



## Article C-Band Linear Polarization Metasurface Converter with Arbitrary Polarization Rotation Angle Based on Notched Circular Patches

Tao Zhang <sup>1,2</sup>, Haoran Wang <sup>1,2</sup>, Chongmei Peng <sup>1</sup>, Zhaohui Chen <sup>2,3</sup> and Xiaoyi Wang <sup>4,\*</sup>

- <sup>1</sup> Institute of Microelectronics, Chinese Academy of Sciences, Beijing 100029, China
- <sup>2</sup> University of Chinese Academy of Sciences, Beijing 100049, China
- <sup>3</sup> Shanghai Institute of IC Materials, Shanghai 201800, China
- <sup>4</sup> Polytechnique Montréal, Montréal, QC H3T 1C6, Canada
- \* Correspondence: xiaoyi.wang@polymtl.ca

**Abstract:** This paper presents a linear polarization metasurface converter with arbitrary polarization rotating angle and stable oblique incident response, which is based on the concept of linear-to-circular polarization decomposition and recombination. A metasurface unit cell is proposed using a notched circular patch with two metallized vias connected to the bottom-layer coplanar waveguide (CPW) transmission lines. By changing the length of the two transmission lines, different polarization rotation angle may be realized. The proposed metasurface polarization converter is theoretically analyzed and full-wave simulated. A 45° metasurface polarization converter with 8 × 8 unit cells is designed and experimentally demonstrated. The experimental results agree well with the simulation, showing that the proposed metasurface polarization converter can achieve a high polarization conversion ratio (PCR) larger than 85% under up to 50° oblique incident wave.



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**Copyright:** © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). **Keywords:** metasurface; polarization converter; linear polarization; circular polarization; notched circular patch

### 1. Introduction

Polarization is one of the key features of electromagnetic waves, which is generally defined by the oscillating direction of the electric field component of an electromagnetic wave in space [1]. The manipulation of the polarization states of electromagnetic waves is important for many applications from microwave to optical frequencies. For instance, radar cross section (RCS) reduction by altering the polarization state of the reflective wave [2–5], information encryption by polarization encoding [6–8], anti-jamming by changing the polarization of the interfered antenna to be inconsistent with the polarization of the interfering electromagnetic wave [9,10] and polarization multiplexing by applying orthogonal polarization isolation of electromagnetic wave [11,12], etc. Conventional methods using natural materials to control polarization states such as liquid crystals and solid crystals, generally have the limitations of narrow operating frequency band and bulky volume [13–15]. As a result, these converters are inappropriate for integration within modern applications with very limited space.

Metasurfaces, the two-dimensional equivalent of bulky metamaterials, have been widely used in various fields thanks to their unique advantages such as low profile, low cost, easy manufacturing, and the strong capability to manipulate properties of electromagnetic waves [16]. Many applications based on metasurfaces have been reported during the past decade, such as wavefront reshaping [17–19], energy absorption [20,21], frequency converters [22,23], performance enhanced antennas [24–27], and electromagnetic camouflaging [28,29], to name a few.

With the development of metasurface technology, more and more metasurface-based polarization converters with various forms and functions are developed. For instance, linear

polarization rotators [30–34], linear polarization to circular polarization converters [35–41], and other hybrid modes with multiple bands [42,43], etc.

However, most linear polarization converters reported to date are limited to crosspolarization conversion. Only a few of them can achieve arbitrary linear polarization conversion. In this paper, we propose a novel linear polarization metasurface converter with arbitrary polarization rotating angle and stable oblique incident response based on a notched circular patch unit cell. The polarization conversion is achieved by firstly decomposing the linear polarization electromagnetic wave into a left-hand and a righthand circularly polarized components, then, adding different phase delays to the two components, and finally, recombining the two circularly polarized components in free space. The arbitrary linear polarization conversion can be controlled by adjusting the phase delays added to the two circularly polarized components. Compared with most other reported metasurface polarization converter, the proposed metasurface polarization converter provides a simple way to control the polarization rotating angle by adjusting the phase delays added to the two circularly polarized components. Meanwhile, the proposed metasurface polarization converter exhibits a stable response under wide oblique incident waves due to the almost same responses the two circularly polarized components experience in the metasurface decomposing process.

The rest of this paper is organized as follows: Section 2 introduces the general concept and the unit cell design of the proposed metasurface polarization converter. Then, Section 3 explains the operating principle of the proposed metasurface polarization converter based on the concept of linear-to-circular polarization decomposition and recombination. Next, Section 4 provides full-wave simulation results of the proposed metasurface unit cell and Section 5 demonstrates the design with experiment. Finally, Section 6 concludes this work.

#### 2. General Concept and Metasurface Unit Cell Design

Figure 1 illustrates the conceptual function of the proposed metasurface polarization converter. The metasurface polarization converter consists of a group of periodic notched circular patches. An *x*-polarized harmonic incident wave,  $E_i(t)$ , impinges on the metasurface-based polarization converter, the incident wave interacts with the metasurface particles and is scattered back as the reflected wave,  $E_r(t)$ , to the free space. The linear polarization of the reflected wave,  $E_r(t)$ , is rotated by an angle of  $\theta$ , compared with the incident wave,  $E_i(t)$ .



**Figure 1.** Functional schematic diagram of the proposed metasurface-based linear polarization converter. The polarization of the reflected electromagnetic wave rotates by an angle  $\theta$  compared with the incident wave.

Figure 2 shows the unit cell of the proposed metasurface polarization converter. Figure 2a shows the perspective view of the metasurface unit cell, which consists of a top-layer notched circular patch and a bottom-layer ground that are printed on a Roger 4350 dielectric substrate with the dielectric constant 3.66 and the loss tangent is 0.004. The top layer and bottom layer are connected through two metallized vias, as shown in the side view of Figure 2b. Figure 2c shows the top-layer structure, a notched circular patch with two symmetric notches on its two sides.

There are two vias that are located on the left part of the patch which are connected to the bottom layer of the unit cell and can pick up the two circularly polarized components, respectively. Figure 2d shows the bottom layer of the unit cell. Two coplanar waveguide (CPW) transmission lines with different length,  $l_1$  and  $l_2$ , are connected with the top layer through the two metallized vias to adjust the reflecting phase of the two circularly polarized components. The bottom layer has two functions. Firstly, it is used as the ground plane to reflect the incident wave. Meanwhile, it is also applied as the ground for the two CPW transmission lines. The overall design parameters of the unit cell are listed in Table 1.



**Figure 2.** Unit cell of the proposed linear polarization metasurface converter. (**a**) Perspective view. (**b**) Side view. (**c**) Top layer. (**d**) Bottom layer.

 Table 1. Design parameters of the proposed metasurface unit cell.

Parameter	w	h	<i>r</i> <sub>0</sub>	d	$w_s$	$l_s$	w <sub>c</sub>	s
Value (mm)	25.00	1.524	8.00	0.35	2.40	1.30	0.40	0.22

# 3. Operating Principle Based on Linear-to-Circular Polarization Decomposition and Recombination

Figure 3 illustrates the basic principle of the proposed metasurface polarization converter based on the concept of linear-to-circular polarization decomposition and recombination. It can be divided into three steps.



Figure 3. Operating principle of the proposed metasurface polarization converter.

The first step is to separate the linearly polarized incident wave  $E_i(t)$  into two orthogonal left-hand circularly polarized (LHCP) and right-hand circularly polarized (RHCP) waves. It is well known that any linearly polarized wave may be divided into two orthogonal circularly polarized wave. For instance,

$$E_{i}(t) = e^{-j\omega_{0}t} \mathbf{x}$$
  
=  $\frac{1}{2} (e^{-j\omega_{0}t} \mathbf{x} + e^{-j(\omega_{0}t + \pi/2)} \mathbf{y}) + \frac{1}{2} (e^{-j\omega_{0}t} \mathbf{x} - e^{-j(\omega_{0}t + \pi/2)} \mathbf{y}),$  (1)

where  $\omega_0$  is the angular frequency of the incident wave. The first term in the last equivalent represents the RHCP component and the second term in the last equivalent represents the LHCP component, which are

$$E_{i,RHCP}(t) = \frac{1}{2} (e^{-j\omega_0 t} \mathbf{x} + e^{-j(\omega_0 t + \pi/2)} \mathbf{y}),$$
  

$$E_{i,LHCP}(t) = \frac{1}{2} (e^{-j\omega_0 t} \mathbf{x} - e^{-j(\omega_0 t + \pi/2)} \mathbf{y}),$$
(2)

respectively. In our design, this is realized by the top-layer notched circular patch in the unit cell of Figure 2c. By introducing the notch perturbations on the patch, degenerate modes can be realized. As a result, the LHCP and RHCP components of the incident wave can be picked up by the two vias and sent to the bottom-layer CPW transmission lines. This process can be understood with the help of cavity model. If there are no two notches, the regular circular patch can be regarded as a lossy resonator, where the top-layer patch and the ground are electric walls, and the space around the circular patch is magnetic wall. This circular patch antenna usually works in the main mode. When two notches are loaded, the current path on the surface of the patch is subject to geometric perturbation, so that the main mode is separated into two adjacent modes. By selecting the appropriate notch size, the two modes can be orthogonal to each other, with equal amplitude and  $90^{\circ}$ phase difference, thus forming circular polarization [44,45]. In order to demonstrate the linear-to-circular polarization decomposition or recombination function of the proposed unit cell, the two via locations on the top-layer patch are used as the feeding ports of the patch to perform full-wave simulation, respectively. Figure 4 plots the current distribution on the top-layer patch, where in Figure 4a, port 1 is selected as the feeding point, and in Figure 4b, port 2 is selected as the feeding point. It clears shows that in Figure 4a, the current rotates counterclockwise, while in Figure 4b, the current rotates clockwise, which

demonstrates that port 1 and port 2 will pick up the LHCP and RHCP components of the incident wave, respectively.



**Figure 4.** Full-wave simulated surface current distribution of the notched circular patch under different feeding ports. (a) Fed by port 1. (b) Fed by port 2.

The second step is to add different phase delays to the two circularly polarized components. For instance, if  $0^{\circ}$  and  $\beta$  are added to the RHCP and LHCP components, the two components in the reflective wave becomes

$$E_{r,RHCP}(t) = \frac{1}{2} (e^{-j(\omega_0 t + 0)} \mathbf{x} + e^{-j(\omega_0 t + \pi/2 + 0)} \mathbf{y}),$$
  

$$E_{i,LHCP}(t) = \frac{1}{2} (e^{-j(\omega_0 t + \beta)} \mathbf{x} - e^{-j(\omega_0 t + \pi/2 + \beta)} \mathbf{y}),$$
(3)

respectively. In our design, this is realized by the bottom-layer CPW transmission lines in the unit cell of Figure 2d. By changing the length of the two CPW transmission lines, different phases are given to the two circularly polarized components.

The final step is the combination of these two reflected orthogonal circularly polarized components, which is

$$\begin{split} E_{\mathbf{r}}(t) &= E_{\mathbf{r},\mathrm{RHCP}}(t) + E_{\mathrm{i},\mathrm{LHCP}}(t) \\ &= \frac{1}{2}e^{-j\omega_{0}t}(1+e^{-j\beta})\mathbf{x} + \frac{1}{2}e^{-j(\omega_{0}t+\pi/2)}(1-e^{-j\beta})\mathbf{y} \\ &= \frac{1}{2}e^{-j\omega_{0}t}[(1+e^{-j\beta})\mathbf{x} - j(1-e^{-j\beta})\mathbf{y}] \\ &= \frac{1}{2}e^{-j\omega_{0}t}[(e^{j2\pi} + e^{-j\beta})\mathbf{x} - j((e^{j2\pi} - e^{-j\beta})\mathbf{y}] \\ &= \frac{1}{2}e^{-j\omega_{0}t}e^{j(2\pi-\beta)/2}\Big\{ [e^{j(2\pi+\beta)/2} + e^{-j(2\pi+\beta)/2}]\mathbf{x} - j[e^{j(2\pi+\beta)/2} - e^{-j(2\pi+\beta)/2}]\mathbf{y} \Big\} \\ &= e^{-j\omega_{0}t}e^{j(2\pi-\beta)/2}\{\cos\left[(2\pi+\beta)/2\right]\mathbf{x} + \sin\left[(2\pi+\beta)/2\right]\mathbf{y}\} \\ &= -e^{-j\omega_{0}t}e^{j(2\pi-\beta)/2}[\cos\left(\beta/2\right)\mathbf{x} + \sin\left(\beta/2\right)\mathbf{y}]. \end{split}$$

Equation (4) shows that the reflected wave,  $E_r(t)$  is a linearly polarized wave with the polarization direction

$$\boldsymbol{\theta} = \arctan \frac{E_{\mathrm{r,y}}(t)}{E_{\mathrm{r,x}}(t)} = \frac{\beta}{2}.$$
(5)

Similarly, if  $0^{\circ}$  and  $\beta$  are added to the LHCP and RHCP components, the reflected wave,  $E_{r}(t)$ , becomes

$$\begin{aligned} \mathbf{E}_{\mathbf{r}}(t) &= \mathbf{E}_{\mathbf{r},\mathrm{RHCP}}(t) + \mathbf{E}_{\mathbf{i},\mathrm{LHCP}}(t) \\ &= \frac{1}{2}e^{-j\omega_{0}t}(e^{-j\beta}+1)\mathbf{x} + \frac{1}{2}e^{-j(\omega_{0}t+\pi/2)}(e^{-j\beta}-1)\mathbf{y} \\ &= \frac{1}{2}e^{-j\omega_{0}t}[(e^{-j\beta}+1)\mathbf{x} - j(e^{-j\beta}-1)\mathbf{y}] \\ &= \frac{1}{2}e^{-j\omega_{0}t}[(e^{-j\beta}+e^{j2\pi})\mathbf{x} - j((e^{-j\beta}-e^{j2\pi})\mathbf{y}] \\ &= \frac{1}{2}e^{-j\omega_{0}t}e^{j(-\beta+2\pi)/2} \Big\{ [e^{j(-\beta-2\pi)/2} + e^{-j(-\beta-2\pi)/2}]\mathbf{x} - j[e^{j(-\beta-2\pi)/2} - e^{-j(-\beta-2\pi)/2}]\mathbf{y} \Big\} \\ &= e^{-j\omega_{0}t}e^{j(\beta-2\pi)/2} \{ \cos\left[(-\beta-2\pi)/2\right]\mathbf{x} + \sin\left[(-\beta-2\pi)/2\right]\mathbf{y} \} \\ &= -e^{-j\omega_{0}t}e^{j(2\pi-\beta)/2} [\cos\left(-\beta/2\right)\mathbf{x} + \sin\left(-\beta/2\right)\mathbf{y}], \end{aligned}$$

whose polarization direction is

$$\boldsymbol{\theta} = \arctan \frac{\boldsymbol{E}_{\mathbf{r},\mathbf{y}}(t)}{\boldsymbol{E}_{\mathbf{r},\mathbf{x}}(t)} = -\frac{\beta}{2}.$$
(7)

Equations (5) and (7) show that the rotated polarization angle  $\theta$  of the reflective wave is exactly half of the added phase difference between the two circularly polarized components,  $\beta$ . The polarization rotating direction can be adjusted by switching the components in which  $\beta$  is added. In our design, the two orthogonal circularly polarized components picked up by the top-layer patch are reflected by their corresponding CPW transmission lines to the top-layer patch and recombine as the polarization-rotated reflective wave in the free space.

#### 4. Full-Wave Simulation and Analysis

The proposed metasurface unit cell is full-wave simulated to demonstrate the proposed unit cell. Figure 5 plots the magnitudes of the reflection coefficients for different  $l_1$ , when  $l_2$  is fixed to 0. It shows that when  $l_1 = 0$ , which is corresponding to the case  $\beta = 0^\circ$ , there is almost no polarization conversion. As the length of  $l_1$  increases, the co-polarization reflection coefficient  $|S_{xx}|$  decreases, while the cross-polarization reflection coefficient  $|S_{yx}|$  increases. When  $l_1 = 2.6$  mm,  $|S_{xx}| = |S_{yx}|$ , which is the case of 45° polarization conversion.



**Figure 5.** Magnitudes of reflection coefficients for different  $l_1$ , when  $l_2 = 0$ .

Figure 6 plots the phases of the reflection coefficients for the two cases,  $l_1 = 0$ ,  $l_2 = 2.6$  mm (case 1), and  $l_1 = 2.6$  mm,  $l_2 = 0$  (case 2). In both cases, it is a 45° polarization converter, as

shown in Figure 5. However, the co-polarization and cross-polarization reflection coefficients are in phase for case 1 and out of phase for case 2, which demonstrates that in case 1, the polarization is counterclockwise rotated, while in case 2, the polarization is clockwise rotated.



**Figure 6.** Phases of reflection coefficients for  $l_1 = 0 \text{ mm}$ ,  $l_2 = 2.6 \text{ mm}$  (case 1) and  $l_1 = 2.6 \text{ mm}$ ,  $l_2 = 0 \text{ mm}$  (case 2).

Figure 7 plots the simulated magnitude difference between co-polarization and crosspolarization reflected wave under *x*-polarized incident wave with different oblique incident angle  $\alpha$ , for the case  $l_1 = 2.6$  mm,  $l_2 = 0$ , which is corresponding to 45° polarization converter. It shows that the 45° metasurface polarization converter has a stable performance under a wide oblique incidence up to 50°, with the performance,  $||S_{yx}| - S|_{xx}|| < 3$  dB, from 5.44 GHz to 5.87 GHz.



**Figure 7.** Simulated magnitude difference between co-polarization and cross-polarization reflected wave under *x*-polarized incident wave with different oblique incident angle  $\alpha$ , for the case  $l_1 = 2.6$  mm,  $l_2 = 0$ , corresponding to a 45° polarization converter.

Figure 8 plots the full-wave simulated electric field distribution of the designed 45° metasurface under x-polarized normal incident wave at 5.7 GHz at the plane z = 10 mm. This result shows that the direction of the reflective electric field becomes 45°, which demonstrates the 45° polarization conversion performance.

Figures 9 and 10 study the 45° metasurface polarization converting performance with different notching sizes,  $l_s$  and  $w_s$ , under normal x-polarized incident wave, respectively. They show that the polarization converting performance is very sensitive to the size of the notches. This is due to the fact that only notches with appropriate size can introduce the perturbations for degenerate modes to separate the two circularly polarized components of the incident wave. In our design, we choose  $w_s = 2.4$  mm and  $l_s = 1.3$  mm.



**Figure 8.** The full-wave simulated electric field distribution of the designed  $45^{\circ}$  metasurface under *x*-polarized normal incident wave at 5.7 GHz at the plane z = 10 mm. The blue arrow represents the average direction of the electric field.



**Figure 9.** Simulated magnitude difference between co-polarization and cross-polarization reflected wave for different  $l_s$ , under normal x-polarized incident wave.



**Figure 10.** Simulated magnitude difference between co-polarization and cross-polarization reflected wave for different  $w_s$ , under normal *x*-polarized incident wave.

#### 5. Experimental Demonstration

Finally, a 45° metasurface polarization converter with 8 × 8 proposed unit cell is designed, fabricated, and experimentally demonstrated, in which the length of the two CPW transmission lines  $l_1$  and  $l_2$  are set as  $l_1 = 2.6$  mm and  $l_2 = 0$ . Figure 11 provides the photos of the fabricated metasurface prototypes, where Figure 11a,b show the top view and bottom view of the metasurface prototype, respectively. Figure 12 shows the experimental setup. The overall setup is surrounded by absorbing materials to avoid undesired scattering. A pair of horn antennas are placed on an arc track, which work as the transmitting and receiving antennas, respectively, and are connected to a vector network analyzer (VNA). The metasurface to be tested are placed at the center of the arc track.



Figure 11. Photos of the fabricated metasurface prototype. (a) Top view. (b) Bottom view.

Figure 13 plots the measured results of the magnitude difference between crosspolarization and co-polarization under x-polarized incident waves with different oblique angle  $\alpha$ . The measured results agree well the simulation results in Figure 7, showing that the designed metasurface polarization converter reflects balanced x- and y-polarized components in a wide band for 45° polarization conversion. Finally, Figure 14 plots the 45° polarization conversion ratio (PCR) under x-polarized incident wave with different oblique angle  $\alpha$ , based on the measured results using the equation

$$PCR(\theta) = \frac{|S_{yx}\sin\theta + S_{xx}\cos\theta|^2}{|S_{yx}|^2 + |S_{xx}|^2},$$
(8)

where  $\theta = 45^{\circ}$ . It shows that the designed metasurface polarization converter can achieve a high conversion ratio larger than 85% from 5.38 GHz to 5.78 GHz under a wide oblique incident wave up to 50°. As the oblique incident angle  $\alpha$  increases to larger than 50°, the decreasing of the PCR in the operating band becomes innegligible, which is due to the fact that as the incident angle increases, the resonate frequency of the top-layer patch shifts, resulting in less energy is captured by the metasurface and less PCR.



Figure 12. Photo of the experimental setup.

Finally, Table 2 compares the polarization conversion performance between this work and other reported works. The comparison shows that the proposed metasurface polarization converter exhibits the unique features of arbitrary linear rotating angle and stable high PCR under a wide oblique incident angle up to 50°.



**Figure 13.** Measured magnitude difference between cross-polarization and co-polarization under x-polarized incident waves with different oblique angle  $\alpha$ .



**Figure 14.** Measured 45° polarization conversion ratio (PCR) under x-polarized incident wave with different oblique angle  $\alpha$ , obtained by Equation (8).

Work	Polarization Rotating Angle	Oblique Incident Angle	PCR	
Ref. [46]	90.00	0–30°	$\geq\!68.6\%$	
Ref. [47]	90.00	$0-41.5^{\circ}$	$\geq 80.0\%$	
Ref. [48]	90.00	$0-45^{\circ}$	$\geq 80.0\%$	
Ref. [49]	90.00	$0-45^{\circ}$	$\geq 95.0\%$	
Ref. [50]	90.00	$0–50^{\circ}$	$\geq 90.0\%$	
This work	Arbitary	$0–50^{\circ}$	$\geq 85.0\%$	

Table 2. Comparison between reported work and this work.

#### 6. Conclusions

A novel linear polarization metasurface converter with the features of arbitrary polarization rotation angle and stable response under wide oblique incidence is presented in this paper. The proposed metasurface polarization converter is guided by the concept of linear-to-circular polarization decomposition and recombination and is realized based on a notched circular patch unit cell, whose polarization rotating phase is tunable by altering the length of the CPW transmission lines connected to the notched circular patch. The metasurface polarization converter is theoretically analyzed and demonstrated by both full-wave simulation and experiment, which shows that the proposed metasurface polarization can realize more than 85% polarization conversion efficiency at an oblique incident angle of up to 50°. The proposed arbitrary polarization metasurface converter may provide a new solution to flexible polarization manipulation metasurface design.

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