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Citation: J. Appl. Phys. 114, 074508 (2013); doi: 10.1063/1.4819017
View online: http://dx.doi.org/10.1063/1.4819017
View Table of Contents: http://jap.aip.org/resource/1/JAPIAU/v114/i7
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Broadband polarization rotator based on multi-order plasmon resonances and high impedance surfaces

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(Received 18 January 2013; accepted 6 August 2013; published online 19 August 2013)

We experimentally investigate the electromagnetic (EM) responses of a broadband reflective polarization rotator under normal incidence. It is found that the rotator can generate multi-order plasmon resonances at three neighboring frequencies. At each frequency, the rotator behaves as a high impedance surface along one axis while as a metallic reflective surface along the other axis. Thus, a 180° phase difference is generated between the two orthogonal components of reflected waves. When the incident wave is polarized by 45° with respect to the symmetry axis of the rotator, the polarization of reflected waves is rotated by 90°. The designed rotator presents broadband properties. It can perform perfect 90° polarization rotation at three frequencies and maintains a polarization conversion efficiency greater than 56% in 2.0–3.5 GHz. The rotator provides a route to broadband polarization rotation and has application values in polarization control. © 2013 AIP Publishing LLC.

I. INTRODUCTION

Polarization is one of the most important properties of electromagnetic (EM) waves. It is of great significance to have full control of polarization states of EM waves. Conventional methods of manipulating polarization, such as optical activity crystals and Faraday effects, usually require quite long propagation distance to obtain the phase accumulation. Quite bulky devices are needed in these conventional methods. Hence, it is important to develop novel polarization control devices with small thickness and light weight.

Metamaterials refer to artificial materials or structures exhibiting unique properties that cannot be found in naturally occurring materials. By delicate designs, many fascinating functional devices can be developed based on metalodielectric structures, such as high-impedance surfaces (HIS), perfect absorbers, and EM cloaks. Particularly, using metamaterials, much thinner polarization controller can be developed. One method of implementing polarization control is to mimic molecule chirality (the fundamental of optical activity crystals) by designing planar or 3D chiral metamaterials. An alternative approach is to use achiral anisotropic metamaterials. However, to date, the operating bandwidths of metamaterial polarization rotators are quite narrow, which limits the practical applications of these designs.

In this paper, we show that anisotropic high-impedance surfaces can be used to achieve perfect polarization rotation. Furthermore, the operating frequency range can be broadened based on high-order plasmon resonances. We designed a broadband reflective polarization rotator operating in 2.0–3.5 GHz. The rotator can rotate the polarization plane by 90° while maintain the linearly polarized property. Experiment and simulation results validate the design. This paper is organized as follows. In Sec. II, we describe the design and simulation results of the rotator. Section III presents the fabricated sample and the experiment results. The polarization rotation effect and broadband property are analyzed theoretically. Section IV summarizes the results and concludes the paper.

II. DESIGN AND SIMULATION

Figure 1(a) schematically depicts the designed broadband polarization rotator illuminated by linearly polarized EM waves. The rotator can convert the polarization state completely to its orthogonal counterpart after reflection. The structure consists of three layers, with resonant microstructures arranged on the top layer periodically. The middle layer is dielectric substrate and the bottom layer is a full metallic sheet. Figure 1(b) gives the top view of an individual unit cell, a resonance structure composed of square metal patch with a square aperture in the center and an oblique cut gap on one corner. The structure can be considered as a modified split ring resonator (SRR). The geometrical parameters of the SRR are as follows: the periodicity $a = 20.2$ mm, the square side length $a = 18.4$ mm, the frame width $w = 7.8$ mm, and the gap-side arm length $b = 18.2$ mm. The gap width is 0.28 mm. The thicknesses of the dielectric substrate and metallic patterns are $d = 4$ mm and $t = 0.03$ mm, respectively.

In order to verify the designed broadband polarization rotator, numerical simulations were performed using the frequency domain solver in CST Microwave Studio. In the simulations, the metal material is copper (with a conductivity of $5.8 \times 10^7$ S/m) and the substrate is FR4 (with a dielectric constant 4.3 and a loss tangent 0.025).

The reflected waves generally consist of both $x$- and $y$-polarized components, even when the incident waves are in only one of the two polarization states. We define $r_{xx} = |E_{xx}/E_i|$ and $r_{xy} = |E_{xy}/E_i|$ to represent the reflection ratio of $x$-to-$x$, and $x$-to-$y$ polarization conversions, respectively.

Figure 2(a) gives the simulated magnitudes of $r_{xx}$ and $r_{xy}$. The curve of $r_{xy}$ shows three peak values that are near...
1.0. This means that at the three frequencies (2.044, 2.572, and 3.476 GHz), nearly all energy of x-polarized incident waves (x-polarization) is converted to y-polarized ones. We name these three key frequencies as first-, second-, and third-plasmon resonance frequencies, respectively. We will discuss them further in Sec. III. In between the three peak values, there are two dips for \( r_{xy} \), 0.77 and 0.8. This means that more than half the energy is converted to y-polarized waves at the two dips. For \( r_{xx} \), the magnitude is near zero at the three resonance frequencies, indicating that there is no x-polarization component in reflected waves and the electric field vector is rotated by 90°. The simulation results of \( r_{yy} \) and \( r_{xx} \) show that \( r_{yy} = r_{xx} \), \( r_{yx} = r_{xy} \). Here, we need to consider only \( r_{xx} \) and \( r_{xy} \).

Define polarization conversion ratio (PCR) \(^{12}\) as:

\[
\text{PCR} = \frac{r_{xy}}{\left(r_{xx}^2 + r_{xy}^2\right)^{1/2}}
\]

Fig. 2(b) gives the simulated PCR versus frequency. It is shown that in 2.0–3.5 GHz, PCR is all above 0.56 and achieves 1.0 at the three resonance frequencies. Fig. 3 gives the polarization ellipses of reflected waves at the three PCR peak frequencies as well as at the two PCR dip frequencies under x-polarized illumination.

### III. EXPERIMENT RESULTS AND DISCUSSIONS

#### A. Sample fabrication and measurement results

Fig. 4(a) shows the photo of the fabricated broadband polarization rotator, which contains 15 × 15 units in all, covering an area about 303 × 303 mm². The sample is fabricated by conventional printed circuit board (PCB) techniques. A double-side copper-cladding PCB board is etched with resonator patterns on one side while the copper cladding is kept on the other side.

The reflections \( |r_{xx}|^2 \) and \( |r_{xy}|^2 \) were measured using the Agilent E8363B network analyzer. Based on the complementary relation of \( |r_{xx}|^2 \) and \( |r_{xy}|^2 \) (\( |r_{xx}|^2 + |r_{xy}|^2 = 1 \) for lossless case), we test and verify the rotator’s operating frequency range and rotation effect.

Fig. 4(b) gives the measured reflection spectrum in 1.0–5.0 GHz. The measured reflection spectrum is very similar to the simulated ones except that there is a minor blue-shift for the resonance frequencies, owing to the fabrication precision and the finite number of unit cells in the test sample.
B. Broadening the frequency band by multi-order plasmon resonances

From the simulation and experiment results, it can be found that the rotator has a broadband property. This is resulted from the structure’s multi-order plasmon resonances. Meanwhile, the resonances couple with the back copper sheet, leading effectively to anisotropic HIS. The two orthogonal components of reflected waves acquire different reflection phases, so the polarization of reflected waves is rotated.

To understand the principle of the polarization rotator, we can model the structure as an anisotropic homogeneous metamaterial layer (of a thickness $d + t$) with a dispersive relative permeability tensor $\mu$ and a relative permittivity $\varepsilon$, put on top of a perfect metal substrate, as shown in Fig. 5(a). The resonator has a symmetrical axis, marked by $v$-axis, along the 45° direction with respect to x-axis, as shown in Fig. 5(b). Using $u$, $v$, and $z$ as the orthogonal coordinate system, $\mu$ can be expressed by diagonal elements ($\mu_{uu}$, $\mu_{vv}$, and $\mu_{zz}$).

Under normal incidence, the resonator can present multi-order plasmon resonances, just like other SRR structures. Odd-order plasmon resonances can be excited when the incident E field is perpendicular to the resonator’s gap (i.e., along the u-axis), while even-order plasmon resonances can be excited when the incident E field is parallel to resonator’s gap (i.e., along the v-axis). When the incident wave’s polarization is along x-axis, multi-order plasmon resonances can be excited, due to superposed contributions from the two individual orthogonal electric field components. Without the backing metal sheet mirror, these resonances exist but are quite weak. When the metal sheet is put on the back, the resonances will couple with the surface current induced on the metal sheet, enhancing the intensity remarkably.

Fig. 6 shows the current distribution at the three resonance frequencies calculated by simulation. We can find that the three resonances are just the three lowest-order plasmon resonances of SRR. At the first-order resonance frequency, a current loop is induced on the split ring, which can be modeled as gap-capacitive LC circuit. At the second resonance frequency, the current flows on the arms with the lower-right corner as a standing wave node. At the third resonance frequency, the current can be divided into three segments and there are two nodes on the bottom and right arms.

The resonance frequencies can be shifted by adjusting the resonator’s size parameters. In simulations, we find that by decreasing the gap the third resonance can be shifted closer to the second one; by increasing the frame width $w$, the second resonance get closer to the first one. Hence, by optimizing the parameters, we can implement optimized designs of broadband polarization rotators.

C. Perfect polarization conversion achieved by anisotropic high impedance surfaces

The split ring resonator possesses plasmon resonances in response to the incident E fields. Furthermore, the plasmon resonance can interact with the metal sheet to generate a composite resonance. According to Faraday’s law, surface currents of opposite signs will be induced in response to the time-varying B field sandwiched between the structure and the metal sheet. Hence, the entire system’s resonances serve as magnetic responses. At the resonance frequency, $\mu$ is divergent, which in turn gives a very large surface impedance ($Z = \sqrt{\mu/\varepsilon}$) and thus introduces in-phase reflection.

When the incident EM wave’s polarization direction is along u-axis, odd-order plasmon resonances can be excited. When the polarization direction switches to v-axis, even-order plasmon resonances can be excited. The structure presents anisotropy and $\mu_{uu}$, $\mu_{vv}$ are different. Therefore, at the resonant frequency, in one direction, the surface serves as a high impedance surface to present in-phase reflection, while in the other direction it produces anti-phase reflection.

Suppose the incident wave’s polarization has an angle $\theta$ with respect to u-axis, then we can write the E vector at $z = 0$ plane as $\vec{E}_i = E_{iu}\hat{e}_u + E_{iv}\hat{e}_v$, where $\hat{e}_u$, $\hat{e}_v$ are the unit vectors...
in \( u \) and \( v \) directions, respectively. At the resonance frequency, reflected electric components \( E_{ru} \) and \( E_{rv} \) get a 180° phase difference, so the reflected electric vector \( E_r \) will be rotated by 20°. Fig. 5(c) gives the example of the first-order resonance. \( E_{rv} \) is generated by anti-phase reflection, with a 180° phase difference relative to \( E_{iv} \). So, \( E_{rv} \) is anti-parallel to \( E_{iv} \). In contrast, \( E_{ru} \) is generated by the in-phase reflection, with the same direction as \( E_{iu} \). So, after reflection, \( E_r^* \) and \( E_i^* \) is symmetrical with respect to u-axis, resulting in a 20° angle between their polarization directions. When the incident wave’s polarization is along x-axis, \( \theta = 45° \), then the rotation angle is just 90°, leading to a perfect cross-polarization rotation.

D. Polarization rotation dependent on incident EM wave’s polarization

As is indicated by the above discussion, the rotator’s rotation effect is dependent on incident wave’s polarization direction. This is the inherent characteristic of all polarization control design based on anisotropy. Fig. 7(a) gives the simulation result of \( r_{xy} \) under different \( \theta \). It is shown that \( r_{xy} \) is nearly zero for \( \theta = 0° \). There is almost no x-to-y conversion, and thus, the polarization direction is unchanged. With \( \theta \) increased to 45°, the magnitude of \( r_{xy} \) rises to its maximum. Fig. 7(b) gives the simulation result of \( r_{xx} \) under different \( \theta \). Fig. 7(c) gives the experiment data of \( r_{xx} \) under \( \theta = 22.5° \). The experiment results agree well with the simulation ones.

IV. CONCLUSIONS

In conclusion, we experimentally investigate the electromagnetic responses of a broadband reflective polarization rotator under normal incidence. It is found that the rotator can generate different-order plasmon resonances at three neighboring frequencies in 1.0–5.0 GHz. At each resonance frequency, the rotator presents high impedance along one anisotropic axis while exhibits low impedance along the other anisotropic axis. So, the two orthogonal components of reflected waves have a 180° phase difference. When the polarization direction of the incident wave is along the 45° direction with respect to the rotator’s symmetry axis, the polarization direction of reflected waves is rotated by 90°. Owing to the three adjacent resonance frequencies, the rotator can achieve a broadband polarization rotation. The PCR is greater than 0.56 in 2.0–3.5 GHz, almost covering S band completely.

ACKNOWLEDGMENTS

The authors are grateful to the supports from the National Natural Science Foundation of China under Grant Nos. 11204378 and 11274389, the Postdoctoral Science Foundation of China under Grant No. 2013MS32131, and the National Natural Science Foundation of Shaanxi Province under Grant No. 2011JQ8031.