Structurally Tunable Reflective Metamaterial Polarization

Transformer based on Closed Fish-scale Structure

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Abstract

A reflective metamaterial polarization transformer (RMPT) is proposed with closed fish-scale structure for high efficient cross-polarization reflection. The maximum efficiency of cross-polarization reflection for normal incidence is 97.2%. The RMPT maintains good performance for incident angles up to 25°, and the RMPT is not restricted to a specific polarization state of the incident wave. Furthermore, the designed RMPT shows excellent structural tunability by optimizing the structural parameters, which make it user-friendly.

Keywords: Reflective metamaterial polarization transformer; Co-polarization reflection; Cross-polarization reflection.

1. Introduction

The manipulation of polarization state of electromagnetic (EM) wave is becoming more and more important for practical applications [1-8]. It is well known that the conventional polarization transformers are based on the mechanism of birefringence and/or total internal reflection which always limit the working bandwidth in applications [7]. Metamaterials are promising in improving the EM characteristics to a great extent from their chemical compositions by artificially designing novel structures at subwavelength scale [9-15]. In the past decade, the control of polarization states of the EM waves with planar metamaterials [7-9] has been a hot spot in the study of functional metamaterials. For example, a kind of reflection-type quarter wave plate was proposed and realized with geometrically anisotropic coding metasurface [16]. Compared with traditional wave plates, metamaterial polarization transformers have the advantages of miniaturized dimension and high efficiency polarization transformation. The polarization transformers based on metamaterial have attracted considerable interest due to these advantages [17-19].

Tremain et al. demonstrated a broadband RMPT with high efficiency and polarization selective characteristics using rectangular birefringent [20]. An

anchor-shaped ultra-wideband polarization converter with the polarization dependent and incident angle insensitivity properties in the microwave frequency was proposed [21]. Guo et al. demonstrated a metamirror to realize polarization transformation with 4-octave bandwidth [22]. Multi-band linear and circular RMPT was proposed using the F-shaped metamaterial [23]. Zhang et al. proposed a broadband reflective polarization converter working in the frequency range of 8.3 GHz to 14.3 GHz based on the asymmetric cross-shaped resonator [24]. The coding metasurfaces proposed in Refs [25, 26] may help realize the directional polarization transformer in the THz range.

The fish-scale structure (also called meandering wire structure) has been widely investigated for its abundant EM properties [27, 28]. A bilayer fish-scale metamaterial was demonstrated for ultrabroad THz band pass filtering [29]. The twist structure comprised of fish-scale wires can be optimized for perfect polarization transformation by the transmission [5]. Recently, the connected fish-scale structure has been proposed to realize broadband absorption at optical frequencies [30]. As demonstrated by Zhang et al, there existed non-zero cross-polarization reflection for the connected fish-scale structure at several frequency ranges under oblique incidence at optical frequencies. In this paper, we show that the connected fish-scale structure can also be employed for broadband RMPT at the microwave frequencies. The RMPT with high polarization conversion rate (PCR) and excellent structural tunability shows weak dependency to the polarization states of the incident EM waves compared with the previous studies.

II. Simulation

The unit cell of the RMPT consists of two metallic layers and a spacing dielectric layer (shown in Fig. 1(a)). The top metallic layer is a closed fish-scale structure while the back metallic layer is continuous. The closed fish-scale structure is a square loop comprised of connected rectangular fish-scale metallic strips. The metal is chosen to be lossy copper whose conductivity is $\sigma = 5.96 \times 10^7$ S/m. TaconicTLY-5 is chosen as the spacing dielectric with relative permittivity and loss tangent of 2.2 and 0.0009, respectively. The copper strips and air-gaps of the closed fish-scale structure are marked by g_1 to g_4 to denote different widths (shown in Fig. 1(b)). Apparently, every side of the closed fish-scale structure is composed of a meandering wire with characteristic parameter of g_i ($i = 1, 2, 3, 4$) and metallic strips with width of $2g_1$.

Fig. 1. (Color online only) Schematic diagram of the RMPT: (a) unit cell, (b) front view of the unit cell.

In the RMPT design, the thick continuous metallic back layer of the RMPT blocks the EM wave propagation, so the incident wave will be mainly reflected back and partially absorbed because of dielectric loss or/and Ohm loss in the RMPT. Then the wave scattering properties of the RMPT for x -polarized incidence can be expressed as [31, 32]: $R_{yx}(\omega) + R_{xx}(\omega) + A_x(\omega) = 1$. The subscript yx in the formula refers to the mode conversion from x -polarized wave to y -polarized wave while xx represents the co-polarization. $A_x(\omega)$ is the absorption for the x -polarized incidence. $R_{yx}(\omega) = |S_{1y1x}(\omega)|^2$ and $R_{xx}(\omega) = |S_{1x1x}(\omega)|^2$ are the cross- and co-polarization reflection, respectively, for the x -polarized incidence. So the cross-polarization reflection R_{yx} of the RMPT is $R_{yx}(\omega) = 1 - A_x(\omega) - R_{xx}(\omega)$. As to the y -polarized incidence, similar formulas can be gained. In order to make an RMPT with good performance, the absorption $A_x(\omega)$ and co-polarization reflection R_{xx} should be suppressed.

III. Results and analysis

As seen, the structural parameters to be optimized in designing the RMPT include the period of the unit cell (P), side lengths of the closed fish-scale structure (l) and the central square hole (b), four characteristic parameters g_1 to g_4 and thicknesses of the copper layer t_c and spacing dielectric layer t_d . Our simulation

results are performed using the finite element method. We use periodic boundary conditions along x and y direction. As to the z direction, open boundary condition is employed. The distance between the RMPT and the receiver is large enough so we can only gain the information of the reflected wave.

In order to realize high performance polarization transformation, the RMPT should be asymmetric as to the incident EM wave. After the optimization of the structural parameters, the RMPT shows excellent performance when the parameters g_1 , g_2 , g_3 and g_4 are set to be an arithmetic sequence and $b = 3g_1$, $l = 7g_1$. The above relationships between the structural parameters indicate that the RMPT has excellent structural tunability which is proved by the simulation results (shown in Fig. 2).

As shown in Fig. 2, the designed RMPT has a main working band with bandwidth of about 2.5 GHz. As seen, this RMPT has excellent structural tunability because its main working band can be moved in the frequency range of 11 to 19.5 GHz when parameter g_1 increases from 1.3 to 2 mm.

In our design, the parameter g_1 is almost at liberty apart from the other structural parameters. When g_1 is determined, there is an optimized set of parameters to realize the best performance of the RMPT (g_1 to g_4 are set to be an arithmetic sequence and $b = 3g_1$, $l = 7g_1$). In a word, the optimization procedure of the RMPT is simpler compared with the previous studies.

After the sweep of parameter g_1 (shown in Fig. 2), we put $g_1 = 1.5$ mm as an example to illustrate the high performance of the RMPT. The other optimal parameters for the RMPT are set to be (in millimeters): $g_2 = 1.2$, $g_3 = 0.9$, $g_4 = 0.6$, $b = 4.5$, $l = 10.5$, $P = 11.1$, $t_c = 0.019$ and $t_d = 3$.

To avoid the strong magnetic coupling between the closed fish-scale structure and the ground metal plane which will result in the narrow working band [22], the thickness of the spacing dielectric layer is set to be 3 mm which is about 1/6 of the central working wavelength for the RMPT with characteristic parameter of $g_1 = 1.5$ mm. When the parameter g_1 increases from 1.3 to 2 mm, the thickness of the dielectric layer is set to be constant ($t_d = 3$ mm).

Fig. 2. (Color online only) Calculated cross-polarization reflection R_{yx} as a function of parameter g_1 and frequency.

The absorption A_x , co-polarization reflection R_{xx} and cross-polarization reflection R_{yx} , R_{xy} as functions of frequency are shown in Fig. 3(a) (for the RMPT with characteristic parameter of $g_1 = 1.5$ mm). From 14 to 19 GHz, there is a main working band (centered at 15.98 GHz) and a secondary working band (centered at 18.38 GHz). The cross-polarization reflection R_{yx} (R_{xy}) of the RMPT is higher than 90% from 15.04 to 17.20 GHz. Especially, the value of R_{yx} (R_{xy}) is higher than 97% from 15.46 to 16.22 GHz (the maximum value is 97.2% at 15.98 GHz). In the main working band, the maximum value of the absorption A_x is lower than 10%.

The corresponding PCR, defined as $|R_{cross}|^2 / (|R_{cross}|^2 + |R_{co}|^2)$ [33], which is an important parameter describing the performance of the polarization transformer is shown in Fig. 3(b). The PCR of the RMPT is higher than 97% from 14.88 to 17.36 GHz.

Fig. 3. (Color online only) (a) Absorption A_x , co-polarization reflection R_{xx} and cross-polarization reflection R_{yx} , R_{xy} , (b) polarization conversion rate of the RMPT.

The rectangular coefficient whose definition is the bandwidth ratio between the high ($>80\%$) and the low ($<20\%$) conversion is also an important parameter to illustrate the performance of the polarization transformer [22]. As to the main working band of the proposed RMPT, the rectangular coefficient is 0.7.

Despite the incidences with polarization angles of 0° (x -polarized) and 90° (y -polarized), the designed RMPT maintains good performance when the polarization angle is lower than 15° or higher than 75° (shown in Fig. 4). The averaged cross-polarization reflection R_{yx} is higher than 70% in the working band of 15.02 to 17.52 GHz for the EM wave with 75° polarization angle. However, R_{yx} is lower than 16% in the main working band for the EM waves with polarization angles between 35° and 55° . The cross-polarization reflection R_{xy} has the same result which is not shown here.

Fig. 4. (Color online only) Polarization-conversion characteristics of the RMPT when the polarization angle increases from 0° to 90° .

The secondary working band of the RMPA is almost independent to the polarization state of the incident wave when the polarization angle increases from 0° to 60° except for a little red shift (shown in Fig. 4). Finally it joins the main working band when the polarization angle is higher than 60° . However, its intensity shows little dependency to the polarization angle compared with the main working band.

To further understand the physical mechanism of the polarization transformer, the surface currents distribution at 15.98 GHz is calculated. As shown in Fig. 5, the incident magnetic field (whose direction is marked by the blue arrow) has a 45° deviation from the magnetic moments induced by the surface currents (whose directions are indicated by the red arrows) which accounts for the polarization rotation of the incident EM wave. To illustrate this result clearly, only one set of currents on the closed fish-scale structure and the back metallic layer are marked in Fig. 5. As seen, there are several sets of currents which can also form the magnetic moments which have 45° deviation from the incident magnetic field.

Fig. 5. (Color online only) Surface current distributions of the RMPT at 15.98 GHz for the y -polarized incidence. The blue and red arrows represent the directions of the incident magnetic field and the surface currents, respectively.

As shown in Fig. 5, the resonance at 15.98 GHz is a magnetic mode according to the currents distributions. This magnetic resonance leads to in-phase reflection because of the high surface impedance $Z = \sqrt{\mu/\epsilon}$ [34]. For the y -polarized incidence, the electric field will be decomposed into components along the u and v axes (shown in Fig. 6(a)), respectively. As shown in Figs. 6(b)-(d), the reflection is in-phase in the u direction at resonance. Due to the geometrical anisotropy of the unit cell, the reflection is out-phase in the v direction at resonant frequency, which is similar to that in Ref [21]. Therefore, the reflected u and v components of the electric field have absolute phase difference of 180° , which leads to the polarization rotation of the y -polarized EM wave [35].

The asymmetry of the closed fish-scale structure for the incident wave with 45° polarization angle is not so strong as to the incident EM waves with polarization angle

of 0° or 90° . So the RMPT shows poor performance for the EM wave with polarization angle near 45° (shown in Fig. 4).

Fig. 6. (Color online only) (a) Decomposition schematic of the electric fields for the y-polarized incidence. Reflection phase for the (b) y-polarized incidence, (c) u -polarized incidence, (d) v -polarized incidence.

As for the non-normal incident wave, the proposed RMPT maintains the effective polarization conversions in a wide frequency band for incident angles up to 25° (shown in Fig. 7). The value of cross-polarization reflection is higher than 40% in the frequency range of 13.74 to 16.55 GHz at 25° incidence. With the increase of the incident angle, the main and secondary working bands have a red-shift. Interestingly, another broadband (about 16.5 to 18.6 GHz) of polarization conversion emerges when the incident angle is higher than 35° and this working band maintains effective polarization conversion until the 80° incidence.

Fig. 7. (Color online only) Cross-polarization reflection of the RMPT for the non-normal incidences.

IV. Conclusion

We have proposed a reflective polarization transformer based on the closed fish-scale structure. With a maximum efficiency of 97.2%, the cross-polarization reflection of the transformer is higher than 90% in a frequency range of 15.04-17.20 GHz at normal incidence. In the main operating band, both the co-polarization reflection and the absorption are almost zero which contribute to the high performance of the polarization transformer.

The total thickness of the RMPT is only 1/6 of the center working wavelength. However, the good performance of the polarization transformer is maintained for incident angles up to 25°. Furthermore, the performance of the RMPT is not restricted to the x - or y -polarized incidences. This RMPT is insensitive to the polarization state of the incident EM wave except that it has poor performance for the incident wave with polarization angle near 45°. The polarization transformer is based on the metamaterial with closed fish-scale structure which showed structurally tunable broadband EM response [30], thus it is possible to achieve structurally tunable RMPT further extending the working bandwidth for practical applications. In a word, the proposed polarization transformer exhibits unique characteristics including high PCR, broad bandwidth, and excellent working-band tunability.

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