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PHOTONICS AND NANOSTRUCTURES Fundamentals and Applications

Photonics and Nanostructures – Fundamentals and Applications 12 (2014) 189–198

www.elsevier.com/locate/photonics

Reflective plasmonic waveplates based on metal–insulator–metal subwavelength rectangular annular arrays

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Received 30 July 2013; received in revised form 3 January 2014; accepted 5 January 2014
Available online 11 January 2014

Abstract

We propose and present a quarter-wave plate using metal–insulator–metal (MIM) structure with sub-wavelength rectangular annular arrays (RAA) patterned in the upper Au film. It is found that by manipulating asymmetric width of the annular gaps along two orthogonal directions, the reflected amplitude and phase of the two orthogonal components can be well controlled via the RAA metasurface tuned by the MIM cavity effect, in which the localized surface plasmon resonance dip can be flattened with the cavity length. A quarter-wave plate has been realized through an optimized design at 1.55 μm, in which the phase difference variation of less than 2% of the $\pi/2$ between the two orthogonal components can be obtained in an ultra-wide wavelength range of about 130 nm, and the reflectivity is up to ~90% within the whole working wavelength band. It provides a great potential for applications in advanced nanophotonic devices and integrated photonic systems.

Keywords: Reflective waveplate; Localized surface plasmon; Rectangular annular arrays; Cavity effect

1. Introduction

Controlling and manipulating polarization state of light is crucial in all optical research and applications. Conventional component to manipulate polarization of light is the birefringent bulky dichotic crystals in which two different refractive indexes along two orthogonal optical axes resulting in a phase difference between the two directions. Recently, sub-wavelength nanoscale metallic devices attract increasing interests as a mean to control the interactions between light and metal by exciting surface plasmon polaritons (SPP) [1–8] resonance relate to the periodicity of the structure and localized surface plasmon (LSP) [9–11] resonance related to the shape effects of the structure. It has been proven that the LSP resonance is accompanied by phase shifts [12,13], from which miniature plasmonic waveplates (half and quarter-wave plates) can then be implemented [14–21].

Transmissive plasmonic waveplates have been proposed with different type of structures. Khoo et al. [14] and Zhao and Alu [15] respectively, proposed a quarter-wave plate based on nanoslits, in which two nanoslits are arranged perpendicular to one another, a $\pi/2$ phase difference of the transmitted field was realized by varying the dimensions of length and width of slits pair. Roberts

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1569-4410/$ – see front matter
http://dx.doi.org/10.1016/j.photonics.2014.01.001

et al. present a similar structure by utilizing resonances of subwavelength cross-shaped apertures in metallic film [16], in which an asymmetry was introduced into the length of the arms of the crosses, the phase difference of the transmitted field along two orthogonal directions at a particular wavelength can thus be tuned. Baida et al. proposed an anisotropic metamaterial plate exhibiting extraordinary transmission through perfectly conductor metallic screens perforated by subwavelength double-pattern rectangular aperture arrays [17]. The metal thickness is a key parameter that must be the integer multiples of half of the designed wavelength in order to get the desired phase difference between the two transversal electromagnetic field components. Li et al. experimentally demonstrate a half-wave plate with plasmonic assisted Fabry–Perot cavity and L-shaped hole arrays inside [18]. The phase difference is found arising from an overlap of the cavity and plasmonic modes in two orthogonal polarization states. The transmission of the device is, however, very low due to the strong absorption of the metallic thin film of the cavity.

In addition to the transmission mode, Hao et al. showed that the polarization states of electromagnetic waves can be manipulated in the reflection mode by an anisotropic metamaterial plate consisting of periodic arrays of H-shaped metallic pattern [19], and all possible polarizations (circular, elliptic, and linear) are realizable via adjusting structure parameters in the microwave band. Pors et al. proposed a nanometer cross consisting of two orthogonal antennas with the same cross section working in the reflection mode. When the length of two Au antennas are different, a phase difference of $\pi/2$ can be achieved [20]. In their structure, however, the incident polarization orientation must be set at 56° with respect to x axis to achieve the equal amplitudes of reflected fields in two orthogonal directions in order to obtain a circular polarization state, rather than 45° as that encountered in conventional wave plates. In 2012, Wang et al. also demonstrated a structure with optical patch nanoantennas arrays that can convert light polarization through reflection [21]. By breaking the azimuthal symmetry, elliptical plasmonic patch antenna arrays of periodic could support both even and odd cavity modes when the electric field incident parallel to long and short axes. Circular polarization state conversion from a linearly polarized incident state after reflection can be realized due to the phase delay of two orthogonal directions caused by resonant cavity modes.

In this paper, we propose a reflective plasmonic waveplate with much higher energy efficiency than those transmissive ones using metal–insulator–metal (MIM) structure. Subwavelength rectangular annular arrays (RAA) were patterned in the upper Au film which is separated with a dielectric spacer from the bottom thick metallic film. It is found that by manipulating asymmetric width of the annular air gaps along two orthogonal directions, the reflected amplitude and phase of the two orthogonal components can be well controlled via the RAA metasurface tuned by the MIM cavity effect, which breaks the limit of the fixed LSP resonance behavior determined by the dimensions of the metasurface only in conventional transmissive structure. By tuning the MIM cavity length, it is found that both the amplitude and phase change rate versus the wavelength can be controlled and optimized which forms solid basis for achieving waveplates with both high reflectivity and wide working bandwidth simultaneously. A quarter-wave plate has been realized through an optimized design at 1.55 μm, in which the phase difference variation of less than 2% of the $\pi/2$ between the two orthogonal components can be obtained in an ultra-wide wavelength range of about 130 nm, and the reflectivity is up to ∼90% within the whole working wavelength band.

2. Theory and structure design

The structure that we proposed is shown in Fig. 1. The structure comprises three functional layers forming a metal–insulator–metal (MIM) cavity on a glass substrate. The upper Au film is patterned with two-dimensional (2D) rectangular annular apertures arrays with periodicity P, and the thickness of the film is H_1, the slit width and length of the annular along y and x directions are W_1, L_1 and W_2, L_2 respectively. The insulator spacing layer is a continuous glass film with a refractive index 1.44 and a thickness of H_2. The lower metal film is continuous Au film with a thickness of H_3 fixed at 100 nm. Due to the thick enough Au film on the back, our system do not allow light transmit, and therefore, reflection properties only will be focused in the following. Finite difference time domain (FDTD) method is used to calculate the reflected field, periodic boundaries conditions were used at the x and y boundaries to simulate the periodic structure, and perfectly matched layers condition is utilized at the z boundaries in the simulation. The optical constants of Au used in our model were taken from Ref. [22]. A linear polarized plane light is normally incident onto the structure at a polarization orientation θ, the reflectivity normalized to the source power in far field was monitored, and from which the amplitude and phase of