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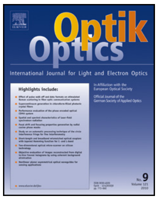

Extraordinary transmission through periodic coaxial aperture arrays at terahertz frequencies

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ABSTRACT

Utilizing the finite-difference time-domain (FDTD) method simulation, transmission properties of normally incident plane wave through symmetric and asymmetric cruciform metallic coaxial aperture arrays (CAAs) are investigated. It is found that odd-order resonant peaks can be observed in symmetric CAAs, and both odd- and even-order ones are showed in asymmetric structure. Moreover, the positions of the resonant peaks are not sensitive to the symmetry of coaxial aperture and the polarization of incident light, but strongly depend on the average circumference in a periodic cell. This assumption is further confirmed by examining the CAAs with different circumferences, shapes, as well as periodicities. The underlying origin of multiple resonances is discussed by the simulated fields. These investigations will facilitate the design of desired operating frequencies for various potential applications such as filters and sensors.

1. Introduction

The demonstration of extraordinary transmission (ET) through the optically thick metallic film pierced with a periodic array of subwavelength holes has renewed opticists' enthusiasm about exploring surface plasmon [1]. Afterwards, Baida et al. proposed a kind of new structure: sub-wavelength annular apertures arrays for achieving high transmission [2]. The structure can enhance optical transmission up to 90% in optical regime due to that a coaxial aperture structure can provide larger cut-off wavelength than a circular one [3]. To date, many theoretical [4–6] and experimental [7–11] studies of the ET properties have been reported. It has been found that the enhanced optical transmission peaks in coaxial aperture structures are mainly attributed to several mechanisms: delocalized (global) surface plasmon [6], localized surface plasmon [9], and resonances of $TE_{m,1}$ guide modes [12]. Recently, Huang et al. have advanced a charge oscillation-induced light emission mechanism and showed a concrete picture of spoof surface plasmons combined with cavity resonance for the ET phenomenon [13].

The manipulation of light with artificial holes arrays on a subwavelength scale can be affected by the shape [14], periodicity [15], and orientation of polarization [16]. The influence of hole-shape on propagation and transmission of light through a single hole or hole arrays in metals have been investigated for many different shapes including cylindrical coaxial [4], rectangular coaxial [17], rectangle-in-cylinder coaxial [18], polygonal coaxial [6], H- [19,20], E-shaped [14], double-hole [21,22], and triangular [23]. In this article, we investigate the transmission characteristics of terahertz pulses through symmetric and asymmetric cruciform metallic CAAs by using the three-dimensional finite difference time-domain method. It is found that odd-order resonant peaks can be observed in symmetric CAAs, both odd- and even-order ones are showed in asymmetric structure. Moreover, the positions of the resonant peaks are insensitive to the symmetry of coaxial aperture and the polarization of incident light, but are determined by the average circumference of the coaxial aperture within a periodic cell. This assumption is further confirmed by examining the CAAs with different circumferences, shapes, as well as periodicities. The underlying origin of multiple resonances is explained by the distribution of the oscillating charges on metal surfaces.

This paper is arranged as follows: Section 2 presents the structure design and simulation method, Section 3 gives the simulation results and discussions, and Section 4 summary the conclusions obtained in this paper.

2. Structure design and simulation method

Fig. 1 shows pictures of the two cruciform CAAs. The first type is a perfect symmetric cruciform CAAs structure in which all arms have

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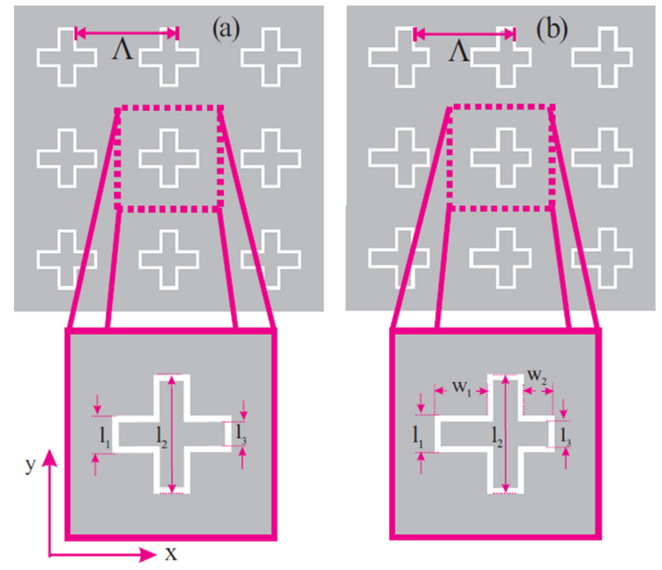

Fig. 1. Schematic of a symmetric CAAs (a) and an asymmetric cruciform CAAs (b).

the same lengths (see Fig. 1(a)). In the second type, we gently break the symmetry between the right and left arms ($w_1 \neq w_2$); .i.e. the asymmetric cruciform CAAs considered here are symmetric to the x axis and asymmetric to the y axis (see Fig. 1(b)). These structures parameters are: $l_1 = 40\,\mu\text{m}$, $l_2 = 200\,\mu\text{m}$, $l_3 = 30\,\mu\text{m}$, $w_1 = 110\,\mu\text{m}$, $w_2 = 50\,\mu\text{m}$, and period $\Lambda = 300\,\mu\text{m}$. The thickness of the metal film is fixed as $50\,\mu\text{m}$. The gray and white parts denote aluminum (Al) and air, respectively. We employ numerical simulations based on the finite-difference time-domain method to investigate the transmission properties of the proposed structures [24]. The calculated constant space step is $1.25\,\mu\text{m} \times 1.25\,\mu\text{m} \times 1.25\,\mu\text{m}$. Since the metallic structure is periodic in the x and y directions, the periodic boundary conditions are imposed in these directions, while in the propagation direction the perfectly matched absorbing boundary conditions are applied at the two ends of the computational space. The polarized plane wave is used as the light source. The metal Al is described by the perfect electric conductivity to fit its realistic characteristic, because the conductivity of the metal is extreme high at terahertz frequencies.

3. Results and discussion

The zero-order transmission spectrum of the metallic film perforated with an array of symmetric cruciform CAAs is shown in Fig. 2(a). Three distinct peaks are located at 0.40 THz, 1.19 THz, and 1.97 THz, respectively. Additionally, according to the momentum matching conduction, the calculated fundamental [1,0] and [2,0] order surface plasmon modes due to periodicity are located at 1.00 THz and 2.00 THz, which agree well with the simulated results.

Different responses are observed in the transmission spectra of the asymmetric cruciform CAAs, as shown in Fig. 2(b). Apart from the three resonant peaks mentioned above, two new resonant peaks appear in the transmission spectra of the proposed asymmetric structure. They are located at 0.79 THz and 1.59 THz, respectively. The fundamental order surface plasmon modes in the transmission spectra is also visible at 1.00 THz. From Fig. 2(b), it is also found that these resonant peaks always appear and their positions are not changed, regardless of the incidence electric field parallel to the x-axis or y-axis. Moreover, breaking the symmetry of the cruciform CAAs has little effect on the positions of these resonant peaks. Here some questions rise: Why do the two new resonant peaks cannot appear in the transmission spectra of the symmetric cruciform CAAs, but appear in that of the asymmetric one? What parameters mainly determine the positions of these resonant peaks?

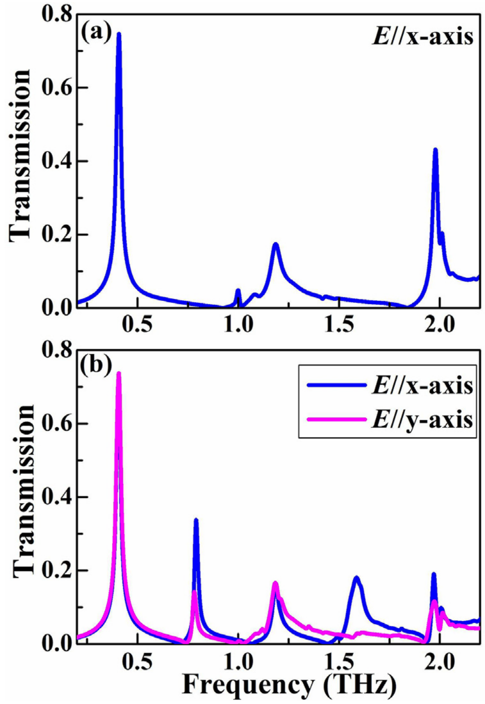

Fig. 2. Transmission spectra for the proposed symmetric cruciform CAAs (a) and asymmetric cruciform CAAs (b).

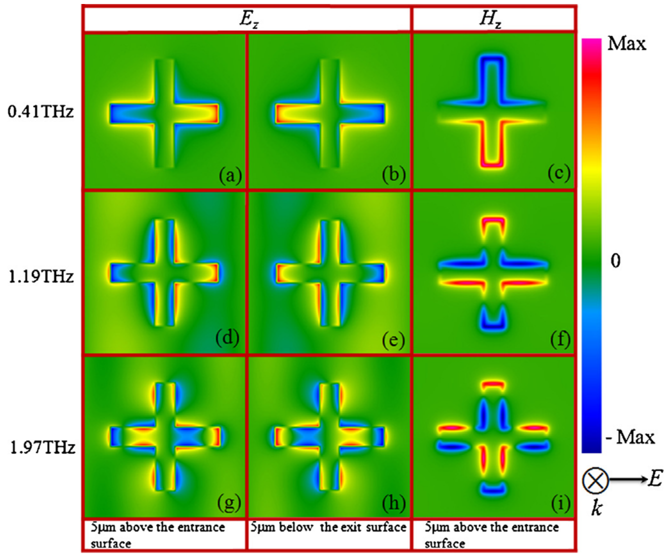

Fig. 3. Simulated E_z and H_z distributions on the surface of symmetric cruciform CAAs. The snapshot moment is when the field amplitude reached its maximum. Only one periodicity on the x–y plane is shown. The polarization of the illuminating electric field E is chosen to be polarized parallel to the y axis. The field quantity is normalized with respect to the incident field E_0.

For answering the above questions and further insight into the origins of the resonant peaks in these structures, the electric and magnetic fields distributions at $z = 5\,\mu\text{m}$ above/below the structures for symmetric and asymmetric cruciform CAAs are shown in Figs. 3 and 4, respectively. The characters of the resonant peaks can be explained using the distributions of E_z component. The positive and negative charges alternately accumulate on entrance/exit edges at each side of the coaxial aperture (Fig. 3(a), (d), (g) and (b), (e), (h)), and form some dipoles. Since these dipoles oscillate with