Dual-band reflective polarization converter based on metasurface*

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In this paper, a dual-band and reflective polarization converter based on metasurface is proposed. Its unit cell is composed of two layers of metal plates separated by a dielectric substrate. The simulation results show that the proposed converter is able to convert x- or y-polarized incident waves into cross-polarized waves perfectly in frequency bands of 6.75—10.59 GHz and 17.78—19.61 GHz, and the polarization conversion ratio (*PCR*) is nearly 100%, which can also convert linearly polarized waves into circularly polarized waves at four frequencies. It can be widely used in applications of radar satellites, antenna design and telecommunication with the function of realizing polarization conversion in two bands and achieving high *PCR* simultaneously.

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Polarization is one of the important characteristics of electromagnetic wave, which must be considered in many applications[1]. Traditional methods to manipulate polarization, such as optical activity crystals and Faraday effects[1], commonly require quite long propagation distance to obtain the phase accumulation. Besides, the sizes of many devices in conventional methods are much larger than the working wavelength, which is not capable to use in practical applications[2]. Therefore, it's extremely desirable to develop a new polarization converter with miniaturization, high efficiency and wide bands.

Metasurface is a two-dimensional planar structure based on metamaterials, which is a kind of periodical artificial media with distinct electromagnetic characteristics[3,4]. Metasurface has unique electromagnetic properties not found in nature. For example, it is an effective method to realize cloaks[5] and super-lens[6]. Besides, metasurface-based structures have important applications in military and aviation fields, such as absorbers[7,8], antennas[9,10] and telecommunication applications. However, it should be noted that metasurface is widely used in the field of polarization control. In recent years, many studies have been concentrated in this field. For example, metasurface is used to realize high-efficiency polarization conversion based on anisotropic structure in two frequency bands[11]. A tri-band cross-polarization converter based on metasurface is proposed[12]. The simulated results demonstrate that the cross-polarization transmission with a high efficiency and polarization conversion ratio (*PCR*) is more than 99%. Furthermore, a proposed reflective polarization transformer maintains the effective polarization conversion in the frequency range of 15.04—17.20 GHz, and the cross-polarization reflection is higher than 90%[13].

Many scholars have also propose that the applications of metasurface include linear-to-linear polarization converters[14,15], linear-to-circular polarization converters[16,17] and circular-to-circular polarization converters[18]. In addition, Refs.[19] and [20] have found that anisotropic or chiral metasurface can achieve polarization conversion of electromagnetic waves. These polarization converters have the advantages of miniaturization and easy processing, which improve their practical performances. All the literatures mentioned above show that metasurface-based structures have many applications in polarization conversion. However, the existing polarization converters based on metasurface in the literature either achieve high *PCR* within one band or low *PCR* in multi-bands. It is hard to achieve the polarization conversion based on metasurface with multi-bands and high *PCR*.

In this paper, a dual-band reflective polarization conver

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ter based on metasurface is proposed, which can achieve approximately 100% cross-polarization conversion in two bands of the microwave. The proposed converter can produce different phase shifts and amplitudes in two orthogonal directions to achieve polarization conversion. Numerically simulated results show that the converter can realize the polarization conversion of linearly polarized wave to cross-polarized wave almost perfectly over two frequency bands of 6.75—10.59 GHz and 17.78—19.61 GHz, and the *PCR* is approximately to 100%. Moreover, the linear-to-circular polarization conversion can also be achieved at four frequencies. The converter has great application value in radar satellite.

The polarization converter in this paper is shown in Fig.1. As can be seen from Fig.1(a), the structure has three layers. On the top layer is a metal resonant structure. The middle layer is a dielectric substrate, and the bottom layer is a full metal backing plate. The metal resonant structure is made of an elliptical metal plate with a rectangular shape subtracted from the middle and a long metal strip added. The metal resonant structure mentioned above is rotated counterclockwise by 45° with respect to the horizontal direction. The material of the intermediate dielectric substrate is selected as Taconic TLY-5, the relative dielectric constant is ε_r=2.2 and the loss tangent of the dielectric substrate is tanδ=0.000 9, while the thickness of the dielectric substrate is h=3.76 mm. The material of metal resonant structure and the metal backing plate are selected as copper, its electrical conductivity is 5.8×10^7 S/m, and the thickness is t=0.035 mm. The period of the unit cell is chosen as P=10 mm in the x-y plane. As can be seen from Fig.1(a), the length and width of the added metal strip are denoted by L and w, respectively. The semi-major axis and the semi-minor axis of the elliptical metal plate are denoted by a and b, respectively, as shown in Fig.1(b). The parameters of the converter are set as follows: a=5 mm, b=2 mm, L=13 mm, w=0.5 mm, and the width of the rectangle subtracted from the elliptical metal plate is m=3 mm and n=6 mm.

The working principle of the designed structure is briefly introduced as follows. The x-y coordinate system is rotated counterclockwise by 45° to obtain the v-u coordinate system as shown in Fig.2. It is assumed that the linearly polarized incident wave is a x-polarized wave, and the propagation direction is z direction. The electric field is expressed as E_i. When the electromagnetic wave in free space is perpendicularly incident on the converter, the electric field is decomposed into two components E_{vi} and E_{ui} along the v-axis and the u-axis, and the two components satisfy this equation E_{vi}=E_{ui}. The reflected wave is expressed as E_r. E_{vr} and E_{ur} denote the electric fields of v-polarized and u-polarized reflected waves, respectively. Moreover, there will be a phase difference ($\Delta\varphi$) between E_{vr} and E_{ur}. The reflected component E_{vr} is in 180° out of the phase with the incident component E_{vi}, and the reflected component E_{ur} is in phase with the incident component E_{ui} because of the anisotropy of the converter. For brevity, we summarize the principles of the cross-polarized waves and circular-polarized waves produced by the polarization converter. Due to the interaction of the front resonant structure and the metal backing plate, the phase of the reflected wave changed, causing the conversion of linear-to-cross polarized waves. Therefore, the phase difference $\Delta\varphi$ is critical to the polarization state of the cross-polarized reflections. Furthermore, as we know, if the amplitudes of the two components E_{vr} and E_{ur} are equal and the phase difference is ±90°, the reflected wave is in a circular polarization state. Therefore, the amplitudes of the two reflected components and the phase difference $\Delta\varphi$ are the key factors realizing the circular-polarized waves.

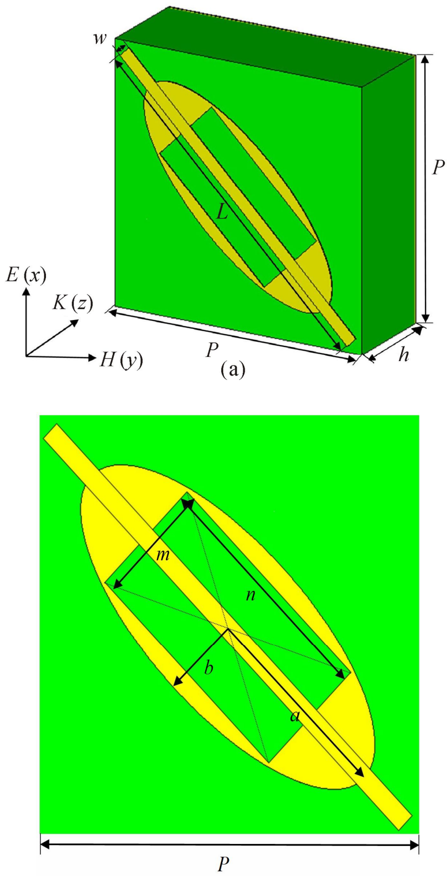


Fig.1 (a) Perspective view of the polarization converter unit cell structure; (b) Front view of the unit cell structure

The numerical simulation based on the finite element method is used to analyze the reflection characteristics of the polarization converter. In simulation, the periodic boundary conditions of the unit cell are used in the x-y plane and open for the z direction in the environment of free space. The obtained reflected waves include both the co-polarized reflected wave and the cross-polarized reflected wave. For the incident x-polarized wave, to understand the reflective characteristics of the converter, the co- and cross-polarized reflections are defined respectively as follows[21]

$r_{xx} = |E_{xr}| / |E_{xi}|,$

$$r_{yx}=|E_{yr}|/|E_{xi}|. \tag{1}$$

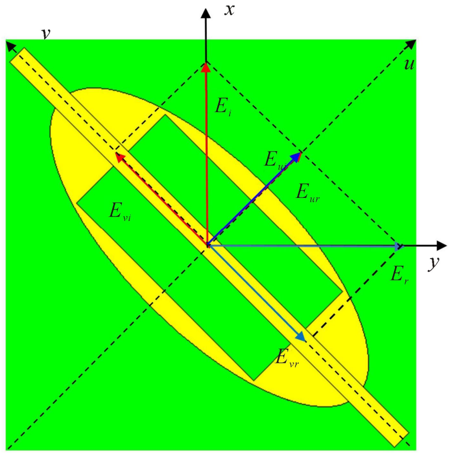


Fig.2 Principle analysis diagram of the polarization converter

These two reflections represent polarization transitions from x polarization to x polarization and x polarization to y polarization, respectively. The subscripts i and r represent incident and reflected electromagnetic waves, and the subscripts x and y indicate the directions of the reflected electromagnetic waves. In addition, the polarization conversion ratio is defined as follows

$$PCR=r_{yx}^{2}/(r_{yx}^{2}+r_{xx}^{2}), \tag{2}$$

which is for linear polarization ($r_{yx}=|\boldsymbol{r}_{yx}|$, $r_{xx}=|\boldsymbol{r}_{xx}|$). According to the formula, if the dielectric loss is ignored, $|\boldsymbol{r}_{yx}|^2+|\boldsymbol{r}_{xx}|^2=1$[13]. At the same time, due to the existence of the metal backing plate, the transmission coefficient is approximately to zero and the reflected wave exists only. The phase difference between the co-polarized reflection r_{xx} and the cross-polarized reflection r_{yx} is defined as $\Delta\varphi_{yx}=\arg(r_{yx})-\arg(r_{xx})$[21], and the value of $\Delta\varphi_{yx}$ is a key factor in the polarization state of the reflected wave. $\Delta\varphi_{yx}$ can take arbitrary values in the range of [−180°, 180°] according to the different frequencies, which means that all polarization states (circular, linear, elliptical) are probable for the reflected waves. $\Delta\varphi_{yx}=0°$ or $\Delta\varphi_{yx}=\pm180°$ indicates the obtained reflected wave is in a linear polarization state. $\Delta\varphi_{yx}=\pm90°$ and $|\boldsymbol{r}_{yx}|/|\boldsymbol{r}_{xx}|=1$ indicate the obtained reflected waves are in a circular polarization state, while others are elliptically polarized waves. It should be noted that the positive or negative value of $\Delta\varphi_{yx}$ determines the revolving direction of the polarization converter. $\Delta\varphi_{yx}>0$ indicates that the direction of the polarization revolving direction is counterclockwise (right-handed circularly polarized wave). On the contrary, the polarization revolving direction is clockwise (left-handed circularly polarized wave).

The simulation results of the co- and cross-polarized reflections are shown in Fig.3(a). It can be found that the co-polarized reflection r_{xx} is approximately close to 0 and the cross-polarized reflection r_{yx} is greater than 90% in the two working bands (6.75—10.59 GHz, 17.78—19.61 GHz). More narrowly, in the frequency range of 7.38—9.50 GHz, the cross-polarized reflection is higher than 99%. And in the frequency range of 18.30—19.27 GHz, the cross-polarized reflection is higher than 97%. Therefore, it can be concluded that nearly all x-polarized incident waves are converted to y-polarized reflected waves within the two working bands (7.38—9.50 GHz, 18.30—19.27 GHz), achieving a perfect polarization conversion effect.

The *PCR* of the converter is also obtained, as shown in Fig.3(b). It can be found from the figure that the minimum value of the *PCR* is 99% within the two working bands (6.75—10.59 GHz, 17.73—19.67 GHz). Therefore, it can be concluded that the 99% polarization conversion bands are from 6.75 GHz to 10.59 GHz and 17.73 GHz to 19.67 GHz, indicating that the incident waves can achieve high-efficiency polarization conversion in these two working bands.

In addition, the phase difference $\Delta\varphi_{yx}$ between the co-polarized reflection and cross-polarized reflection is calculated (shown in Fig.3(c)). As can be seen from Fig.3(a) and (c), the reflections r_{yx} and r_{xx} are approximately equal to 0.5 at the four frequencies of 5.94 GHz, 12.29 GHz, 16.81 GHz and 20.08 GHz. The phase difference $\Delta\varphi_{yx}$ is almost close to 90° or −90° at the four frequencies, which means the reflected waves at these four frequencies are circularly polarized waves but not pure. In more detail, the phase difference $\Delta\varphi_{yx}$ is almost equal to 90° at 5.94 GHz and 12.29 GHz, indicating the circularly polarized wave is a right-handed circularly polarized wave at the two frequencies. The phase difference $\Delta\varphi_{yx}$ is almost equal to −90° at 16.81 GHz and 20.08 GHz, indicating the circularly polarized wave is a left-handed circularly polarized wave at the two frequencies.

Furthermore, to better understand the working physical mechanism of the polarization converter, we have observed the surface current distributions of the converter's front and back layers at the two frequencies of 9 GHz and 18.5 GHz, respectively, within the two working bands (as shown in Fig.4). At the frequency of 9 GHz, the surface current directions of the front metal resonant layer are opposite to the current directions of the metal backing layer. Therefore, an equivalent current is generated between the front metal resonant layer and the metal backing layer. Such surface current distributions produce a magnetic resonance[21]. At the frequency of 18.5 GHz, the surface current directions of the front metal resonant layer are nearly parallel to the current directions of the metal backing layer, which can generate an electrical response. Besides, the current distributions in the center of the metal backing layer are opposite to the front metal resonant layer, thus the magnetic resonance is induced in the center of the converter, and there will be a combination of the electric and magnetic resonances at the frequency of 18.5 GHz.

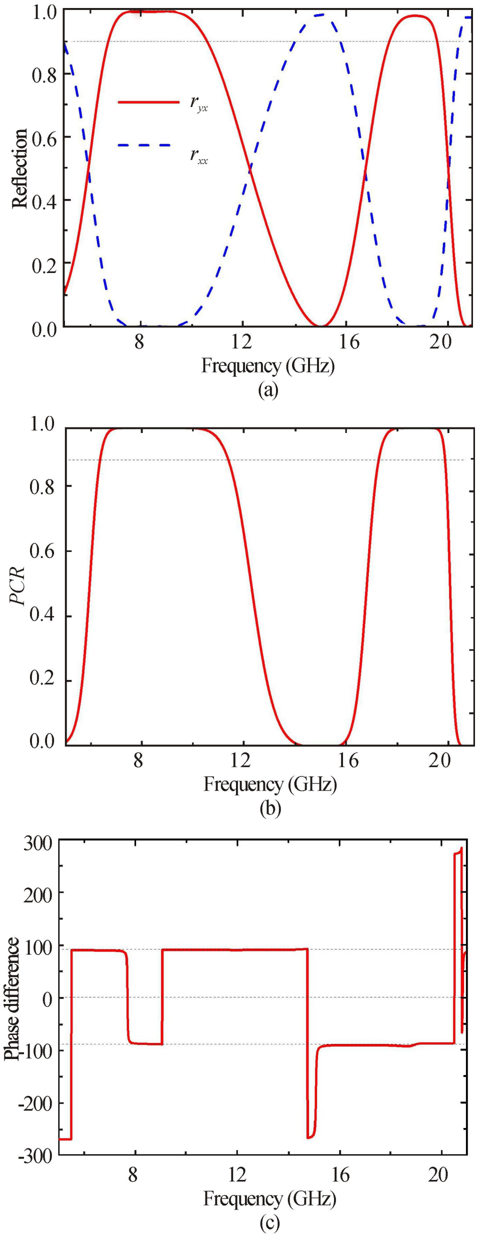
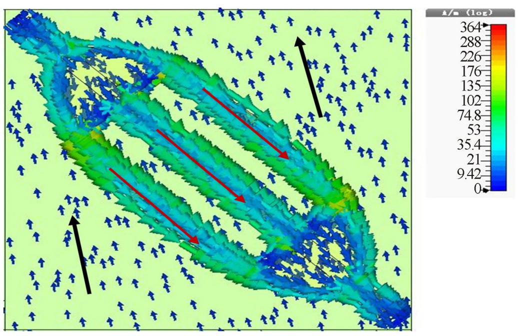
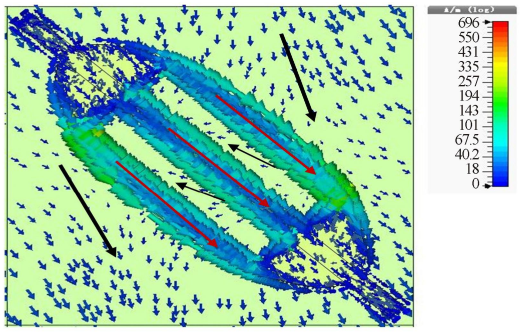


Fig.3 Simulation results of the polarization converter: (a) Simulated reflections of r_{yx} and r_{xx}; (b) Polarization conversion ratio of the converter; (c) Simulated phase difference $\Delta\varphi_{yx}$ between r_{yx} and r_{xx}



f =9 GHz
(a)



f=18. 5 GHz
(b)

Fig.4 Surface current distributions of the polarization converter with the front layer and the back layer at the resonant frequencies for incident *x*-polarized waves at (a) 9 GHz and (b) 18.5 GHz

In summary, this paper proposes a dual-band polarization converter based on metasurface. Numerical simulations demonstrate that the polarization converter is able to achieve high-efficient polarization conversion in two working bands, and 90% polarization conversion bands are from 6.75 GHz to 10.59 GHz and 17.78 GHz to 19.61 GHz. Furthermore, the *PCR* of the converter in this paper is close to 100% in the two working bands (6.75—10.59 GHz, 17.73—19.67 GHz), so it is indicated that the polarization converter can perfectly convert the linearly polarized wave to cross-polarized wave. Moreover, the converter proposed in this paper can convert the linearly polarized wave to circularly polarized wave at four frequencies. The polarization converter based on metasurface has broad application prospects in antenna design and telecommunication.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

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