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All-dielectric metasurface realizing giant asymmetric transmission for linearly polarized wave

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ABSTRACT

In this paper, a kind of chiral all-dielectric metasurface is demonstrated numerically to achieve giant asymmetric transmission (AT) in fiber communication region. The incoming polarized electromagnetic wave excites magnetic and electric resonances and the resonances in AT spectrum coincide with eigen frequencies of this structure. The all dielectric metasurface shows more excellent properties compared with its metal counterpart. AT is influenced significantly by material permittivity as well as unit cell period. The concept of all-dielectric metasurface offers a new way to manipulate electromagnetic waves and the phenomenon remains effective in other frequencies.

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1. Introduction

Asymmetric transmission (AT) of electromagnetic (EM) waves, as one of novel properties of chiral metamaterials, was first reported by Fedotov [1] for circularly polarized EM waves. This new effect is fundamentally distinct from conventional gyrotropy of bulk chiral media and the Faraday effect. Contrasted to the non-reciprocal Faraday effect, the AT phenomenon in the chiral metamaterial does not violate the reciprocal theory and requires no magnetic medium. It results from different polarization conversion efficiencies between two orthogonal polarized states for waves propagating in opposite directions. Also, there is no diffraction in the transmission wave because of subwavelength unit cell of the chiral metamaterial. This AT concept was later extended to linearly polarized EM waves [2–4], in which the structure broke symmetry in the propagation direction. Subsequently, a large number of sophisticated metal-based metamaterials were proposed to achieve customized functionalities e.g. high performance asymmetric transmission metasurfaces [5,6], broadband asymmetric transmission metasurfaces [7,8] and 90° polarization rotator [9,10]. Nevertheless, one of the major limitations in metal-based metamaterials is the presence of Ohmic damping which results in absorption [11]. Moreover, as the plasmon resonant frequency is approached, the kinetic induction of the electrons in the metal results in saturation of the magnetic response, limiting the use of metal-based metamaterials at high frequencies [12]. Additionally, with scaling to high frequencies, dimensions of the unit cells get extremely small and the intricate unit cell designs prohibit large area scalability because of the expensive patterning equipment.

Recently, high-refractive-index dielectric particles (usually silicon, germanium and tellurium) offer an alternative way to these issues. Such particles exhibit magnetic and electric dipoles, which correspond to the first and second Mie resonances [13]. The magnetic Mie resonance possesses unique circular displacement currents and shows minimal absorption loss [14–18]. Meanwhile, coupling effects between all-dielectric nano-resonators can lead to interesting phenomena similar to their metallic counterparts, but with significantly enhanced efficiency and unique functionalities [18–21].

Very recently, it was shown theoretically that AT in the chiral photonic system is strongly related to the far-field properties of eigen modes of the system [22]. And the Mie resonance based silicon metasurfaces provide a way to considerable miniaturization due to their subwavelength features.

In this paper, we present the design specifications and insight analysis of AT for an all-dielectric chiral metasurface. It is shown that the normally incident EM waves excite magnetic and electric dipoles for different frequencies and AT is induced by mode coupling between these dipoles. The calculated eigenmodes' E-fields distribution is coincided with AT resonant frequencies E-fields distribution. It is shown that all-dielectric metasurfaces exhibit significantly enhanced efficiency and functionalities compared to their metallic counterparts. For all-dielectric metasurface, material permittivity is also a key factor to its properties.

2. Design and characterization

Fig. 1(a) illustrates the concept of AT in chiral photonic system. The x-polarized EM wave is normally incident on the system in the

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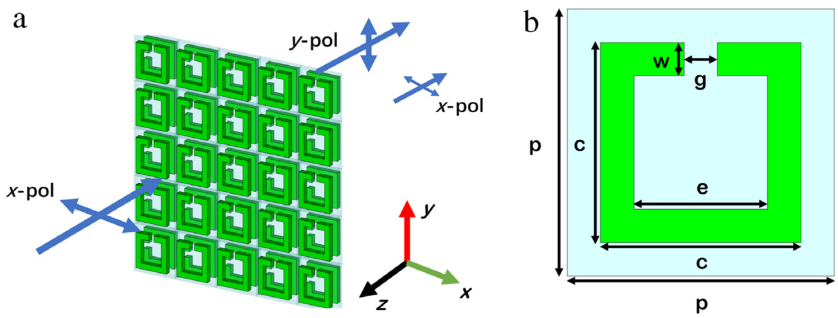

Fig. 1. (a) Schematic diagram of AT. (b) Unit cell of the structure, geometrical parameters: $p = 1200$ nm, $g = 150$ nm, $c = 900$ nm, $e = 600$ nm, $w = 150$ nm, and the thickness of the SRR is 150 nm. The distance (along z axis) between two layers is 250 nm, dielectric spacer's relative permittivity $\varepsilon_0 = 1.9$ and SRR's relative permittivity $\varepsilon_1 = 18$ with 0.001 tangent loss.

forward direction, the transmitted EM wave therefore contains both x-polarized and y-polarized components. The Jones matrix is described as $T^f = \begin{pmatrix} t_{xx} & t_{xy} \\ t_{yx} & t_{yy} \end{pmatrix}$, the superscript f indicates the forward propagation. By rotating the chiral media 180° with respect to either x or y axis [23], we get $T^b = \begin{pmatrix} t_{xx} & -t_{yx} \\ -t_{xy} & t_{yy} \end{pmatrix}$. AT is the difference of the total transmittances in forward and backward direction for a certain polarized wave. It has been shown that for reciprocal materials AT is equivalent to the difference between cross-polarization conversion between two orthogonally polarized waves [22–24]. Thus, the AT parameter Δ for linearly polarized wave is described as $\Delta^x = \left|t_{yx}\right|^2 - \left|t_{xy}\right|^2 = -\Delta^y$.

In order to realize giant AT for linearly polarized wave only, we use 90° twisted SRR structure [3]. The parameters are presented in Fig. 1(b). Germanium (Ge) was subsequently selected as the resonator material due to its large index of refraction and low loss at infrared region (n = 4.275 + i0.00567 at 1.55 μm and n = 4.135 + i0.000134 at 1.9 μm) [25]. We use commercial electromagnetic analysis software CST to analyze the chiral structure. The boundary condition is set as unit cell in x and y axis and open add space in z direction. Frequency domain solver is used to get the S-parameters, which is a common method used in many other papers [26].

3. Result and discussion

Fig. 2 shows the simulated transmission and reflection spectra and the calculated AT parameters. There are four resonant peaks and the AT parameter Δ reaches a maximum 0.81 at 193 THz, which shows a giant effect in fiber communication wavelength region. The remarkable AT originates from the polarization conversion difference of the chiral structure. When the x-polarized wave is normally incident on the structure, the wave is well coupled to the structure and converted mostly to y-polarized wave due to the cross coupling between two SRRs, while the y-polarized wave can hardly be coupled to the structure resulting in a weak transmission. In general, both transmitted and reflected waves are elliptical polarization. Only in some specific frequencies, e.g. for x polarized incident wave, at the frequencies of about 161 THz and 192 THz, the reflected wave is nearly linearly polarized. And at the frequencies of about 175 THz and 193 THz, the transmitted wave is nearly linearly polarized.

The first and second two resonant peaks are attributed to magnetic Mie resonance while the third and fourth resonant peaks are attributed to electric magnetic resonance. To provide a further insight, we simulate the E-field distribution around the structure at the resonant frequencies as shown in Fig. 3. At 137 THz (Fig. 3(a), the first resonant peak), the E-field forms same direction loop displacement current in both SRRs, which excites symmetric dipoles. These magnetic dipoles cause lower resonant frequency due to longitudinal coupling [27,28]. The situation at 158 THz (Fig. 3(b), the second resonant peak) is opposite to 137 THz which forms anti-symmetric dipoles in both SRRs. And the anti-dipoles result in higher resonant frequency. At 175 THz (Fig. 3(c), the third resonant peak), the electric dipoles in top SRR are same as bottom SRR, which cause symmetric mode. The situation at 193 THz (Fig. 3(d), the fourth resonant peak) is opposite to 175 THz which forms anti-symmetric electric dipoles in both SRRs. In addition, the E-field distribution at the third and fourth resonant peaks is similar as its metal counterpart.

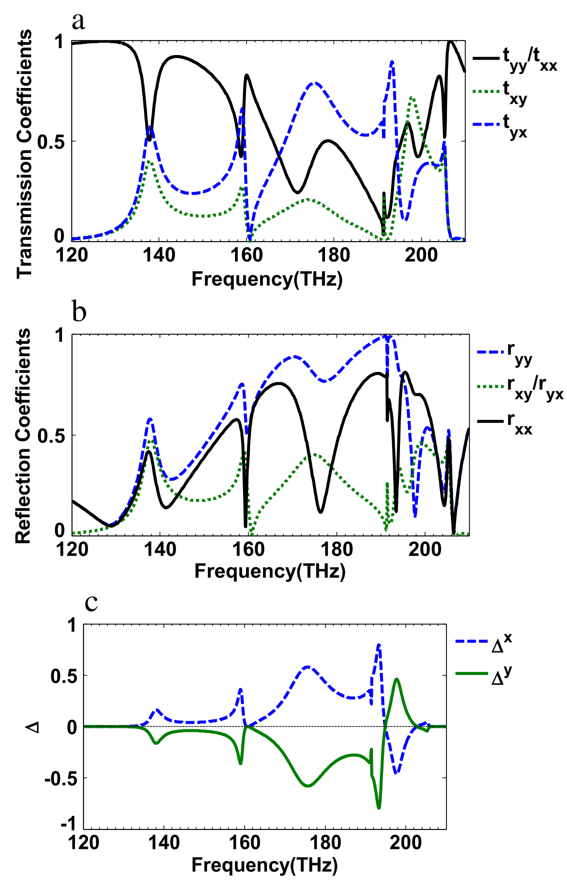

Fig. 2. (a) Simulated transmission coefficients (amplitude). (b) Simulated reflection coefficients (amplitude). (c) Calculated AT parameters Δ. Germanium (Ge) was subsequently selected as resonators with relative permittivity $\varepsilon_1 = 18$ and 0.001 tangent loss.

The resonances in the AT spectrum indeed coincides with the real parts of the eigen frequencies of the structure. Using the eigen mode solver, we calculated the eigen modes of the unit cell. As indicated in Fig. 4, the unit cell eigen mode E-field distribution is the same as infinite period array E-field distribution in AT resonances spectrum (As shown in Fig. 3(a) and (b)). Calculated eigen frequency is 138 THz and the resonant frequency is 137 THz, shows little frequency shift. The other three calculated eigen frequencies are 156 THz, 176 THz and 194 THz.

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