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Cross-polarization conversion with periodic perforated silver film in the near-infrared spectral range

Tie-Zhu Qiao[a,b], Hong-Mei Gong[c], Wei-bang Ji[a,b,*]

[a] Key Lab of Advanced Transducers and Intelligent Control System of Ministry of Education, Taiyuan University of Technology, Taiyuan 030024, P. R. China
[b] Department of Physics and Optoelectronics, Taiyuan University of Technology, Taiyuan 030024, P. R. China
[c] School of Science, Nanjing University of Science and Technology, Nanjing 210094, P. R. China

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ABSTRACT

An enhanced polarization rotation of the zero-order transmission in the near-infrared spectral range is realized by using a silver film with an array of perforated normal and oblique rectangular holes. The ellipticity is small when the phase difference between E_x and E_y components approaches to π, and the transmitted field is nearly linear polarized within a wide spectral range. The polarization of transmitted field is determined by the intensity ratio between x and y components of electric field, which is modified by manipulating the incident wavelength or the incident polarization. Without changing the geometry parameters, one can get any desired rotation angle using the designed structure. In addition, the transmission is strong, and the designed structure can be used as a subwavelength half wave plate.

1. Introduction

Many important applications depend on the control of polarization of an electromagnetic wave, which has been realized using chiral or anisotropic materials, but with specific thickness and bulky configuration issues. Recently, a lot of microstructures and nanostructures have been proposed and demonstrated to achieve device miniaturization for polarization manipulating, such as helix metamaterials [1,2], spiral bull-eye structures [3–6], surface plasmon polaritonic crystals [7], non-Hermitian plasmonic metamaterials [8], and three-dimensional metamaterials [9]. Artificial chiral [10–14] and nonchiral [15,16] structures also have been used to realize polarization rotation, but the rotation angle is small for planar structures. Therefore, multilayer structures are designed to achieve a high rotation angle. For example, there is a 90° polarization rotation in multilayer artificial chiral structures [17–21], which can be used as half or quarter wave plates [22,23]. Nevertheless, it would be hard to fabricate multilayer devices.

Extraordinary optical transmission (EOT) in periodic perforated metallic structures has attracted considerable attentions in recent years [24], where there are enhanced zero-order optical transmissions. Different kinds of subwavelength holes have been investigated, among which rectangular holes influence dramatically the resonance position, the polarization, and the transmission [25–28]. With judicious engineering of metallic nanostructures, polarization rotation can be achieved by employing EOT effect. For example, the polarization of the zero-order transmitted light would rotate because of the charge transfer effect by using L-shaped nanohole arrays [29–31]. Unfortunately, the polarization rotation angle for a single-layer L-shaped nanohole arrays is hard to exceed 45° [32,33].

Not long ago, an S-shaped nanohole array is used to achieve a high polarization conversion [34], where the rotation angle is modulated due to the phase retardation of surface plasmon polaritons, and a 90° polarization rotation is demonstrated by manipulating the film thickness. Nevertheless, the transmission is less than 0.2 around the near-complete cross-polarization conversion spectral range, and it is still an issue to improve the transmission intensity. Besides that, the S-shaped nanohole array is not suitable using as half-wave plate. It also has been proposed that a subwavelength double-pattern rectangular aperture array composed of perfect electric conductor can be used to achieve a 90° polarization rotation [35,36]. However, there are strong non-radiative losses of realistic metals in the visible and near-infrared spectral range, and the perforated metallic film cannot be treated as perfect electric conductor. As a result, it is hard to achieve a cross-polarization conversion using the double-pattern rectangular aperture arrays within these spectral ranges. In this study, we show that an array of perforated oblique rectangular hole has the same optical responses as that of normal rectangular holes, and the phase difference as well as transmission intensity ratio between normal and oblique rectangular holes can be well tuned by manipulating geometry

* Corresponding author. Tel.: +86-351-6018014.
E-mail address: jiweibang@tyut.edu.cn (W.-b. Ji).

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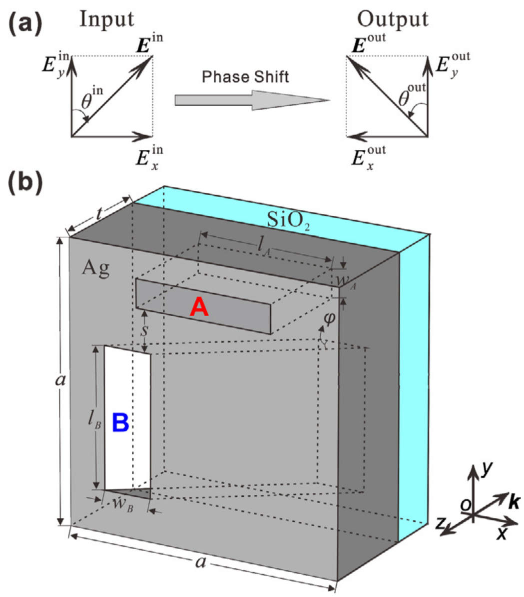

Fig. 1. (a) Schematic of the physical mechanism to realize an enhanced optical rotation. (b) One unit cell of the designed structure, where Holes A and B are normal and oblique rectangular holes, respectively. The geometry parameters used are t = 300 nm, w_A = 72 nm, w_B = 44 nm, l_A = 418 nm, l_B =Y532 nm, φ = 60°, s = 48 nm, and a = 700 nm.

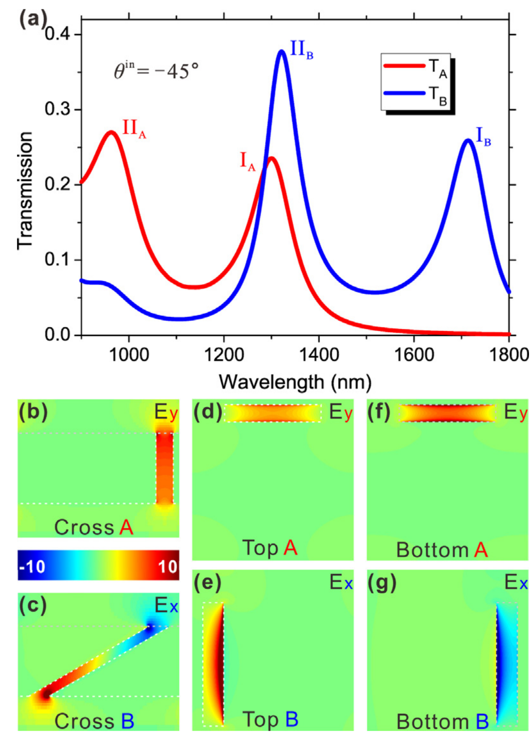

Fig. 2. (a) Transmission spectra of perforated silver films with Hole A (red solid line) and Hole B (blue solid line), where the incident polarization θ^{in} = -45°. (b,c) Electric field distributions of E_y (E_x) components at the central cross section of perforated film with Hole A (Hole B), (d, e) top interface, and (f, g) bottom interface, where the incident wavelength is 1308 nm, the white and gray dashed lines indicate the air−silver and glass−silver interfaces, respectively.

parameters. Therefore, an enhanced polarization rotation of the zero-order transmission is realized by using a silver film with an array of perforated normal and oblique rectangular holes in the near-infrared spectral range. The transmission is larger than 0.45, and the designed perforated film can be used as a subwavelength half wave plate.

2. Physical mechanism to achieve polarization rotation

The physical mechanism to realize a large polarization rotation is illustrated in Fig. 1a, where the incident field is linearly polarized, the phase difference δ^{in} between x and y components of the electric field (E_x^{in} and E_y^{in}) is 0, θ^{in} is the polarization angle versus y-axis, and the propagation direction is along−z-axis. For the output field, the ellipticity e can be modified by manipulating the phase difference δ^{out} between E_x^{out} and E_y^{out}, and it is linearly polarized when $\delta^{out} = n\pi$. The polarization angle θ^{out} depend on the intensity ratio between E_x^{out} and E_y^{out}. Thus, a polarization rotation angle in the range of 0–90° can be achieved by adjusting the phase difference and the intensity ratio. For example, suppose θ^{in} = −45°, θ^{out} = 45° when $\delta^{out} = \pi$ and E_x^{out}/E_y^{out} = 1, then a complete cross polarization conversion is obtained.

3. Result and discussion

A silver film with an array of perforated subwavelength holes is used to modify the phase difference and intensity ratio, and Fig. 1b shows a unit cell of the designed structure. There are two kinds of holes, where Holes A and B are, respectively, normal and oblique rectangular holes. Previous studies have demonstrated that extraordinary transmission through rectangular holes is very strong, and the transmission is highly dependent on the incident polarization. The long axes of Holes A and B are perpendicular with each other. Therefore, plasmons of Holes A and B can only be excited by y and x components of the electric field, respectively.

In addition, it is well known that EOT through rectangular holes is caused by the excitation of surface plasmon polaritons and localized plasmons, and it cannot be trivially separated in two distinct contributions. However, the transmission resonance mainly has a localized nature when the period of the array is smaller than the cutoff wavelength, that is, the transmission resonances are mainly related to Fabry-Pérot-like modes [25–27]. Thus, the phase difference δ^{out} between Holes A and B can be modified by adjusting the Fabry-Pérot-like resonances. The intensity ratios (E_x^{out}/E_y^{out}) can also be well tuned by manipulating the geometry parameters of the two holes. As a result, any polarization rotation angle can be achieved by using the designed structures.

First, the optical responses of perforated silver films with individual kinds of holes will be investigated. The red and blue solid lines in Fig. 2a represent the zero-order transmission spectra of Holes A and B, respectively. Finite difference time domain (FDTD) method is used to calculate the spectra, where the unit cell size of the mesh covering the film is 2 × 2 × 2 nm^3, perfectly matched layers (PML) at the−z and z directions are used to absorb the scattered field, periodic boundary is used in the other directions to simulate the infinite arrays, the permittivity of the glass substrate is supposed to be ε_{SiO2} = 2.2, and the dielectric responses of silver are taken from the literature [37]. In the calculations, the following parameters are used: the incident polarization angle θ^{in} = -45°, the film thickness t = 300 nm, the width w_A = 72 nm, w_B = 44 nm, the length l_A = 418 nm, l_B = 532 nm, the angle of obliquity of Hole B φ = 60°, and the period of the arrays a = 700 nm.

There are two pronounced transmission resonances in the calculated spectral range for the array consisting of Hole A. The short axis of Hole A is along the y-direction. Thus, the transmission resonances are mainly related to the y-component of the incident field. For the resonance with lower energy (peak I_A), Fig. 2b,d,f shows the electric field distributions of E_y components at the central cross section, top interface, and bottom interface, respectively. In order to have a comparison with the arrays consisting of Hole B, the chosen spectral position (1308 nm) is slightly away from the resonance.