A Novel Multi-Functional Electronically Tuned Polarization Converter Based on Reconfigurable Reflective Metasurface

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Abstract **─** In this paper, a novel multi-functional electronically tuned polarization converter based on reconfigurable reflective metasurface is proposed. The proposed polarizer can convert linearly polarized waves to left-hand circular polarization, right-hand circular polarization and crossed linear polarization waves without changing the polarization of incident waves. By controlling the varactors that mounted on the metasurface element, the reflection phase difference of the two orthogonal components of the incident linear polarization waves covers from -110° to 210° when the polarizer operates from 4.65 GHz to 5.35 GHz. Moreover, a 14 × 14 prototype is fabricated and measured to validate the proposed polarizer. Measured axial ratios agree well with the simulation results.

Index Terms **─** Axial ratio, multi-functional polarizer, reconfigurable metasurface, varactor.

I. INTRODUCTION

Polarization converter, which is also known as polarizer, is a special device that can convert polarization of electromagnetic (EM) waves from one form to another form, e.g., from linear polarization (LP) to left-hand circular polarization (LHCP) or right-hand circular polarization (RHCP), and LP to crossed linear polarization (CLP) [1, 2]. Having such characteristics, polarization converters were widely used in phased array feeding systems, wireless communication systems, and satellite communication systems [3-5].

As the definition of circular polarization (CP) implies, CP waves can be decomposed into two orthogonal LP waves with same amplitude and 90° phase difference. Therefore, to realize polarization conversion, we need to advance or delay the phase of one of the orthogonal components. Inductive and capacitive components can give rise to this effect. As a result, metallic stripes, meander-line and equivalent structures were used to achieve different inductive or capacitive features [1, 6-7]. When they are properly excited, polarization conversion will be implemented.

In recent years, metamaterials, which can readily manipulate EM waves and show abnormal and excellent EM properties, are proposed to tailor EM waves [8-11]. Metamaterials that are made of subwavelength special artificial structures and arrangements were employed to realize polarization converters [12-17]. Metasurfaces, which are the planar two dimensional form of metamaterials, can also exhibit polarization conversion characteristics [18].

Recently, researchers have shown an increased interest in reconfigurable polarizers using active metasurfaces. Reconfigurability was realized by introducing mechanical rotation, PIN diode, varactor diode, and liquid crystal to metasurfaces [19-24], etc. Comparing to conventional design of polarizer, reconfigurable polarization metasurfaces show multi-functionalities, e.g., from LP incident waves to CP (including RHCP and LHCP) or CLP waves.

However, current reconfigurable polarizer can only convert LP waves into RHCP or LHCP. To get the crossed CP, a CLP incident waves are required. In this paper, a novel polarizer based on reconfigurable reflective metasurface is proposed to convert LP waves into RHCP and LHCP without changing the polarization of incident waves. The electronically multi-functional polarization converter is implemented by mounting varactor diodes on metasurfaces. The proposed polarizer operates from 4.65 GHz to 5.35 GHz. The RHCP, LHCP and CLP waves are obtained at the working frequency band when the correct bias voltages are applied. Due to the bias voltage of varactor can be tuned continuously, phase difference of the decomposed reflected LP waves ranges from -110° to 210°, thereby, elliptical polarization waves also can be generated.

This paper is organized as follows. Manipulation principle and varactor tuned polarizer element are described in Section II. In Section III, a 14 × 14 reconfigurable polarization converter is constructed and tested. Finally, Section IV concludes this paper.

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II. MANIPULATION PRINCIPLE AND RECONFIGURABLE ELEMENT

A. Manipulation principle

Previous designs of reconfigurable polarizer using metasurface mainly focused on advancing or delaying phase of the orthogonal components of incident LP waves. By introducing PIN diode or varactor along one of the orthogonal components, we can manipulate the phase of this component. To continuously regulate the phase differences, varactor is used in this paper. In our previous study [19], truncated square metallic patch showed good polarization conversion characteristics. When the size of the truncated corner varies, phase of the two decomposed LP components leads alternatively. Based on this result, we use two varactors at the truncated corner to formally adjust the corner size. Therefore, as bias voltage changes, LHCP, RHCP, CLP and elliptical polarization waves can be realized.

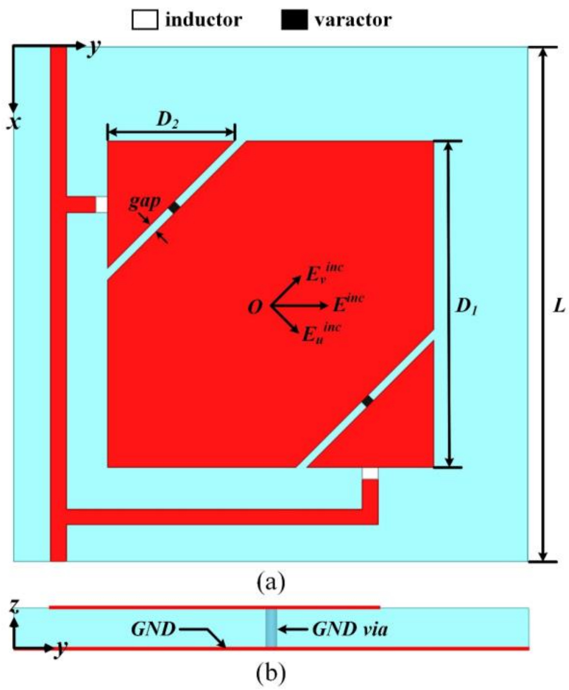

Fig. 1. The proposed reconfigurable polarizer element: (a) top view and (b) side view.

B. Reconfigurable element design

As aforementioned, a varactor tuned reconfigurable polarizer element is designed, as shown in Fig. 1. Period of the element is L = 26 mm. Side length of the truncated square patch is D_1 = 16.5 mm with corner size D_2 = 7 mm. Gap of the truncated patch and the triangle corner patch is *gap* = 0.4 mm. The element and the bias lines are etched on a F4B substrate with permittivity of 2.65 and tanδ = 0.005. And thickness of the substrate is 2 mm. Metallic ground plane is designed to reflect the incoming waves. A ground via is placed at the center of truncated patch, thereby, the ground plane serves as radio frequency (RF) and direct circuit (DC) ground. Bias lines are connected to the triangle corner patch to regulate the two varactors simultaneously. It should be noting that two 1 uH inductors are designed to choke RF circuits. Width of all bias lines is 0.8 mm. The Skyworks SMV 1405-040LF varactor is selected in this design. The junction capacitance ranges from 0.63 pF to 2.67 pF as the reverse voltage ranges from 30 V to 0 V.

The proposed element can realize polarization conversion when incident LP wave along *y*-axis is applied. Let us decompose the incident LP wave E^{inc} into E_u^{inc} and E_v^{inc}, thereby, the total reflected waves can be expressed as the sum of reflected waves along *u* and *v* directions:

$$E^{ref} = R_u e^{j\varphi_u} \bullet E_u^{inc} + R_v e^{j\varphi_v} \bullet E_v^{inc}, \tag{1}$$

where $R_u e^{j\varphi_u}$ and $R_v e^{j\varphi_v}$ are the reflection coefficients. Phase difference $\Delta\varphi = \varphi_u - \varphi_v$ changes when the bias voltage changes.

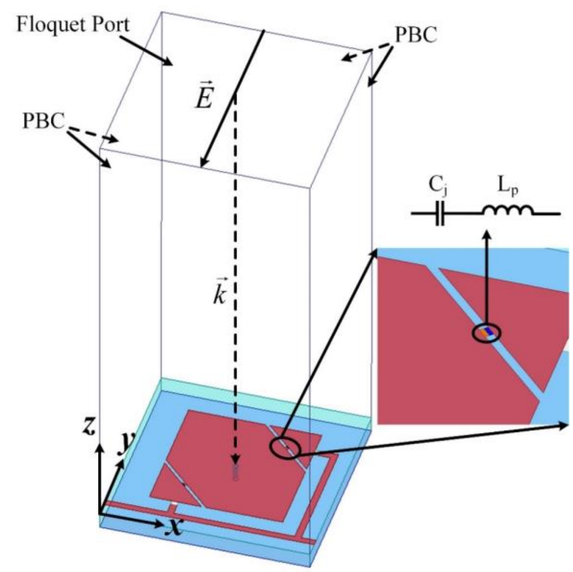

Fig. 2. Full-wave simulation configuration.

We simulated the proposed reconfigurable polarizer element by using Ansys HFSS 15.0, as shown in Fig. 2. It worth noting that the element was simulated under periodic boundary condition (PBC) combined with Floquet port. Plus, the inductors and varactors were modeled with lumped RLC boundary condition. The incident LP waves propagates in negative *z*-direction. Equivalent circuit of the selected varactor is junction capacitance in series with package inductance. The package inductance is 0.45 nH which can be founded in the datasheet of varactor. It should be pointed out that the equivalent circuit is modeled with two adjacent lumped

RLC boundary condition in HFSS 15.0, which is shown in the inset of Fig. 2. Detail simulation approach of reconfigurable element is described in [10].

First, we simulated the S-parameter with incident LP waves along y-axis, which is shown in Fig. 3 (a). It can be clearly seen that reflection magnitude is less than -1 dB when bias voltages varies, which indicates good reflection characteristic. Then, we assigned incident LP waves along u- and v-axis to investigate the $\Delta\varphi$ versus bias voltages, which is shown in Fig. 3 (b). From the figure, we can obtain that $\Delta\varphi$ can reach -90°, 90°, and 180° when bias voltages are 0 V, 4 V, and 20 V respectively. Therefore, LHCP, RHCP, and CLP waves can be achieved as reverse voltage assigned correctly. The operational bandwidth of the element generating LHCP waves is from 4.65 GHz to 4.95 GHz, while the RHCP waves is from 4.8 GHz to 5.1 GHz.

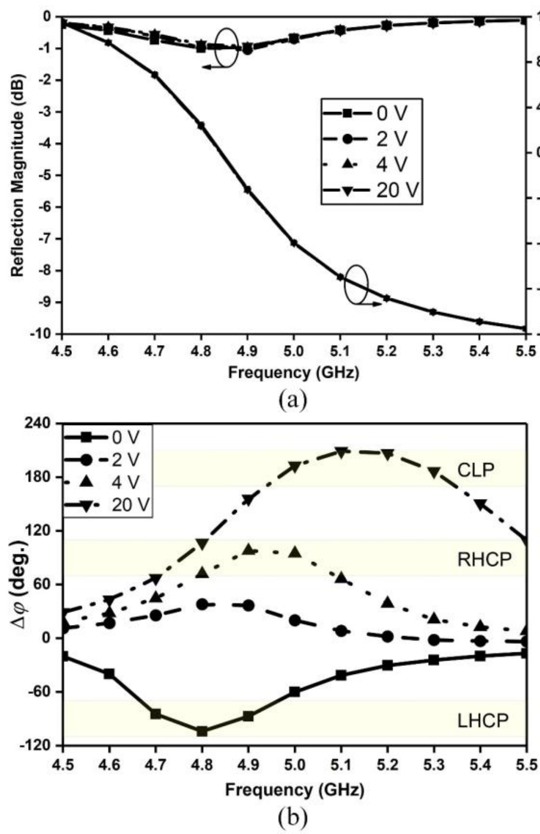

Fig. 3. (a) Simulated reflection magnitudes and phases versus different bias voltages. (b) $\Delta\varphi$ versus different bias voltages.

Moreover, the surface current distributions on the truncated square patch are investigated to figure out how the reflected circular polarizations are generated. The incident waves are y-axis polarized. In Fig. 4, we illustrate surface current vector distributions for four time phases which ranges from 0° to 270° with a 90° interval. As mentioned before, when the reverse voltages are 0 V and 4 V, LHCP and RHCP can be generated. Figure 4 (a) shows the surface currents rotate in the clockwise direction at 4.8 GHz when the reverse voltage is 0 V, indicating a LHCP waves. As the reverse voltage applied to varactor changes to 4 V, the surface currents rotate in the opposite direction at 5 GHz. Undoubtedly, the reflected waves are RHCP polarized.

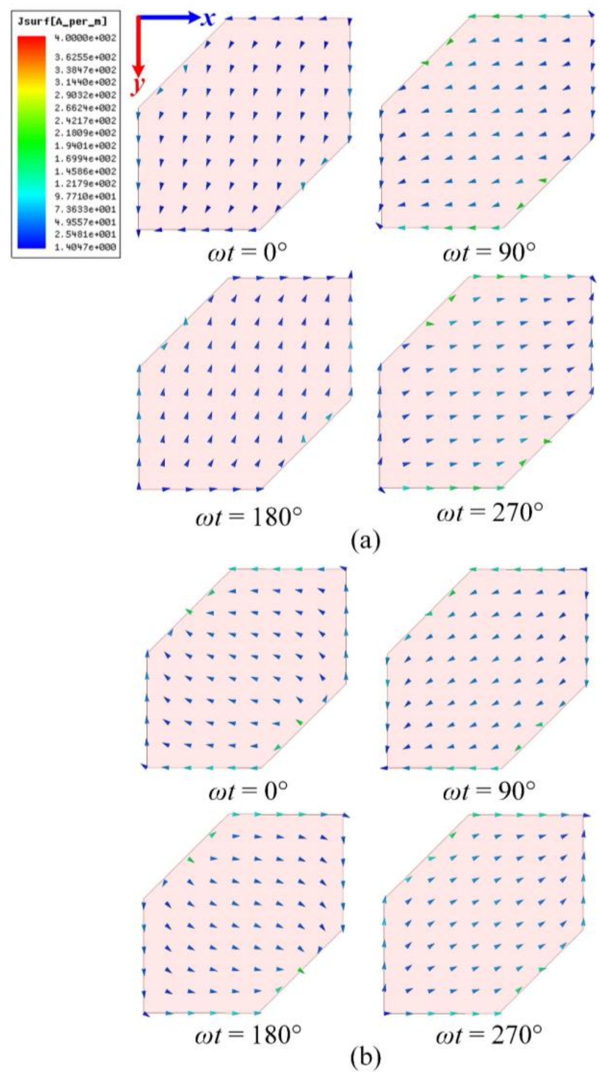

Fig. 4. Surface current distributions on the truncated square patch for four different instants and polarizations: (a) LHCP at 4.8 GHz and (b) RHCP at 5.0 GHz.

III. PROTOTYPE DESIGN AND MEASUREMENT

A. 14 × 14 prototype design

Based on the proposed reconfigurable element, a 14 × 14 polarization converter prototype is designed and fabricated, as shown in Fig. 5 (a). Total size of the prototype is 430 × 410 mm^2. A LP horn antenna whose working frequency band is from 2 GHz to 18 GHz is placed 400 mm from the polarizer, serving as LP incident wave which is along *y*-axis. It worth noting that the polarizer is at the far-field of the feed horn.

Due to all the varactors should be regulated simultaneously, all bias lines are gathered together as positive DC power. Additionally, the gathered bias lines pass through a metallized via hole which is designed at the edge of the metasurface to the bottom plane. Moreover, a positive DC power line was soldered to the gathered bias line pad. Meanwhile, we soldered a line on the ground plane, serving as negative DC power. The bias voltage configuration is shown in Fig. 5 (b).

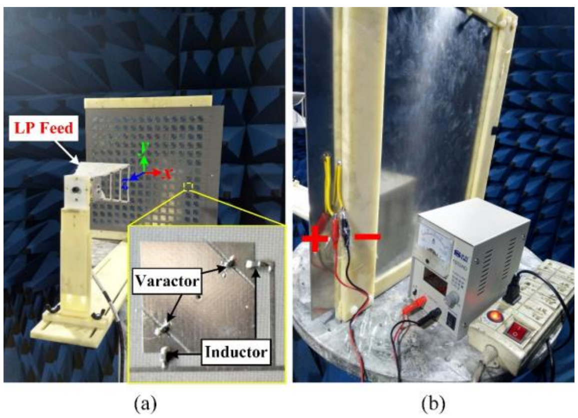

Fig. 5. (a) Fabricated 14 × 14 reconfigurable polarization converter. (b) Bias voltage configuration, red line as positive power and black line as negative power.

B. AR and pattern measurement

We measured the fabricated 14 × 14 reconfigurable polarization converter in anechoic chamber. In order to investigate the axial ratio (AR) of the prototype, we placed the polarizer on the turn table. Next, boresight AR characteristics were measured in the far-field when 0 V and 4 V bias voltages were supplied. It worth noting that *E*-field in two orthogonal directions were measured for calculating the ARs. The simulation and measurement results are plotted in Fig. 6 (a) and Fig. 6 (b). As can be seen from the figure, measured ARs at 0 V and 4 V agree well with the simulated ones. The LHCP and RHCP waves were successfully generated and measured. However, the measured AR shows slightly working frequency band offset. This is mainly due to the fabrication and measurement errors. The measured LHCP 3 dB AR absolute bandwidth is from 4.65 GHz to 4.95 GHz. And the measured RHCP 3 dB AR absolute bandwidth is from 4.88 GHz to 5.2 GHz.

Furthermore, directivity patterns of the two reflected CP waves for 0 V and 4 V are measured, which are shown in Fig. 7. The two patterns are measured at 4.8 GHz and 5.0 GHz respectively in *xoz*-plane. However, crossed polarization of the CPs are not shown due to measurement limitation. From the measured patterns, we obtained the LHCP and RHCP waves as the reverse voltage varies without changing the incident LP polarization.

Prior studies realized the reconfigurable polarizer by using PIN diodes and varactor diodes. To obtain the LHCP and RHCP waves, LP feed or the polarization converter should be rotated. This constraint limits the application of the previous reconfigurable polarizer in some conditions. In this paper, varactor tuned truncated square patch is proposed to implement polarization conversions without mechanical rotation. The reflected LHCP and RHCP waves are generated and measured successfully. From the view of Poincaré sphere, previous reconfigurable polarizer only can cover the half space of the sphere. Nevertheless, in this paper, the proposed electronically tuned polarizer can cover the hole Poincaré sphere.

In summary, a novel multi-functional electronically tuned polarizer is designed and measured. It can thus be suggested that LP to diverse elliptical polarization waves including CP waves can be achieved through advancing and delaying phases states using varactors.

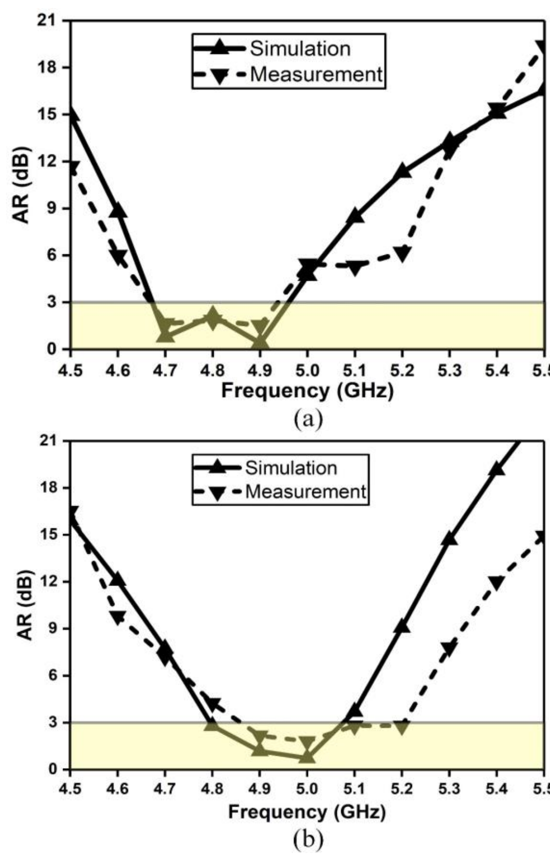

Fig. 6. Boresight AR results of simulation and measurement at bias voltage of: (a) 0 V (LHCP) and (b) 4 V (RHCP).

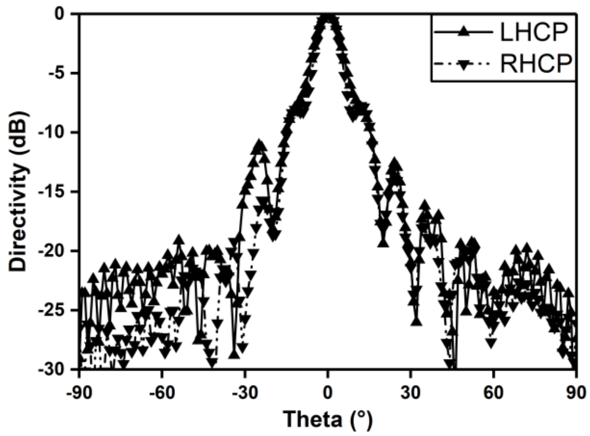

Fig. 7. Measured directivities of the two reflected circular polarization waves for 0 V (LHCP) at 4.8 GHz and 4 V (RHCP) at 5.0 GHz.

IV. CONCLUSION

This paper presents a novel multi-functional electronically tuned polarization converter which is based on reconfigurable reflective metasurface. The polarizer can convert incident LP waves into LHCP, RHCP and CLP waves without changing the polarization of incident waves. The approach, which can both advance and delay the phase of the orthogonal components of the incident LP waves, is feasible to convert LP waves to desired CP and elliptical polarization waves. By leveraging varactors, we can design multi-functional polarization converter based on reconfigurable metasurface. It is applicable for developing satellite communication systems, RCS reduction, and polarization transformers.

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