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A Simple Design of Polarization Reconfigurable Fabry-Perot Resonator Antenna

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ABSTRACT This paper presents a simple design of high gain Fabry-Perot (FP) antenna with polarization diversity. The proposed antenna is composed of a reconfigurable microstrip patch, a partially reflective surface, and a planar metallic reflector. By electrically controlling the ON/OFF states of two p-i-n diodes, the polarization of the antenna can be switched among dual-sense circular polarization and single linear polarization. Notably, the biasing wires, which are generally used in designing reconfigurable antennas, are not necessary in the proposed design. Thus, the undesirable effects of the biasing wires on the antenna's operating characteristics can be eliminated. An antenna prototype, whose overall dimensions are $2.0\lambda \times 2.0\lambda \times 0.6\lambda$ at the center operating frequency, is fabricated and measured to validate the design concept. The measured overlapped bandwidth for -10 dB $|S_{11}|$ and 3-dB AR bandwidths of all polarization states is 4% (7.3–7.6 GHz). The desired radiation patterns are also observed with a peak gain of 15.1 dBi.

INDEX TERMS Fabry-Perot, high gain, polarization reconfigurable, PRS.

I. INTRODUCTION

Polarization reconfigurable antennas have attracted lots of attention among the antenna researchers due to their advantages of enhanced channel capacity and suppressed channel interference [1], [2]. Antennas with both linear (LP) and circular polarizations (CP) are useful in different electromagnetic enviroments. Various reconfigurable antennas have been designed using microstrip patch structures [3]–[7]. Metasurface (MS) has also been extensively studied recently in designing reconfigurable antennas [8]–[10]. In fact, these antennas are featured by low-profile configuration, but narrow operating bandwidth (BW). Better performances can be achieved in [11]–[16], in which the radiating elements are constructed by dipole or dielectric resonator structures.

The gain of the aforementioned designs [3]–[16] is still limited to less than 10 dBi. Thus, they may not be suitable for some application scenarios, where both high gain and polarization reconfigurability are strongly demanded. The most common method to enhance the gain of an antenna is to utilize a partially reflective surface (PRS) placed at a proper distance from the ground plane of the radiating element [17]. This antenna type is known as Fabry-Perot (FP) resonator antenna. Several FP resonator antennas with polarization diversity have been proposed in literature [18]–[22]. However, each antenna suffers from a typical drawback. To the best of the authors' knowledge, there is only one FP design with both dual-sense CP and single LP operating modes presented in [22].

This paper presents a FP antenna whose polarization can be switched among right-hand CP (RHCP), left-hand CP (LHCP), and LP modes. The proposed antenna consits of a reconfigurable patch antenna and a single-layer PRS. The polarization switching mechanism is based on electrically controlling two p-i-n diodes. To demonstrate the advantages of the presented antenna, Table 1 shows the performance comparison among the FP antennas with polarization diversity in literature. It can be seen that the designs in [18]–[21] work either in LP or CP modes only, but not both. Additionally, reconfigurable characteristic is not achieved in [18], [19]. In [20], the reconfigurability is based on mechanical operation, which might be difficult to control and hardly applicable in fast time-varying systems. Although wide operation BW can be achieved in [21], [22], they have several drawbacks compared to the proposed design. Firstly, the reconfigurability requires large number of p-i-n diodes, resulting in complicated biasing circuit. Secondly, the use of power divider significantly increases the design complexity and also introduces some power loss. Finally, the interference of the biasing wires on the antenna's RF performance ($|S_{11}|$ or AR) is not avoidable in these designs.

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TABLE 1. Performance comparison among the FP antennas with polarization diversity.

Ref.	Overall size (λ)	Reconfigurable capability	Method	No. of diodes	DC biasing wires	No. of states		BW (%)	Peak gain (dBi)	Aperture efficiency (%)
						CP	LP			
[18]	4.20 × 4.20 × 0.60	No	No	0	No	0	2	1.8	18.6	41.6
[19]	2.12 × 2.12 × 0.65	No	No	0	No	0	2	19.0	15.5	61.1
[20]	3.31 × 3.31 × 1.22	Yes	Mechanical	0	No	2	0	6.7	14.1	51.3
[21]	1.40 × 1.40 × 0.50	Yes	Electrical	4	Yes	0	2	21.0	15.1	93.1
[22]	1.84 × 1.84 × 0.60	Yes	Electrical	8	Yes	2	1	13.1	11.2	33.1
Prop.	2.00 × 2.00 × 0.60	Yes	Electrical	2	No	2	1	4.0	15.1	42.3

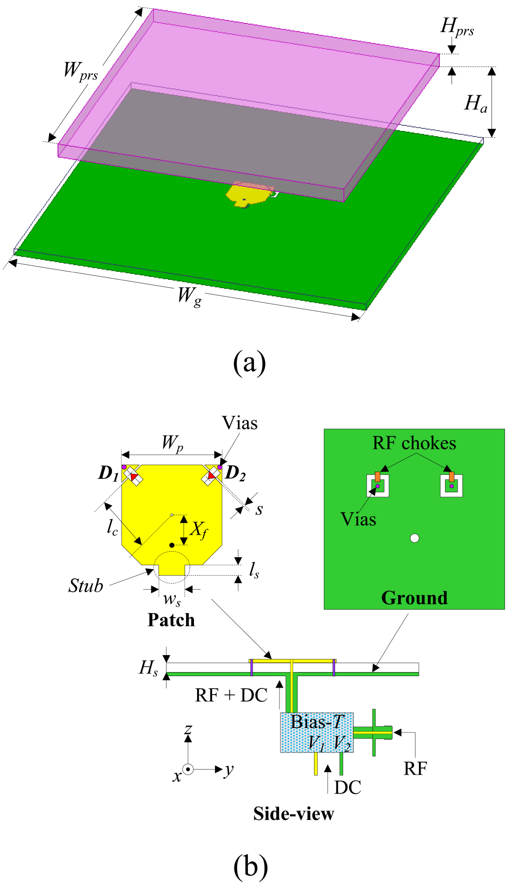

FIGURE 1. Geometry of the proposed polarization reconfigurable Fabry-Perot antenna: (a) 3-D view and (b) detailed configuration of the reconfigurable patch.

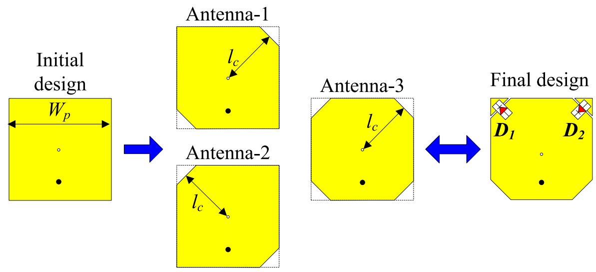

FIGURE 2. Evolution design of reconfigurable patch antenna.

II. ANTENNA GEOMETRY

The geometry of the proposed polarization reconfigurable FP antenna is shown in Fig. 1. The antenna is designed on a 1.52-mm-thick Taconic RF-35 substrate with dielectric constant of $\varepsilon = 3.5$ and loss tangent of $\tan\delta = 0.0018$. It is directly fed by a 50-Ω coaxial cable through a Bias-T. A Cer-10 with thickness of 3.18 mm, dielectric constant of $\varepsilon = 10$ and loss tangent of $\tan\delta = 0.0035$ is chosen as the PRS. The optimized parameters are as follows: $W_{prs} = 65$, $H_{prs} = 3.18$, $H_a = 20$, $W_g = 100$, $W_p = 9$, $l_c = 4.8$, $X_f = 3$, $s = 0.4$, $l_s = 2$, $w_s = 2.6$ (unit: mm).

The reconfigurable feature of the proposed antenna is achieved by using only two p-i-n diodes, which are of type MADP-042305-13060 (MACOM Technical Solutions). When working in forward state, the diode is equivalent to a resistance of $R_{p-i-n} = 1.32$ Ω. In contrast, a capacitance of $C_{p-i-n} = 0.15$ pF can be used as an equivalent circuit of the diode working in reverse mode [23]. The two diodes are designated as D_1 and D_2 and they are positioned between the center square patch and the corner triangular patches, which are then DC grounded through two vias and two 220-nH RF chokes. Finally, the operation of the diodes can be coveniently accomplished with the aid of the BT-52-400D Bias-*T*.

III. ANTENNA DESIGN PROCEDURE

A. RECONFIGURABLE PATCH ANTENNA

In the early stage, the microstrip patch with polarization reconfigurability is first considered. Fig. 2 shows the evolution structure of the final microstrip patch. The initial design is a square-shape patch and its dimension is chosen to be about half-effective-wavelength at the desired resonance. Due to the symmetric geometry, the initial design with single feed is able to excite LP waves. For CP realization, two orthogonal modes with equal magnitude and 90° out of phase are required. Here, the corners of the square patch are truncated and by truncating different set of corners, RHCP (Antenna-1) or LHCP (Antenna-2) waves are excited. When truncating all the corners as Antenna-3, this symmetrical design will become a LP source. Finally, the geometry of a reconfigurable patch antenna inspired from Antenna-1, −2, −3 is proposed with two p-i-n diodes (D_1, D_2).

The diodes D_1 and D_2 can be turned ON or OFF by using only a single DC voltage source with DC potentials of V_1 and V_2 applied to the Bias-T. According to Fig. 1, the main square patch and the inner coaxial conductor will have similar voltage of V_1. On the other hand, as the corner patches are DC grounded through the shorting pins and the RF chokes,

TABLE 2. Operating modes of the reconfigurable patch by different states of the P-i-n Diodes.

(V_1, V_2)	D_1	D_2	Operating mode
(1.5 V, 0V)	ON	OFF	RHCP
(0 V, 1.5 V)	OFF	ON	LHCP
(0V, 0V)	OFF	OFF	LP

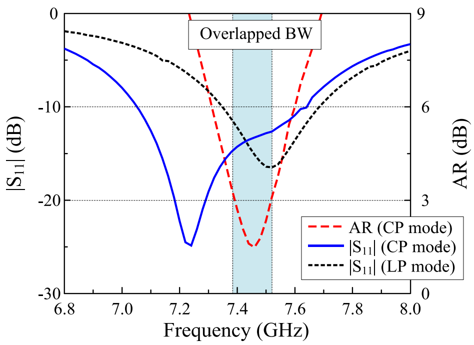

FIGURE 3. Simulated performances of the polarization reconfigurable patch antenna.

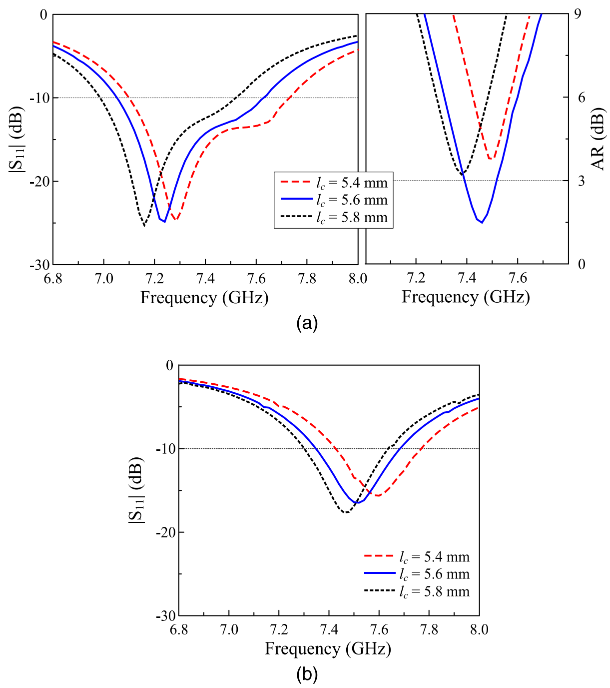

FIGURE 4. Simulated performances of (a) RHCP mode and (b) LP mode for different values of l_c.

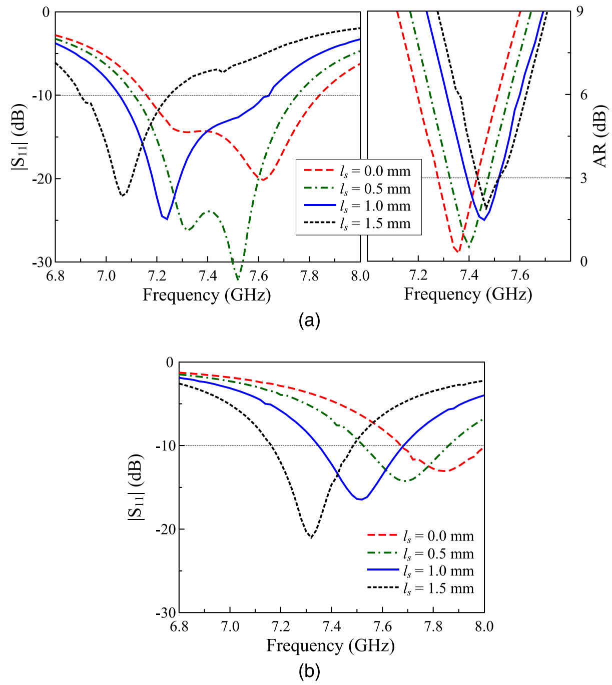

FIGURE 5. Simulated performances of (a) RHCP mode and (b) LP mode for different values of l_s.

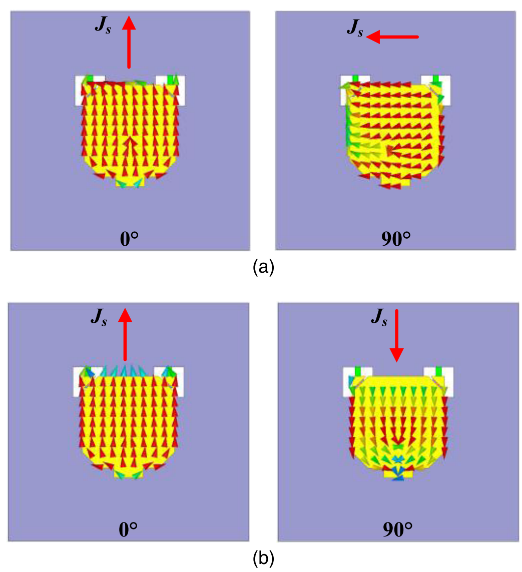

FIGURE 6. Simulated current distributions at 7.5 GHz for (a) RHCP mode and (b) LP mode.

their voltage will be similar to that of the outer conductor of the coaxial cable, V_2. By tuning V_1 and V_2, the desirable operating modes summarized in Table 2 can be achieved. It is also noted that there are no biasing wires connected directly to the antenna structure.

Fig. 3 presents the simulated performances of the reconfigurable patch antenna working in different polarization states. The data indicate that the antenna has well overlapped BW between the CP and LP modes. In optimizing this antenna, one of the critical factors is the truncated corner parameter, l_c. As seen in Fig. 4(a), l_c has significant effect on the AR value of the CP operating mode. In addition, decreasing l_c will make the center patch smaller and thus, the resonance occurs in higher frequency range. This can be seen obviously in Fig. 4, in which the $|S_{11}|$ and AR resonances shift upwards with decreasing l_c. The second important parameter is the length of the stub (l_s), which will contribute to increase the length of the center patch when working in both CP and LP

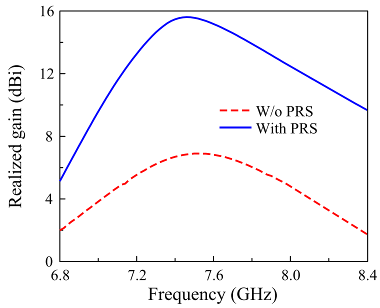

FIGURE 7. Simulated antenna gain operating in LP mode with and without PRS.

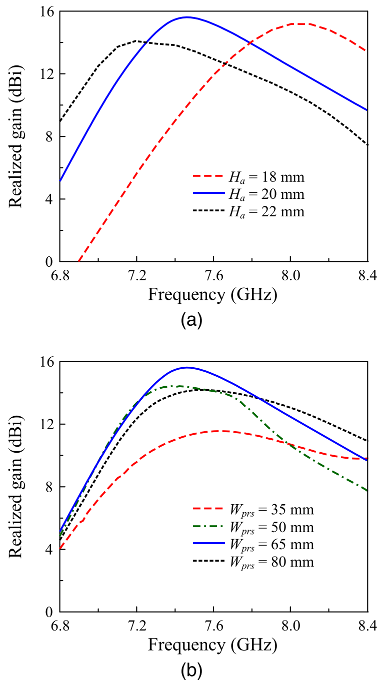

FIGURE 8. Simulated antenna gain operating in LP mode for different (a) cavity thickness, H_a, and (b) PRS size, W_{prs}.

modes. Fig. 5 shows the antenna results for different values of l_s. The data indicate that l_s is very useful parameter to control the overlapped BW of the CP and LP states. For instance, with $l_s = 0$ mm, the operating band of the LP mode is very high around 7.9 GHz. Meanwhile, the operating band of the CP mode is around 7.35 GHz. When l_s is increased, in fact the length of the center patch will be extended. This results in lower $|S_{11}|$ resonances of both CP and LP modes. However, the effect of l_s on the LP mode is more significant than that on the CP state. Meanwhile, the CP resonance slightly moves toward higher frequency with increasing l_s. Finally, the parameters l_c and l_s are opted so that the overlapped BW between the -10 dB $|S_{11}|$ and 3-dB AR BWs is maximized.

As further demonstration of the CP and LP operations, Fig. 6 shows the simulated surface current on the antenna at 7.5 GHz at different phases. As observed, when the phase changes from 0° to 90°, the vector current rotates 90° in

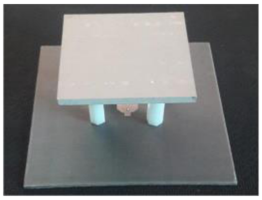

FIGURE 9. Photographs of fabricated antenna.

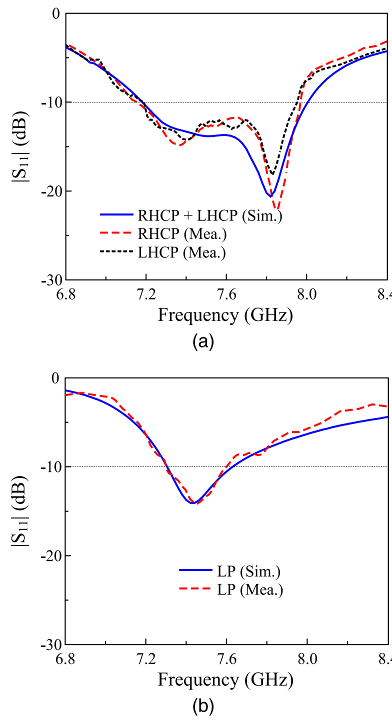

FIGURE 10. Simulated and measured $|S_{11}|$ of (a) dual-CP modes and (b) LP mode.

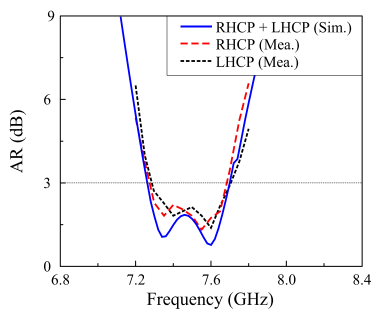

FIGURE 11. Simulated and measured AR of the dual-CP modes.

counter-clockwise direction. It demonstrates the RHCP operation of the proposed design. On the other hand, for the LP mode, the direction of the vector current does not change for different phases.

B. RECONFIGURABLE PATCH ANTENNA AND PRS

Theoretically, the maximum gain of the patch antenna presented in Section 3a is about 7 dBi. To improve the broadside

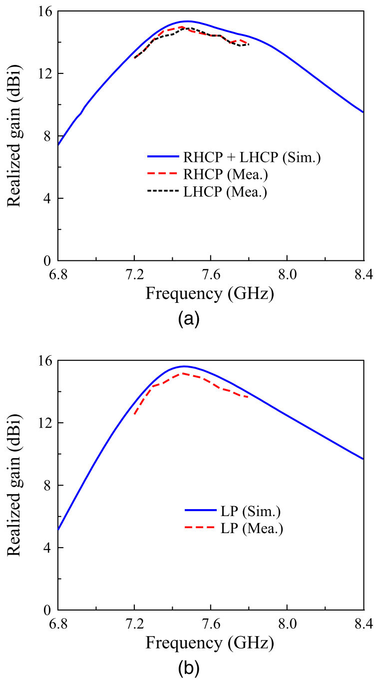

FIGURE 12. Simulated and measured realized gain of (a) dual-CP modes and (b) LP mode.

gain, the PRS (thickness of about quarter effective wavelength) is placed at a proper distance (half free-space wavelength at the operating frequency) from the ground plane. It is noted that since the gain enhancement of the CP and LP states when using PRS is quite similar, only the simulated result for the LP mode is presented for brevity. Fig. 7 shows the gain comparison of the reconfigurable antennas with and without PRS. It can be seen that the gain is significantly increased from 6.9 to 15.6 dBi with the presence of the PRS.

In order to optimize this antenna, besides the optimization of the $|S_{11}|$ and AR using l_c and l_s presented in Section 3a, the cavity height (H_a) and the PRS lateral size (W_{prs}) are two important parameters determining the gain performance of the proposed design. Fig. 8 shows the antenna gain for different values of H_a and W_{prs}. It can be seen that the peak gain happens in the higher frequency region with decreasing H_a. Meanwhile, when W_{prs} increases from 35 to 65 mm, the broadside gain improves from 12.0 to 15.6 dBi due to the increase of the effective radiating aperture. However, the gain slightly reduces when W_{prs} is increased beyond 65 mm. The reason is that as W_{prs} increases, more fields are radiated off-broadside by the leaky wave effect rather than diffracted from the edges of the PRS.

IV. MESUREMENT RESULTS

An antenna prototype has been fabricated to demonstrate the feasibility of the proposed design. The photograph of the fabricated antenna is depicted in Fig. 9. Overall, the measured and simulated data are well matched. The differences might be caused by the imperfections in fabrication and the measurement setup. Figs. 10 and 11 show the simulated and measured reflection coefficients and AR of the CP and LP modes. It can be seen that the overlapped BW between -10 dB impedance and 3-dB AR BWs is 4% (7.3–7.6 GHz). Within this BW, the antenna gain varies between 14 to 15.1 dBi, as illustrated in Fig. 12.

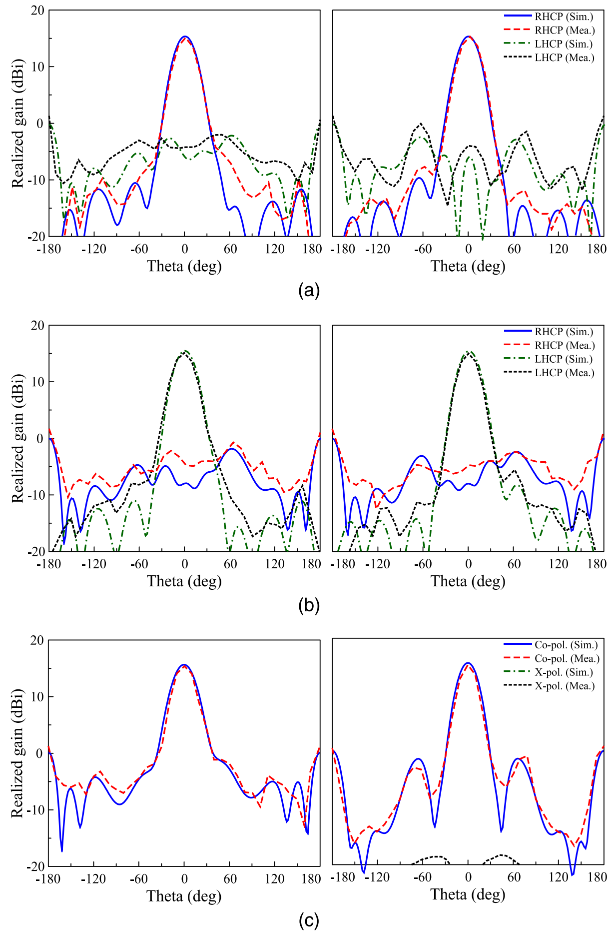

FIGURE 13. Simulated and measured radiation patterns at 7.5 GHz for (a) RHCP, (b) LHCP, and (c) LP modes (left column: *x-z* plane, right column: *y-z* plane).

The simulated and measured data of radiation patterns at 7.5 GHz for all operating modes are shown in Fig. 13. The results indicate that the far-field patterns are symmetric and the maximum gain is on the broadside direction for every working state. In addition, the front-to-back ratio is better than 13 dB and the polarization isolation at broadside direction can reach about 20 dB.

V. CONCLUSION

A simple design of FP antenna with capability of switching among different polarization states is presented. The proposed antenna is based on a reconfigurable microstrip patch and a PRS. Dual-sense CP and single LP can be realized by using only two p-i-n diodes. In addition, proper design of the biasing circuit can eliminate the use of biasing wires, which are commonly used in reconfigurable antenna and cause undesirable effects on the antenna performances. The measured data indicate that the proposed design can have good performances over a BW of 4% and peak gain of 15.1 dBi. The proposed FP antenna can be used for satellite communications.

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