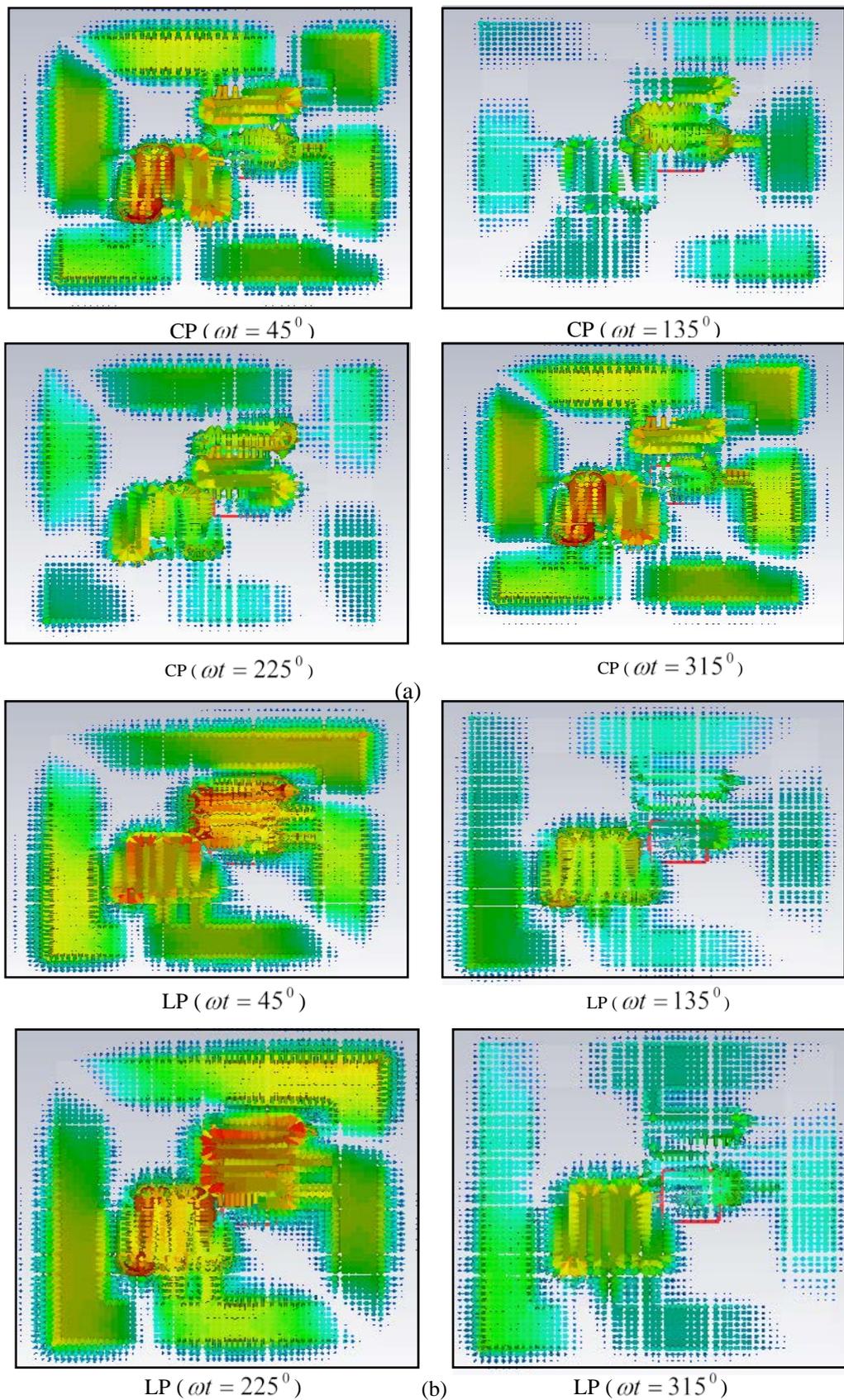


Figure 5: Simulated CST software's surface current density distributions for the antenna in Figure1 for; (a) Circular Polarization case at 2.44 GHz, (b) Linear Polarization case at 3.49 GHz

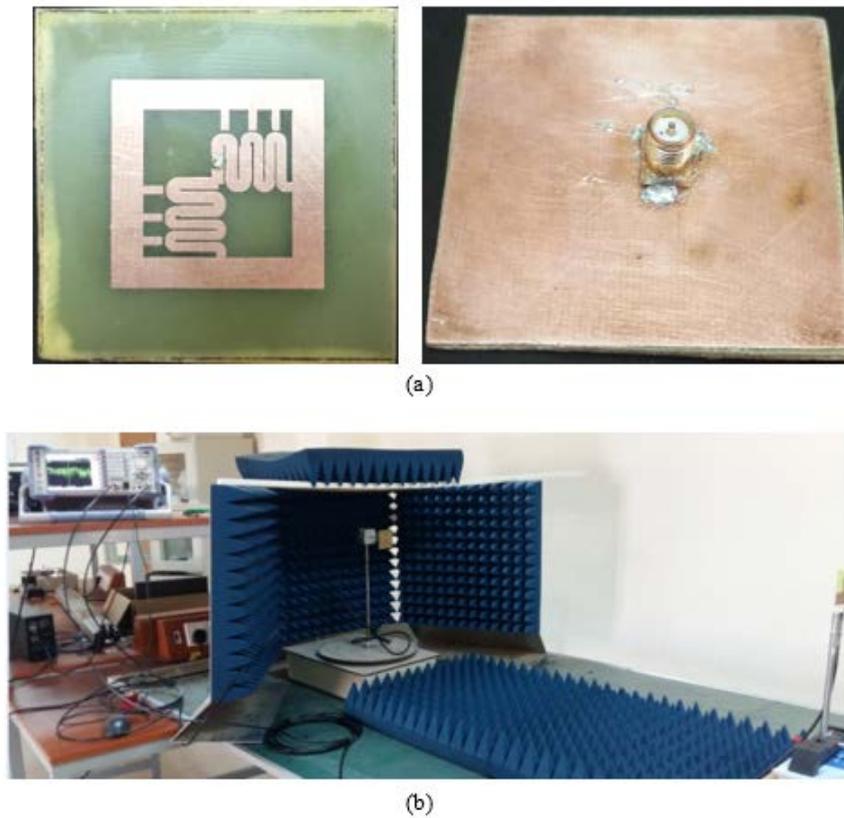


Figure 6: (a) Prototype of the antenna, (b) Radiation pattern measurement of the proposed antenna

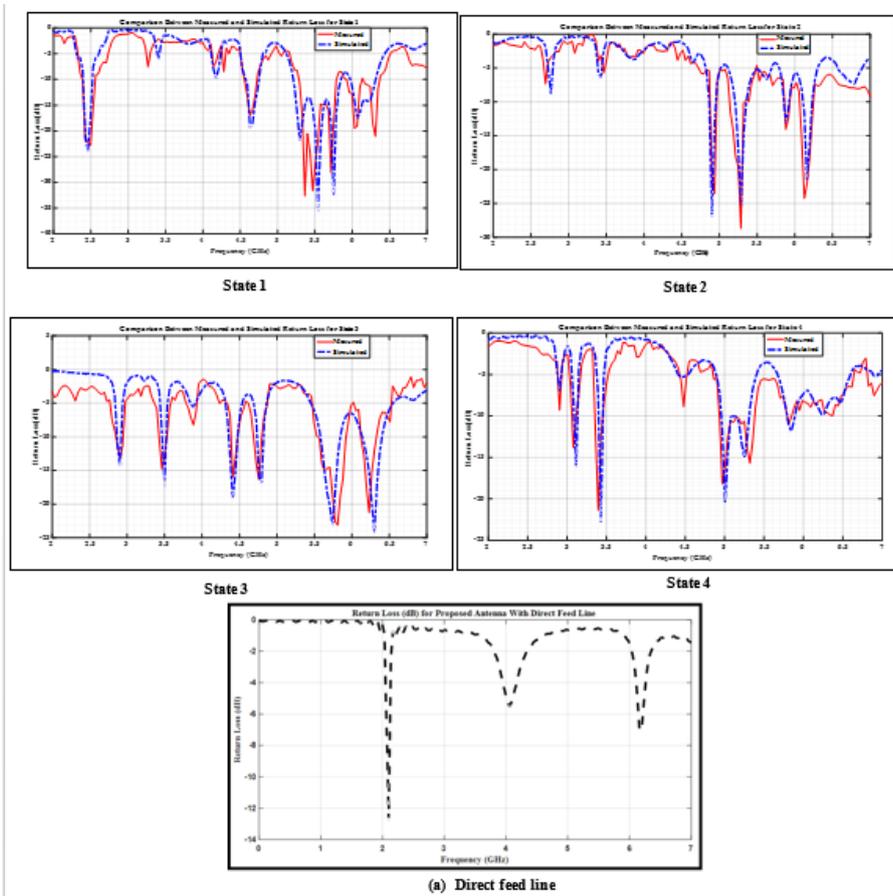


Figure 7: Comparison between simulated and measured return loss of proposed antenna for different switch configurations

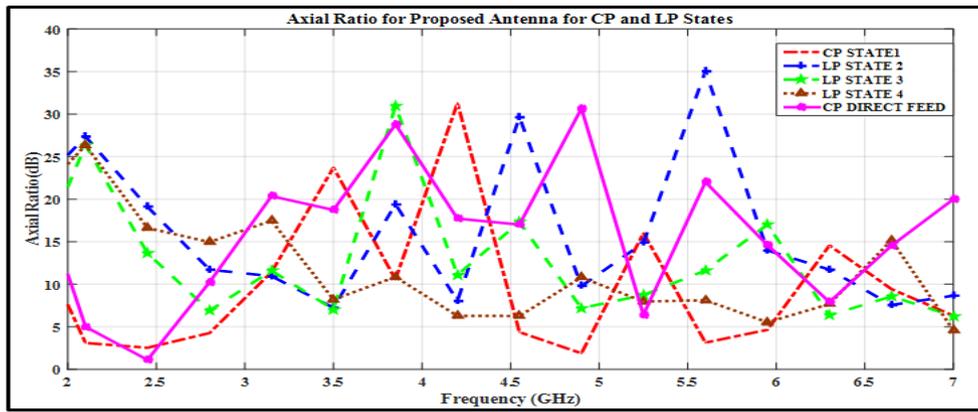
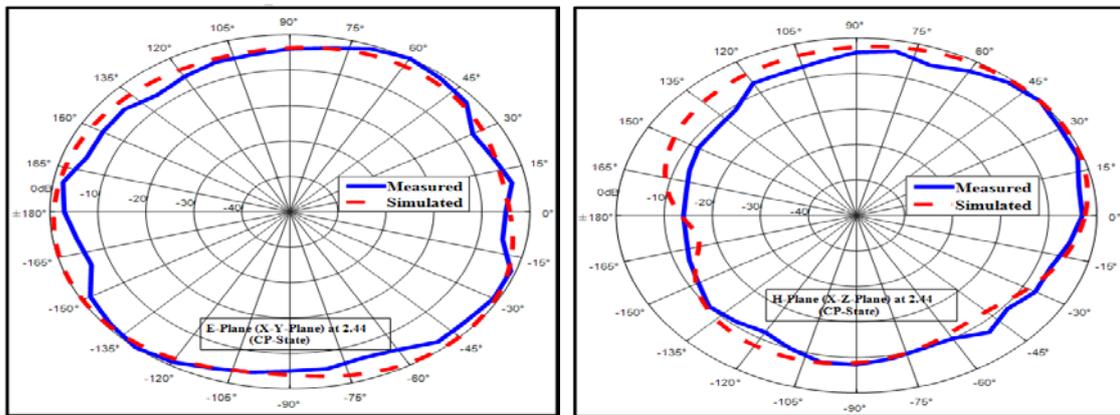


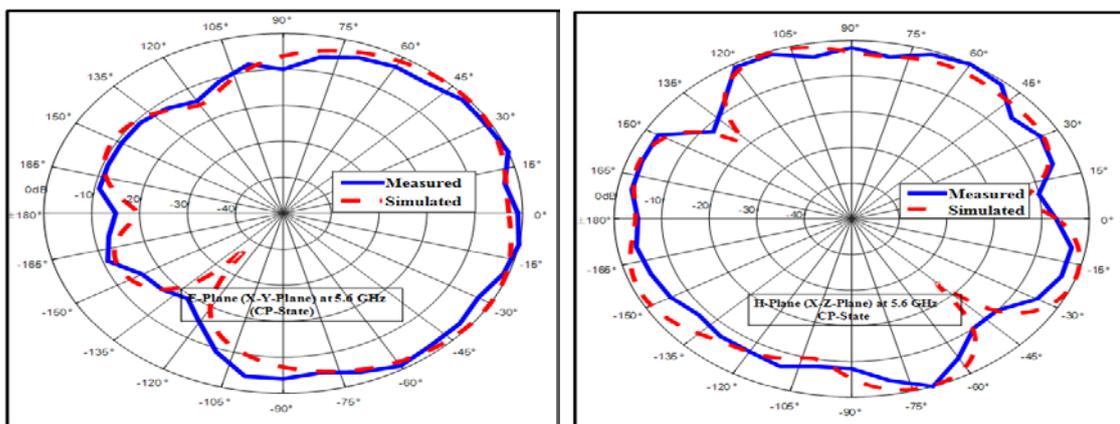
Figure 8: Simulated axial ratio of proposed antenna for different operating states.

Table 2: Proposed antenna's operating modes details

Switch States						Operating Band Characteristics								
S1	S2	S3	S4	S5	S6	Ant. Polar.	Resonant Frequencies (GHz)							
OFF	OFF	OFF	OFF	OFF	OFF	CP	2.44	4.7	5.5	6.2	-	-	-	-
ON	OFF	OFF	ON	OFF	OFF	LP	4.9	5.27	6.16	-	-	-	-	-
OFF	ON	OFF	OFF	ON	OFF	LP	2.89	3.49	4.4	4.7	5.7	6.2	-	-
OFF	OFF	ON	OFF	OFF	ON	LP	49.5	49.3	114	76.5	279.6	278	-	-
							3.1	3.42	5	-	-	-	-	-
							40.2	102	346.6	-	-	-	-	-



(a)



(b)

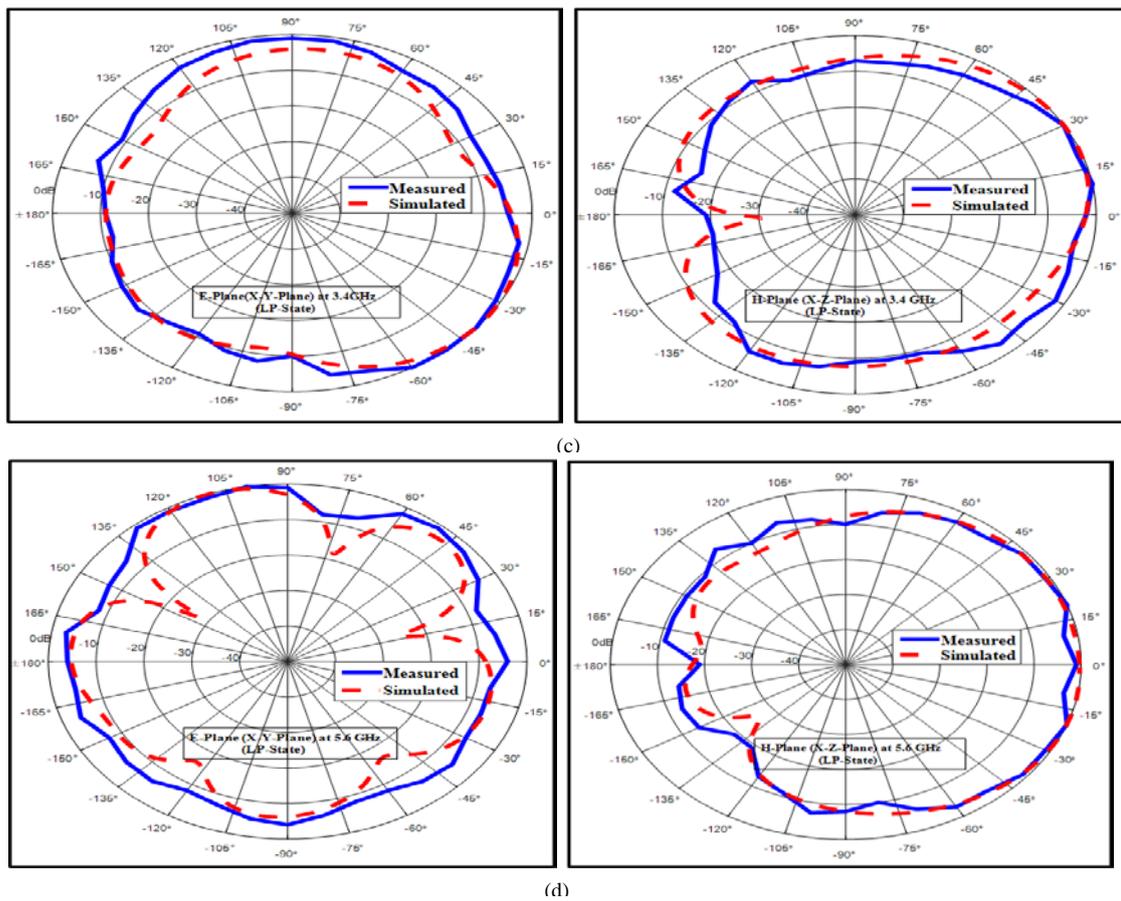


Figure 9: Simulated and measured radiation pattern of proposed antenna.at (a) 2.44GHz (CP), (b) 5.6 (CP), (c) 3.4GHz (LP), and (d) 5.6GHz (LP; left column X-Y\_plane, right column X-Z\_plane).

Table 3: Gain and half power beam width summary for the two operating mode configurations

	Resonant Frequency (GHz)	H-Plane HPBW		Gain(dBi)	
		Simulated	Measured	Simulated	Measured
Circular Polarized	2.44	106.2°	95°	5.56	4.9
	5.6	134°	110°	6.58	5.3
Linear Polarized	3.4	79.4°	88°	6.78	6.5
	5.6	114.8°	100°	6.34	5.8

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