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RECONFIGURABLE PATCH ANTENNAS WITH FOUR-POLARIZATION STATES AGILITY USING DUAL FEED PORTS

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Abstract—Polarization reconfigurable patch antennas which can switch polarization states among vertical and horizontal linear polarization (LP), left- and right-hand circular polarization (CP) is demonstrated in this paper. The original orthogonal linear polarized antenna is a square patch fed by two ports at the adjacent edges. CP operations can be activated by introducing perturbations at the opposite corners of the patch. If a diode is loaded on every perturbed corner, the antenna polarization states can be alternated by controlling the bias voltage of two PIN diodes. Perturbation elements can be cut on the patch or on the ground. Two antenna prototypes are suggested, simulated, and verified by experiments. These polarization reconfigurable antennas have good antenna performances of low reflection coefficient, axial ratio, and cross-polarization (X-pol), and high isolation between two LP operations. They have concise structure with only two PIN diodes being required. The two reconfigurable antennas are low cost and can be integrated easily in wireless communication systems.

1. INTRODUCTION

With the rapid development of wireless communication systems, such as wireless local area network (WLAN), multi-input and multi-output (MIMO) and personal communications service (PCS), radio frequency terminals with multiple functions are required to adapt to various standards and systems. Reconfigurable antennas with frequency adjustability, radiation pattern selectivity, and polarization diversity are good candidates for these applications [1, 2]. Reconfigurable

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antennas are also the components of front-ends for cognitive radio systems [3]. Antennas with polarization reconfiguration can realize frequency reuse, which expands the capacity of communication systems. Polarization agility antennas can also alleviate the disadvantageous influence caused by multipath effects.

Some polarization reconfigurable antennas have been proposed. A square slot antenna can change between two linear polarization (LP) states by controlling the feed structure [4]. Generally, circular polarization (CP) operations are preferred in most applications. Reference [5] proposed a reconfigurable perturbed square slot antenna that could operate at left-hand CP (LHCP), right hand CP (RHCP), or LP. The polarization agility was controlled by four diodes with complicated bias circuits. Patch antennas are good candidates to realize agile polarization states. One method is to change the feed network by using diodes [6–8]. This scheme demands equivalent circuit parameters of the diode to design the impedance matching network. The equivalent circuit parameters are commonly not accurate enough. Another one is to control switches loaded at the perturbation areas. The perturbations are usually small parts truncated from or added to a square [9–11], a circular [12] or a triangular patch [13]. Perturbations can also be various slots on the patches [14–17]. No matter what kind of perturbations are adopted, bias circuits including capacitors and vias are required. For example, reference [15] proposed a cross-slot rectangular patch antenna operating at two orthogonal LPs and a right-hand CP with three capacitors and two diodes being required. Recently, it was suggested that perturbation elements could also be cut on the ground and no extra bias circuit would be required for switching on the PIN diodes [18, 19].

Most of those reconfigurable antennas can switch polarization senses between two CP states, or among one linear and two CP states. Reference [7] proposed an aperture coupled square patch antenna with quadric-polarization agility. The polarization agility was realized by controlling eight PIN diode switches loaded on the feed network, in which complicated bias circuits were required. Reference [20] suggested theoretically that four polarization states could be obtained by two feed ports. However, the probe-feed and four diodes embedded in the substrate made it difficult to be fabricated.

In this paper, the reconfigurable patch antennas with four-polarization states agility are investigated with only two PIN diode switches being used and no extra areas and no elements for the direct current circuits being required. These reconfigurable antennas with concise structure are easy to be manufactured and can be used in various wireless communication systems. Section 2 demonstrates the design principle and the configurations of two kinds of polarization reconfigurable patch antennas with the perturbation elements on the patch and on the ground. Section 3 describes the simulated and experimental performances of the two patch antennas in details. The conclusions are drawn in Section 4.

2. DESIGN PRINCIPLE AND ANTENNAS CONFIGURATIONS

2.1. Original LP Patch Antenna

The original antenna is a square patch fed by two ports at two adjacent edges as shown in Figure 1. The square patch antenna has the side length of L and is printed on a substrate with a thickness of h. The orthogonal linear polarization waves will be produced when the patch is fed at two adjacent edges. TM_{01} mode is excited when the patch is fed at the center of the bottom edge, which is denoted as the V-port. The two edges parallel to x direction are the radiating edges. The operation frequency is mainly determined by the length L from the following formula,

$$f_{01} = \frac{c}{2L\sqrt{\varepsilon_e}} \tag{1}$$

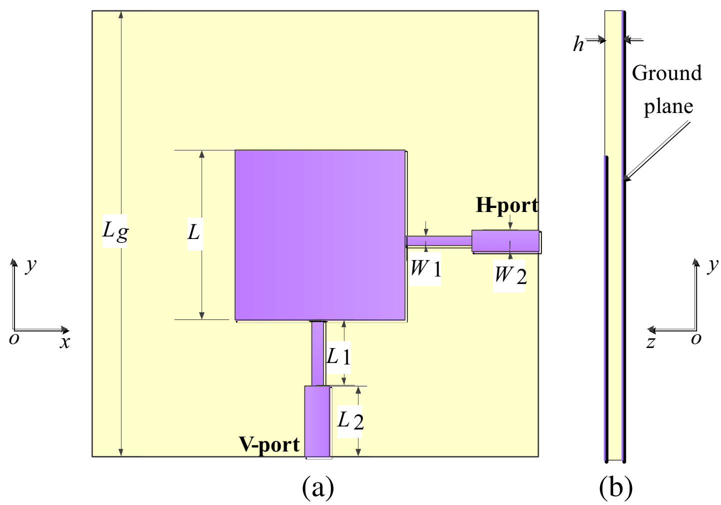


Figure 1. The orthogonal linear polarizations patch antenna. (a) Front view. (b) Side view.

where c is the electromagnetic wave speed in free space and ε_e the effective relative dielectric constant of the substrate. Two sections of $\lambda_g/4$ impedance transformers are applied to convert the input impedance at the feed port of the patch's edges to $50\,\Omega$. The lengths and widths of the two $\lambda_g/4$ transformers are L_1, L_2 and W_1, W_2, respectively.

The current distribution of TM_{01} mode simulated by HFSS software [21] is plotted in Figure 2(a). The current distribution on the left edge is a little higher than that on the right edge because of the existence of another feedline, which has no apparent influences on the antenna's performances. This fact will be verified by means of simulations and experiments in the following sections. Similarly, TM_{10} mode is activated when the patch is fed at the right edge, which is defined as the H-port. A current distribution orthogonal to the V-port feedline is activated as shown in Figure 2(b). The two edges parallel to y direction are the radiating edges and the operation frequency is also determined by formula (1).

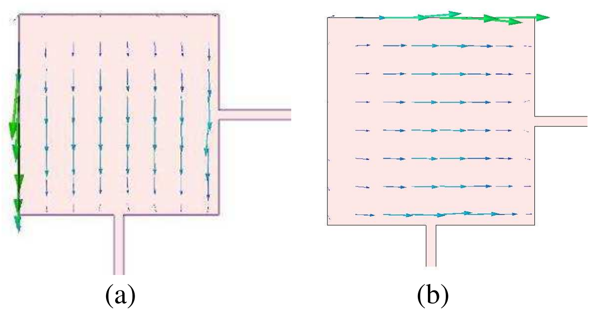


Figure 2. Orthogonal linear polarizations patch antenna and the current distributions. (a) Current distribution for V-port feed. (b) Current distribution for H-port feed.

2.2. Polarization Agility Antenna with Perturbations on the Patch

Two modes of the square patch, TM_{01} and TM_{10}, have the same operation frequencies. When two opposite corners with the side length of L_s are truncated off as shown in Figure 3(a), two resonant frequencies of $f_0 + \Delta f$ and $f_0 - \Delta f$ for two modes of TM_{01} and TM_{10} will be activated. A proper L_s would excites $90°$ phase difference and a CP wave is excited [22]. A LHCP wave will be excited if the patch is fed at the H-port while a RHCP one will be activated when the patch

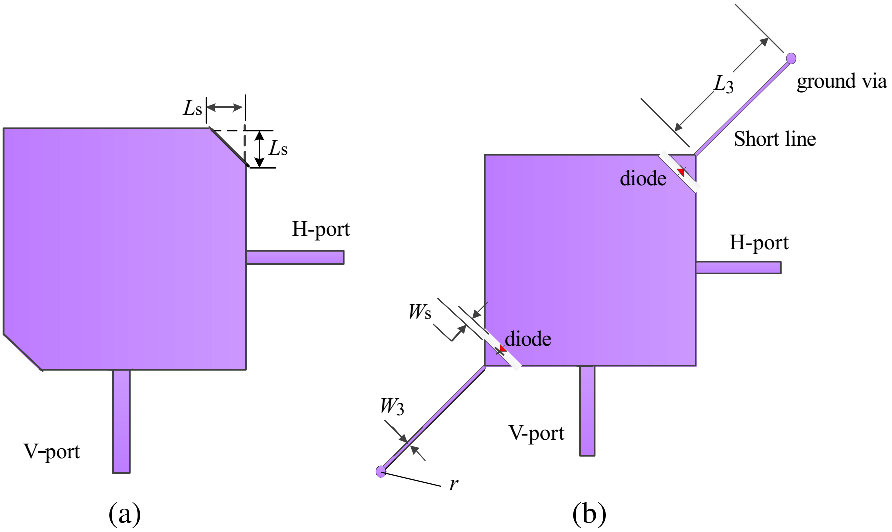


Figure 3. The antenna configuration of four-state polarizations with perturbation on the patch. (a) Orthogonal CP patch. (b) Four-polarization agility patch.

is fed at the V-port.

Four-state polarizations agility would be realized if diode switches are loaded on the slots between the patch and the truncated corners, as is shown in Figure 3(b). The size of the slot width W_s is designed to locate the diode. The truncated corners can be used as the isolated areas so the capacitors are not required and the structure of the reconfigurable antenna is simplified. There is a short line of quarter waveguide length with high impedance at each truncated corners with a via at everyone's bottom. The short lines have the length of L_3 and the width of W_3. The radius of the via is r. The short lines act as the ground for the direct current. For the radio signal, the short line presents open circuits characteristics at the vertex of the truncated corner. So the influences of the direct current on the radio signal can be neglected.

When the diodes are switched off, the radio frequency current flowing to the truncated triangle parts closes to null. The LHCP and RHCP waves will be activated. Figure 4 shows the current distribution on the patch fed at the H-port. It can be seen that the current rotates clockwise with time and a LHCP wave is excited. Correspondingly, RHCP wave can be radiated when the patch is fed at the V-port. When the diodes are switched on, the current will be distributed on

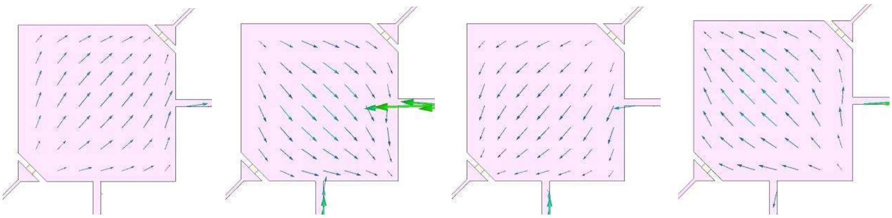


Figure 4. Current distribution on the patch fed at H-port for LHCP wave. (a) 45°, (b) −45°, (c) −135°, (d) −225°.

the whole square patch including the two truncated corners as shown in Figures 2(a) and (b). And the orthogonal linear polarization waves will be excited simultaneously.

2.3. Polarization Agility Patch with Perturbations on the Ground

From the cavity model theory [23], the conducting patch and the ground plane enclose a cavity with open boundary at the perimeter. The upper and lower planes are electric walls while the four open surrounding planes can be regard as magnetic walls. Thus perturbation element for CP operations can also be on the ground just below the opposite corners of the patch, as shown in Figure 5(a). The feed

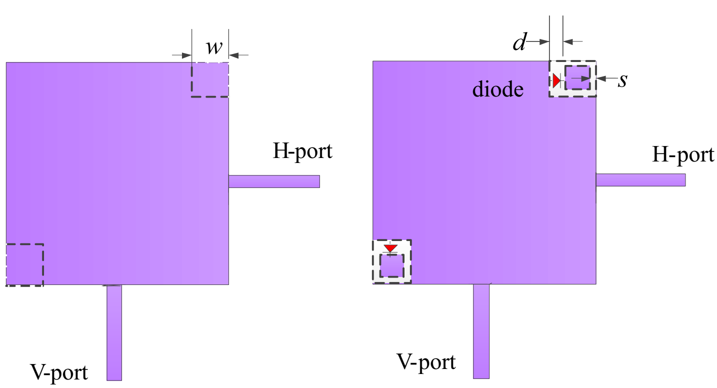


Figure 5. The antenna configuration of four-state polarizations with perturbations on the ground. (a) Orthogonal CP patch. (b) Four-polarization agility patch.

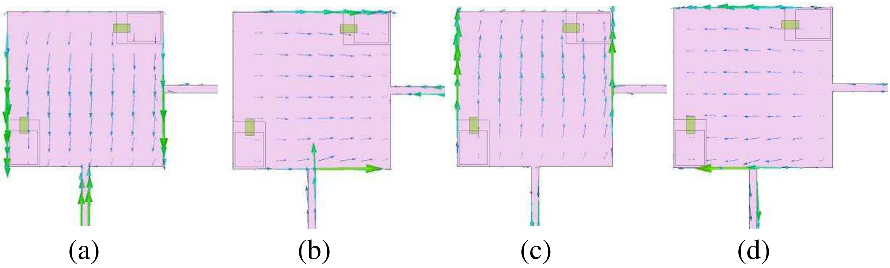


Figure 6. Current distribution on the patch fed at the V-port for RHCP wave. (a) 0°, (b) 90°, (c) 180°, (d) 270°.

structure is the same as the original patch in Figure 1. Two small square patches with the side length of w on the ground plane are cut out. LHCP will be excited when the H-port is fed while RHCP will be operated when the V-port is fed.

The antenna configuration with four-state polarizations agility is suggested in Figure 5(b). A square ring slot with side length w and slot width s is located just below the opposite corners of the square patch. The width of the slot with the diode being loaded is expanded to d in order to allow for the placement of the diode. The antenna operates on two orthogonal linear polarizations when the two diodes are on switch-on states simultaneously. When the diodes are on the switch-off states, the patch operates as LHCP if the feed is at the H-port, and it works as RHCP if the feed is at V-port. Figure 6 plots the current distributions on the patch fed at the V-port. It can be seen that the current rotates counterclockwise with the time and the RHCP wave is activated.

In this antenna configuration, the ground plane is divided into three portions by the two square ring slots. The DC bias voltage on the two diodes can be supplied directly with no other biasing elements and no high impedance lines being required. This reconfigurable antenna avoids the need for the isolation of the DC area, which not only simplifies the antenna structure but also reduces the influences on the antenna radiation performances.

3. SIMULATIONS AND EXPERIMENTS

The substrate has a relative dielectric constant of 2.65 and a thickness of 0.8 mm for the two polarization reconfigurable antennas. The diodes of BAR64-02v, with a size of $1.0\,\text{mm} \times 0.8\,\text{mm}$, are used as the switches. In HFSS software simulations, the diode is equivalent to a resistor of

2.1 Ω on the switch-on status and is modeled as a capacitor of 0.17 pF on the switch-off status according to the company data sheet. The final geometrical dimensions are designed by HFSS software.

3.1. Polarization Reconfigurable Patch with Perturbations on the Patch

The structure of the reconfigurable four-polarization antenna with the perturbations on the patch and its geometrical parameters are plotted in Figure 7. The operation frequency is central at 5.8 GHz. The simulated geometrical parameters are as follows, $L = 15\,\text{mm}$, $L_1 =$

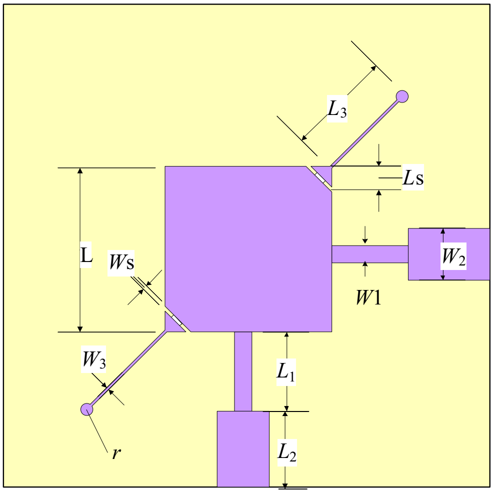
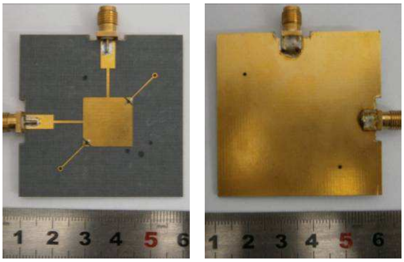


Figure 7. The structure and geometrical parameters of the reconfigurable antenna with perturbations on the patch.



(a) (b)

Figure 8. Pictures of the reconfigurable antenna with perturbation on the patch. (a) Front view; (b) back view.

9.0 mm, $W_1 = 0.7$ mm, $L_2 = 8.5$ mm, $W_2 = 4.3$ mm, $L_s = 2.7$ mm, $W_s = 0.5$ mm, $L_3 = 9.3$ mm, and $W_3 = 0.3$ mm. The radius r of the two ground vias is 0.5 mm. The size of the antenna is 50 mm $\times$ 50 mm.

Figure 8 is the front and the back pictures of the antenna. The S-parameters were measured by Agilent VNA8722ES and the radiation characteristics were measured in the microwave chamber.

3.1.1. Performances of LPs

The measured and simulated S_{11} responses versus frequency for the H- and V-ports are plotted in Figure 9. The measured center frequencies are all at 5.79 GHz for both LP states. The S_{11} at the center frequency and -10 dB bandwidth for the V-port are -22.8 dB and 140 MHz while those for the H-port are -25.6 dB and 160 MHz, which is much better than those of the simulation. The main reason is probably due to the imprecise model of the diode being simulated in HFSS software and the inexact value of the substrate dielectric constant. From Figure 10, the measured isolation is higher than 15 dB within the operation band, which is a little lower than the simulated result. Figure 11 plots the simulated and measured E-plane patterns for the horizontal and the vertical polarizations at 5.78 GHz. The maximum radiation direction shows a shift due to the asymmetric configuration. For the H-port, the measured gains and cross polarizations in the 16° direction are 7.5 dBi and -3.3 dBi, while those in the 0° direction are 6.9 dBi and -6.5 dBi. For the V-port, the measured gains and cross polarizations in the 26° direction are 7.4 dBi and -6.9 dBi, while those in the 0° direction are 4.6 dBi and -7.7 dBi.

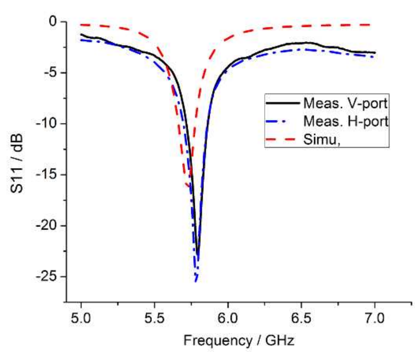


Figure 9. Measured S_{11} of the linear polarization states.

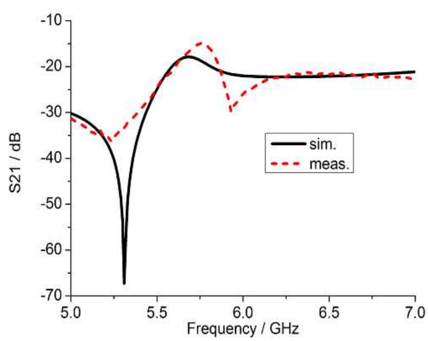


Figure 10. Measured S_{21} of the linear polarization states.

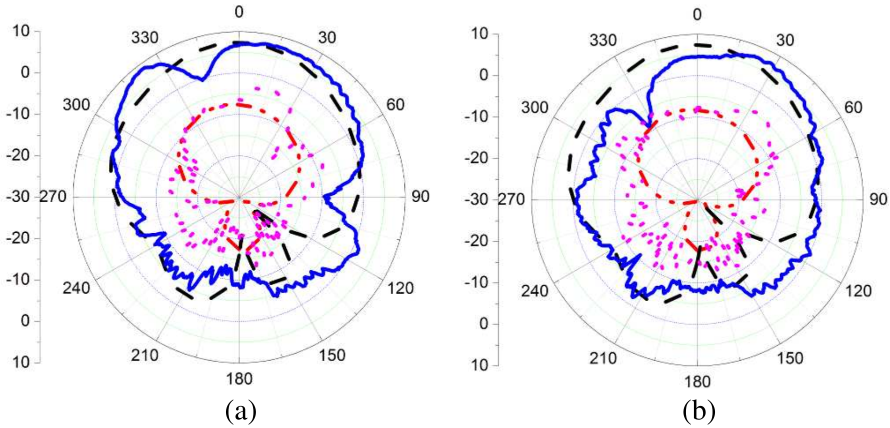


Figure 11. Simulated and measured E-plane pattern for the LP operations at 5.78 GHz. –– –– –– Co-Pol/Sim., —— Co-Pol/Meas., –··–··– X-Pol/Sim., ······ X-Pol/Meas.. (a) H-port; (b) V-port.

3.1.2. Performances of CPs

The measured and simulated S_{11} versus frequency for the circular polarizations are shown in Figure 12. The center frequencies are at 5.87 GHz, and the bandwidths of the S_{11} for less than -10 dB are about 265 MHz for both left- and right-hand CP waves. The measured minimum axial ratios for the left- and right-hand CP waves are 1.5 dB and 1.7 dB while the 3 dB bandwidths are 40 MHz and 45 MHz, respectively, as illustrated in Figure 13. Figure 14 is the

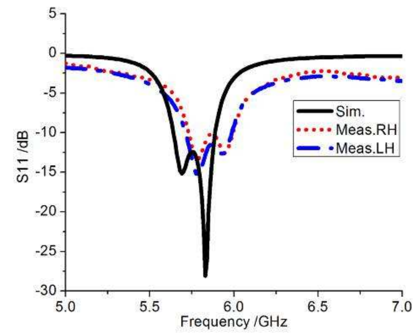


Figure 12. Simulated and measured S_{11} of the CPs.

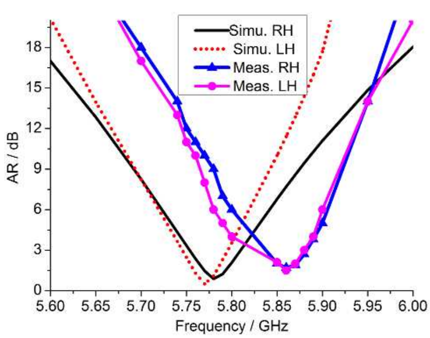


Figure 13. Simulated and measured AR of the CPs.

measured patterns for the left- and right-hand CP waves at 5.86 GHz with a 7.0 dBi gain being achieved. The circular-polarization radiation patterns are measured using spinning linear polarized transmitting antenna. The ripples show the axial ratio versus the angles.

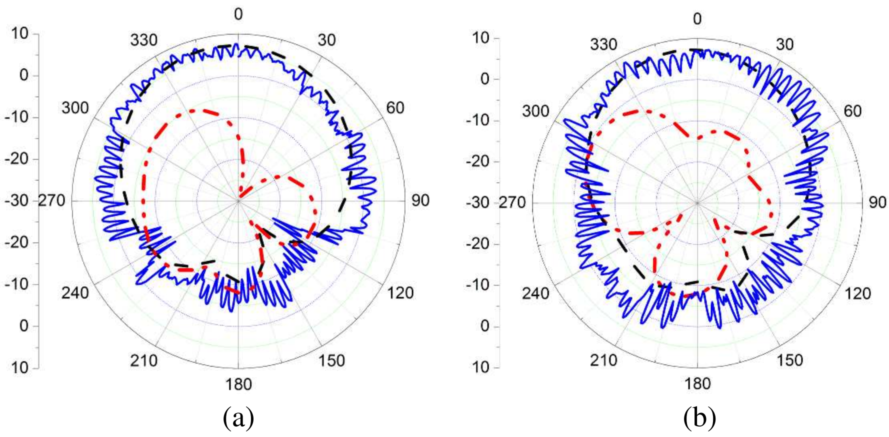


Figure 14. Simulated and measured E-plane patterns for CPs operations at 5.86 GHz. —— —— —— Co-Pol/Sim., —— Co-Pol/Meas., –··–··– X-Pol/Sim.. (a) H-port, LHCP; (b) V-port, RHCP.

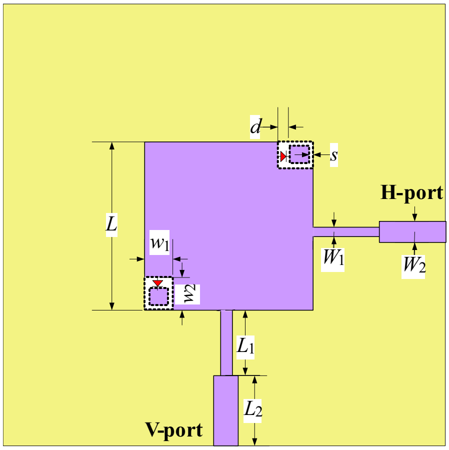
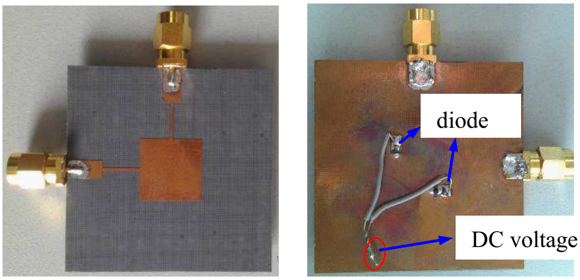


Figure 15. Structure and geometrical parameters of the reconfigurable antenna with perturbation on the ground.

3.2. Reconfigurable Antenna with Perturbations on the Ground

The structure of the reconfigurable four-polarization antenna with the perturbations on the ground and its geometrical parameters are plotted in Figure 15. All the geometrical parameters are as follows: $L = 15\,\text{mm}$, $L_1 = 9.0\,\text{mm}$, $W_1 = 0.7\,\text{mm}$, $L_2 = 8.5\,\text{mm}$, $W_2 = 4.3\,\text{mm}$, $w_1 = 3.1\,\text{mm}$, $w_2 = 4.5\,\text{mm}$, $s = 0.2\,\text{mm}$, $d = 1\,\text{mm}$. The pictures of the manufactured reconfigurable antenna are shown in Figure 16.



(a) (b)

Figure 16. Pictures of the reconfigurable antenna with perturbation on the ground. (a) Front view; (b) back view.

3.2.1. Performances of LPs

Figure 17 is the simulated and measured S_{11} for the LP operations. For the vertical and the horizontal polarizations, S_{11} is $-27\,\text{dB}$ at the center frequency of 5.66 GHz with the $-10\,\text{dB}$ bandwidth of about 170 MHz. Figure 18 is the simulated and measured isolations for the orthogonal LP operations. A good isolation of 16 dB within the operation band is measured, which is a little better than the simulated results.

The simulated and measured patterns of co- and cross-polarizations for the LP operations at the center frequency of 5.66 GHz are shown in Figure 19. The measured gains in the main radiation direction for both ports of H and V are 7.5 dBi, while those of the simulation are 7.8 dBi. However, the measured cross-polarization levels deteriorate to 0.3 dBi, while those of the simulation are about $-9\,\text{dBi}$. The main reason probably lies in the model error of the active element in HFSS software and the measurement errors.

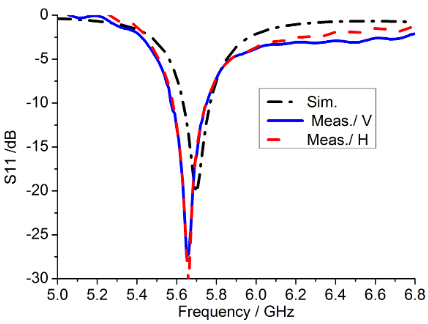


Figure 17. Simulated and measured S_{11} of the LPs.

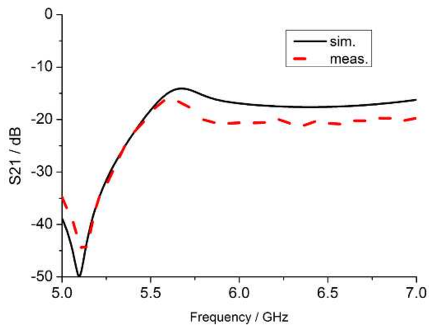
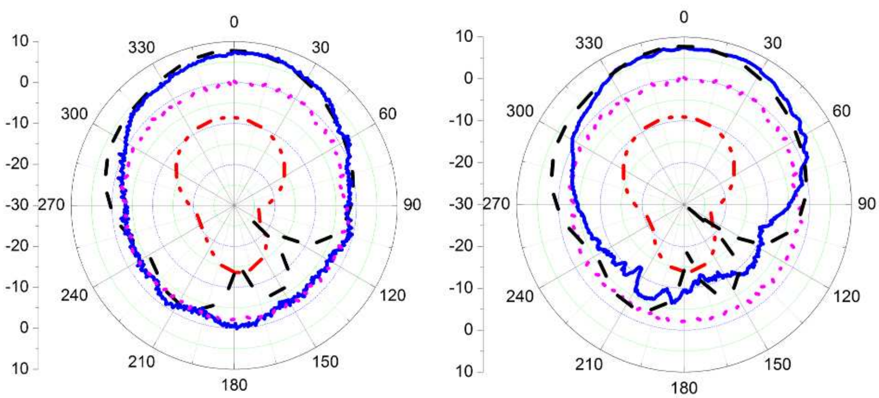


Figure 18. Simulated and measured S_{21} of the LPs.



(a) (b)

Figure 19. Simulated and measured co- and cross-polarization patterns for the LP operations at 5.66 GHz. —— —— —— Co-Pol/Sim., − − − − − −− Co-Pol/Meas., − − · · −− X-Pol/Sim., ······ X-Pol/Meas.. (a) H-port; (b) V-port.

3.2.2. Performances of CPs

The measured S_{11} for the CP operations are plotted in Figure 20 with the −10 dB bandwidth of 330 MHz. Figure 21 shows the simulated and measure axial ratios for the circular polarization operations. It can be seen that the measured minimum axial ratios are 0.9 dB and 1.0 dB for the LHCP and RHCP at 5.8 GHz in the main radiation directions, while the 3 dB bandwidth of 100 MHz for both CPs is from 5.75 GHz to

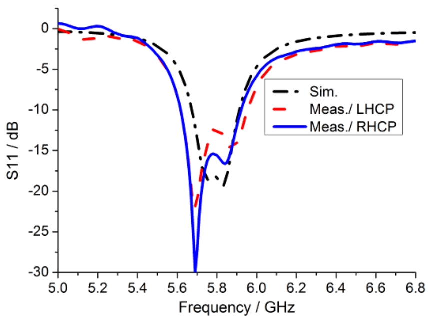


Figure 20. Measured S_{11} of the CP operations.

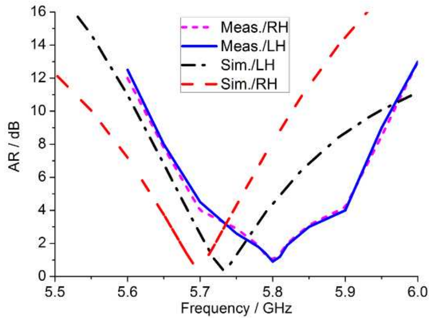
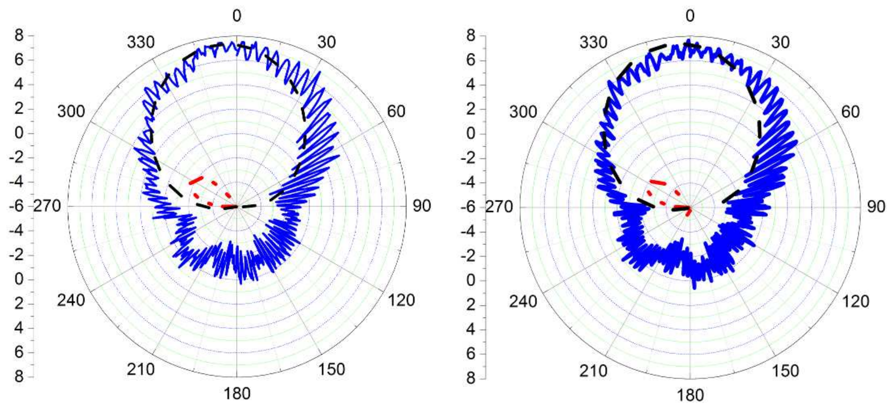


Figure 21. Simulated and measured AR for the CPs.



(a) (b)

Figure 22. Simulated and measured E-plane patterns for CPs operations at 5.8 GHz. −− −− −− Co-Pol/Sim., — — Co-Pol/Meas., –··–··– X-Pol/Sim.. (a) H-port, LHCP; (b) V-port, RHCP.

5.85 GHz. The frequency shift between simulated and measured results is thought to be caused by the manufacture errors, the inaccuracy of the dielectric constant of the substrate and imprecise model of the diode used in the simulation. Figure 22 gives the measured E-plane patterns for the LHCP and RHCP operations. The measured gains for both CP modes are all 7.4 dBi, which agrees well with the simulated results.

4. CONCLUSIONS

Polarization reconfigurable patch antennas with four polarization agility are investigated in this paper. The dual-fed antenna can operates on two orthogonal linear polarizations simultaneously and on two orthogonal circular polarizations alternatively by controlling the perturbation elements on a square patch antenna. Two antenna configurations, the perturbation elements on the patch and on the ground, are proposed. It is noticed that the loaded diodes have obvious influence on the CP axial ratio and have a little influence on the input impedance characteristics and the radiation pattern. The proposed two polarization reconfigurable antennas have concise structure and simple controlling circuits with only two PIN diodes. Both antennas have good characteristics, including the input impedance match, gain, cross-polarization, the isolation between the two orthogonal LPs, and the axial ratio of two orthogonal CP operations. The one with the perturbations on the ground has more simple structure and a better axial ratio characteristic. These two designs provide capabilities that are suitable for modern wireless communication systems.

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