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Electromagnetic near-field coupling induced polarization conversion and asymmetric transmission in plasmonic metasurfaces

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A R T I C L E I N F O

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A B S T R A C T

In this paper, we demonstrate the effect of polarization conversion in a plasmonic metasurface structure, in which each unit cell consists of a metal bar and four metal split-ring resonators (SRRs). Such effect is attributed to the fact that the dark plasmon mode of SRRs (bar), which radiates cross-polarized component, is induced by the bright plasmon mode of bar (SRRs) due to the electromagnetic near-field coupling between bar and SRRs. We find that there are two ways to achieve a large cross-polarized component in our proposed metasurface structure. The first way is realized when the dark plasmon mode of bar (SRRs) is in resonance, while at this time the bright plasmon mode of SRRs (bar) is not at resonant state. The second way is realized when the bright plasmon mode of SRRs (bar) is resonantly excited, while the dark plasmon mode of bar (SRRs) is at nonresonant state. It is also found that the linearly polarized light can be rotated by 56.5^0 after propagation through the metasurface structure. Furthermore, our proposed metasurface structure exhibits an asymmetric transmission for circularly polarized light. Our findings take a further step in developing integrated metasurface-based photonics devices for polarization manipulation and modulation.

1. Introduction

Photonic metamaterials, which consist of unit cells comprising planar or stacked planar nanostructures, created the possibility to capture and control electromagnetic near-field at subwavelength scale. Some exotic phenomena have been demonstrated in metamaterials, such as cloaking [1], perfect absorption [2], negative refraction [3], and the spin-Hall effect of light [4]. Besides the above phenomena, the asymmetric transmission (AT) for circularly [5–8] and linearly [9] polarized light has also been detected in planar and three-dimensional optical chiral metamaterials. Generally, the building blocks of metamaterials are composed of metallic resonators, and they are termed as meta-atoms. A canonical meta-atom is metal split-ring resonator (SRR) [10–13] but many others can be considered as well [14–16]. The electromagnetic properties of metamaterials are determined by the design and structural variations of individual meta-atoms. There exists a near-field coupling among meta-atoms in a metamolecule. The importance of such near-field coupling cannot be underestimated, since the near-field coupling would lead to several fascinating effects including resonance line narrowing, resonance mode splitting, and analogue of electromagnetically induced transparency [17–19]. The nature of such coupling depends mainly on the relative orientation position among meta-atoms.

In the past one decade, the polarization conversion in metamaterials has attracted considerably great interest [20–28]. It has been found that many metamolecule array structures (such as a single-layer gold nanorod array [20], four U-shaped SRRs [21], a meander wire structure [22], and two twisted aperture-type arrays [23]) exhibited polarization conversion performance, and the physical mechanisms including the anisotropic optical resonance mode [20], magnetic dipole coupling [21], interference theory based on the Fabry–Perot-like resonance [22], and the common effect of chirality and tunneling [23] have been revealed. Recently, the polarization control effect originating from near-field coupling between meta-atoms [29,30] and several dynamical tuning methods [14,31–33] have also been reported. For a planar metamolecule array which is composed of two orthogonal SRRs in each unit cell [29,30], the bright mode of one SRR is directly excited by

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incident electromagnetic field, while the dark mode of the other SRR is induced by near-field inductive coupling. The bright and dark modes would radiate orthogonally polarized components in the far field, so the polarization state of the output light is changed. Manipulating the polarization state of the output light has gained tremendous interest due to its various applications, such as polarization encoding [32], wave plates [33], beam splitter [34], vector beam generation [35], and polarization control [36].

In this work, we propose a metasurface structure by integrating a metal bar and four metal SRRs in each unit cell, to steer the polarization state of light. The polarization control in Refs. [29,30] is realized by using near-field inductive coupling between two orthogonally twisted SRRs, while in our proposed structure, the change of polarization state of light is attributed to the electromagnetic interaction between meta-atoms. The electromagnetic near-field coupling between bar and SRRs induces a cross-polarized radiation, which plays a dominant role in determining the polarization state of output light, and the polarization azimuth of linearly polarized light can be rotated by 56.5°. Moreover, our proposed structure exhibits an asymmetric transmission for forwardly and backwardly propagating circularly polarized light, which is helpful in designing a novel class of polarization sensitive devices and polarization transformers [37,38].

2. Model and numerical method

As shown in Fig. 1, we propose a planar metamolecule array that consists of a metal bar and four metal SRRs in each unit cell. A polarized light impinges normally on the structure (i.e., the propagation direction of incident light is perpendicular to the x–y plane). To rule out asymmetric effect due to the presence of a substrate, the metamolecule array is completely embedded in a dielectric medium. The structure can be fabricated by using sputtering deposition, electron-beam lithography, and reactive-ion etching. All the SRRs are identical in size which are made up of silver, and they are situated at the two sides of the metal bar. The right two SRRs are rotated by 180°relative to the left two SRRs. The geometrical parameters are shown in Fig. 1. The permittivity of silver is defined by the Drude model $\varepsilon_{Ag} = \varepsilon_0[\varepsilon_\infty - \omega_p^2/(\omega^2 + \gamma\omega)]$ with $\varepsilon_\infty = 3.8$, $\omega_p = 1.37\times10^{16}$ rad/s, and $\gamma = 5\times10^{13}$ rad/s [39]. The dielectric material is considered to be nondispersive with a relative permittivity of 2.1 [33].

In this work, the numerical simulations were performed by using the Lumerical FDTD solutions based on the finite-difference time-domain method. The spatial mesh cells are set to $\Delta x = \Delta y = \Delta z = \Delta s = 5$ nm, and the time step and the total number of time step are taken as $\Delta t = \Delta s/2c$ (c is the velocity of light in vacuum) and 2×10^4, respectively, which ensures that the electromagnetic fields in spatial grids are convergent and stable. The periodic boundary conditions are imposed in the x and y directions, while in the propagation direction of light the perfectly-matched absorbing boundary conditions are applied at the two ends of computational space.

3. The polarization conversion effect of linearly polarized light

The transmission of a linearly polarized light through the structure under consideration can be characterized by a 2 × 2 complex and dispersive entries t_{ij} of the Jones matrix T_{lin}. The T_{lin} matrix relates the generally complex amplitudes of the incident field to the complex amplitudes of the transmitted field [40]

$$\begin{pmatrix} E_x^{out} \\ E_y^{out} \end{pmatrix} = T_{lin} \begin{pmatrix} E_x^{in} \\ E_y^{in} \end{pmatrix} = \begin{pmatrix} t_{xx} & t_{xy} \\ t_{yx} & t_{yy} \end{pmatrix} \begin{pmatrix} E_x^{in} \\ E_y^{in} \end{pmatrix}, \quad (1)$$

where t_{ij} ($i(j) = x, y$) denotes i-polarized transmission coefficient from j-polarized incidence. In order to describe polarization state, we utilize Stokes parameters to express the output states as $s_0 = |t_{xy(xx)}|^2 + |t_{yy(yx)}|^2$, $s_1 = |t_{xy(xx)}|^2 - |t_{yy(yx)}|^2$, $s_2 = 2|t_{xy(xx)}||t_{yy(yx)}|\cos\Delta\varphi$ and $s_3 = 2|t_{xy(xx)}||t_{yy(yx)}|\sin\Delta\varphi$, where $\Delta\varphi$ is the phase difference between $\varphi_{yy(yx)}$ and $\varphi_{xy(xx)}$ [41,42]. The angle of polarization ellipse (AOP, ψ) and ellipticity (χ) are obtained by the expressions $\tan 2\psi = s_2/s_1$ and $\sin 2\chi = s_3/s_0$, respectively.

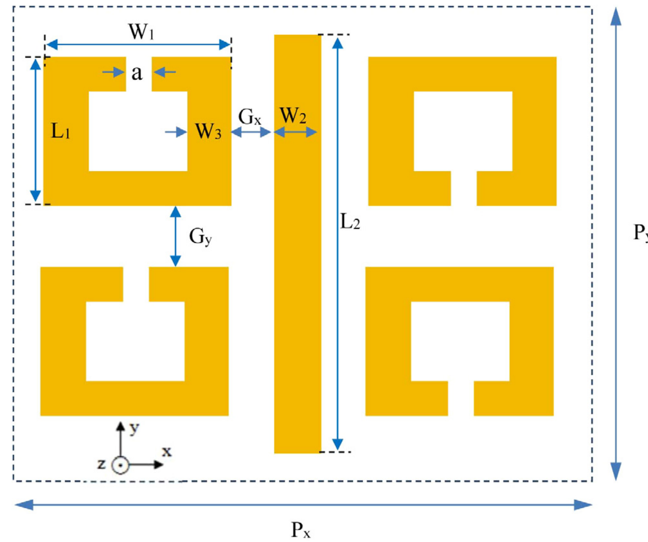

Fig. 1. Schematic model of a unit cell of our proposed planar metamolecular array. All the SRRs are identical in size, and they are situated at the two sides of the metal bar. The right two SRRs are rotated by 180° relative to the left two SRRs. The SRRs and metal bar are arranged in a 2D square lattice with lattice constant $P_x = P_y = 900$ nm. The geometrical parameters are $L_1 = 300$ nm, $W_1 = 260$ nm, $L_2 = 800$ nm, $W_2 = 80$ nm, $W_3 = 50$ nm, $a = 40$ nm, $G_x = 50$ nm, and $G_y = 100$ nm. The thickness of SRRs and metal bar is taken as 100 nm.

Firstly, we focus on the transmission characteristics of our proposed structure as a linearly polarized light propagates along the $-z$ direction. Fig. 2(a) depicts four transmission matrix elements t_{xx}, t_{xy}, t_{yx} and t_{yy}. In the case of x-polarized illumination, the co-polarization transmission t_{xx} has two dips which are located at 3.74 and 4.10 μm, respectively, while the cross polarization transmission t_{yx} reaches its extreme values at the wavelengths of 2.82 and 4.02 μm, respectively. The extreme values of t_{yx} at the two wavelengths are about 0.29 and 0.35, respectively. For the case of y-polarized light incidence, the co-polarization transmission t_{yy} approaches to its extreme value at the wavelengths of 2.86 and 4.15 μm, respectively, the spectrum line of conversional transmission t_{xy} is identical with that of t_{yx}. The existence of the peaks of t_{xy} and t_{yx} means that the bar-SRRs meta-molecule would radiate great orthogonally polarized signals in the far field. The reason for such phenomenon will be discussed subsequently. We calculated the AOP (ψ) as well as ellipticity (χ) of output light, as shown in Figs. 2(b) and 2(c), respectively. The AOP for the x (y) polarization reaches its extreme value 18.2°(−56.5°) at 2.83 (2.86) μm. Meanwhile, at the wavelength the ellipticity is about 0°. It suggests that the output light is linearly polarized and rotated by 18.2°(−56.5°) at 2.83 (2.86) μm for $x(y)$-polarized incidence. When the AOP ψ is −56.5°, the cross-polarized component of output light is larger than its co-polarized component. In Fig. 2(c), the ellipticity χ is in the range of [−20.2°,21.2°], it represents elliptically (linearly, $\chi = 0^0$) polarized light. For the $x(y)$-polarized light, χ approaches to its extreme values at 2.43 and 3.98 (2.70 and 4.04) μm, respectively. The extreme values originate from a large phase lag of the radiation from the indirectly excited dark SRR or bar that radiates a cross-polarized component.

To visualize cross-polarized component, we calculated the field distributions of E_z on the output surface of metamolecule for the transmission peaks of t_{xy} and t_{yx} in Fig. 2(a), as shown in Fig. 3. Fig. 3(a) ((3(c)) and 3(b) (3(d)) correspond to the wavelengths of 2.82 and 4.02 μm for the $x(y)$-polarized incidence, respectively. From the distribution of electric field E_z, we deduce the surface charge density on metal surface and the polarity of surface charge ($\sigma = \varepsilon \mathbf{n}_0 \cdot \Delta\mathbf{E}$, σ denotes