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Design of a wideband reflective linear polarization converter based on the ladder-shaped structure metasurface

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ABSTRACT

In this paper, a ladder-shaped structure metasurface is proposed and investigated theoretically and experimentally, which can efficiently convert a linear polarized electromagnetic (EM) wave to its orthogonal component in a wideband range. The wideband reflective polarization convertibility is resulted from three resonance modes generated by the ladder-shaped structure MM for the normal incident waves. The mechanism of high-efficiency reflective polarization conversion is illustrated by surface current distribution and the destructive interference theory. The experimental measurement results show that the average polarization conversion ratio (PCR) is greater than 90% from 6.9 to 15.4 GHz, which are in good agreement with the numerical simulations and theoretical predictions. The designed metasurface possesses the merits of wideband and high-efficiency, and thus has great application values in novel polarization-control devices.

1. Introduction

Polarization is one of an important characteristic of electromagnetic (EM) waves. It is highly desirable to control the polarization state of EM waves effectively because of its wide use in many areas such as antenna radome, remote sensors, and radiometer [1]. Conventional methods to manipulate polarization are usually employing optical gratings and dichroic crystals [2,3]. In these conventional methods, to broaden the limited bandwidth, the complex designs using multilayered films or Fresnel rhombs are usually required [4]. Therefore, increasing the operational bandwidth and improving efficiency for polarization conversion with small thickness and simple design is highly desirable.

Metamaterials (MMs) are artificial materials constructed with subwavelength periodic structural units possessing some physical properties that do not exist in the natural world [5–11]. Metasurface as a sub of the MMs, which provide additional opportunities to manipulate the EM waves, including the polarization state [12–16]. In the past few years, various metasurface structures have been proposed for polarization manipulation based on anisotropic and chiral structures from microwave to optical frequency ranges [17–30]. These EM wave polarization manipulation devices can either convert one polarization into its orthogonal component or linear (circular) to circular (linear) polarization in some degree. However, narrow bandwidth and low efficiency are still obvious disadvantages that restrict their practical applications. Yin et al. proposed

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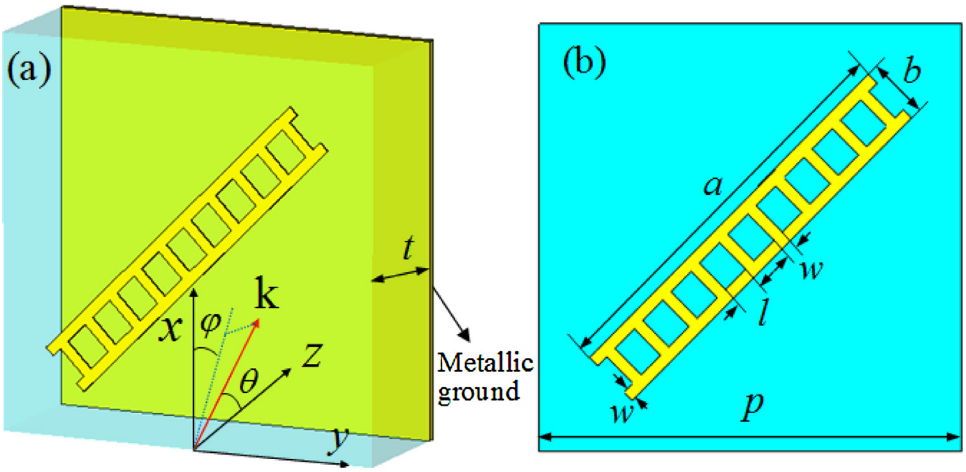

Fig. 1. The design scheme of the polarization converter: (a) side view and (b) front view of a unit cell.

an anchor-shaped structure metasurface, which can convert a linear polarization to its orthogonal component in microwave region [31]. Though a relative wide frequency band is achieved, the design procedure of the structure is rather complicated. Then, Gao et al. proposed a double V-shaped structure metasurface as a linear polarization converter with both wideband and high-efficiency [32]. However, the formulas to calculate the overall reflection coefficients are not explicit enough and the solving process is also not explained as well.

In this paper, we design a wideband and high-efficiency polarization converter based on ladder-shaped structure metasurface. Both numerical simulations and measurements show that the proposed metasurface structure can convert a linear polarization into its orthogonal polarization in the frequency range from 6.9 to 15.4 GHz, in which the average polarization conversion ratio (PCR) is greater than 90%. In addition, three resonances generated by magnetic and electric responses of the metasurface structure can contribute to the expansion of bandwidth. Moreover, we theoretically prove that the high-efficiency is occupied through destructive interference between direct reflection and the following multiple reflections of the co-polarized EM waves.

2. Unit-cell design, simulation and theoretical analysis

The reflective polarization converter usually consist of tri-layer sandwiched structure, including top electric resonator structure, intermediate dielectric layer, and bottom continuous metallic layer [32–35]. In order to generate the orthotropic wave when an x- or y-polarized wave illuminates the metasurface structure, the electric resonator structure should be asymmetric about x- and y-axis. However, the electric resonator structure also should possess a symmetric axis along 45° with respect to x direction so that the 90° polarization conversion can be achieved when the incident wave is x- or y-polarization [35].

Based on the above operational principles and referring to the rectangle-shaped structure shown in the reference [34], we propose a ladder-shaped structure metasurface for reflective polarization conversion as shown in Fig. 1(a). The unit cell is formed by the metallic ladder-shaped structure with a backing metal ground sheet. The metallic ladder-shaped structure and the backing sheet are separated by a FR-4 dielectric spacer with a thickness t = 3.0 mm and a relative permittivity of $\varepsilon_r = 4.3(1 + i0.025)$. The optimized structural parameters are p = 9 mm, a = 8.4 mm, b = 1.3 mm, l = 0.6 mm, and w = 0.25 mm as shown in Fig. 1(b). The metallic layer is modeled as a copper film with a thickness 0.035 mm and electrical conductivity $\sigma = 5.8 \times 10^7$ S/m. To gain insight into the mechanism of the polarization conversion, we performed a full wave simulation based on the finite integration technology (FIT) by using CST Microwave Studio Frequency Domain Solver. In simulation, the periodic boundary conditions were applied to the x and y directions, respectively.

To better understand the polarization conversion of the designed structure, we define $r_{xx} = |E_{xr}|/|E_{xi}|$ and $r_{yx} = |E_{yr}|/|E_{xi}|$ to denote the co- and cross-polarization reflection coefficients for x-polarized normal incident EM waves respectively. Generally, the polarization conversion efficiency can be defined as $\mathrm{PCR} = r_{yx}^2/(r_{yx}^2 + r_{xx}^2)$ for x-to-y polarization. Fig. 2 shows the simulated reflection coefficient magnitudes of co- and cross-polarization and PCR versus frequency. From Fig. 2(a), the reflection coefficient of cross-polarization is larger than 80% in a wideband, and the resonance peak values are up to 0.93, 0.94, and 0.89 at three resonance frequencies of 7.4 GHz, 11.5 GHz and 14.8 GHz. As shown in Fig. 2(b), the PCR is larger than 90% in a wideband from 6.9 to 15.4 GHz except a small dip between first two resonance frequencies. It means that most EM energy of x-polarized incident waves is converted to y-polarized ones in above broadband range. Hence, the ladder-shaped structure metasurface is actually working as a high quality polarization converter when considering both bandwidth and efficiency.