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Numerical study a broad low-loss pass-band optical metamaterials filter through tailoring dispersion

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ABSTRACT

We present a theoretical and numerical study of a compound structure optical metamaterials filter in 14.8-19.8 THz region. Effects of variations in thickness of dielectric layer *H* and structural parameters on the pass-band are surveyed. Simulated results indicate that the sidewall length of the main air hole and the nano-hole mainly define the impedance matching condition. The pass-band can be expanded due to impedance matching condition between the designed structure and air interface is achieved through optimizing the dimensional parameters of the designed structure. Meanwhile, the pass-band can be also expanded by reducing the thickness of dielectric layer.

1. Introduction

The properties of optical metamaterials composed of optically thick metallic films are theory explained and experimental verified by several investigators, such as negative, high indices of refraction [1,2]. These optical properties of metamaterials could be applied to either significantly improve the performance of existing optical devices or develop entirely new optical devices, such as perfect absorber, optical data storage, and nanolithography [3,4]. In recent years, there is an increasing demand for pass-band optical metamaterials filter to make ensuring that multi-frequency operations or high tolerance to manufacture parameters. The broad pass-band characteristics of optical metamaterials filter makes up with artificial periodic structure rely on the geometry parameters arrangement of unit cell. However, the electromagnetic resonant properties of optical metamaterials filter which are excited by effective parameters will result in strong dispersive behavior in pass-band under certain conditions. The strong dispersion behavior therefore results in narrow operational bandwidths or signal distortion, which would significantly limit the application of optical metamaterials filter in practice. To avoid strong dispersion behaviors, many structure designed of optical metamaterials filter are proposed [5–7]. One of the effective designed principles is that applying multiple vertically stacked metallic layers to obtain a broad pass-band. Unfortunately, this designed principle is very complicated and difficult to be applied at optical field. It is because that the electromagnetic resonance responses of optical metamaterials filter require to be cautiously controlled across the pass-band, which results in the geometries parameters arrangement significantly more complexly. An alternative method is reducing the intensity of the resonance band. In this paper, we proposed a modified traditional fishnet structure to obtain a broad pass-band filter by reducing the intensity of dispersive behavior in resonant band. Simulated results indicate that over 96.2% transmittance can be achieved in the pass-band. The intensity of dispersion behavior is effectively reduced and the effective impedance exhibits a well-matched to free-space behavior throughout the whole pass-band. The designed structure is verified by a numerical optimizing with high transmission and nearly constant effective impedance in the pass-band. Such a compound structure could achieve a considerable flexibility to modulate the effective permittivity and permeability from negative to zero/low index values. The designed pass-band filter can provide a desirable filtering means to select targeted frequency band and thus leads to exploit most practical

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applications.

2. Designed structure and the simulated mode

In recent years, properties of resonances of traditional fishnet structure metamaterials attract a great attention and exploit to obtain a narrow pass-band [8–12]. In this paper, to achieve a broad pass-band, a modified traditional metal-dielectric-metal (MDM) sandwiched structure is designed, as shown in Fig. 1. The designed structure is simulated by Ansoft's HFSS 13.0 which is an useful software in simulating periodic structure [13]. Two ideal magnetic conductor planes are used on the boundary normal to the y axis, two ideal electric conductor planes are applied on the boundary normal to the x axis [14]. The frequency step is 0.02 THz. In simulations, two Floquet ports are applied at the top and bottom boundaries of the modified fishnet structure to simulate a normally-incident wave. And the whole numerical mode will be tested in air. A unit cell of the compound structure is shown in Fig. 1, top and bottom layers are assigned finite conductivity boundary which consists to that of silver. The intermediate dielectric layer is SU-8 [15]. The thickness of the silver film and SU-8 layer are 50 nm and 450 nm, respectively. The lattice constant of the designed structure is P. The total thickness of our designed structure is 550 nm and such thin metamaterial can be applied for replace some complex thick multilayer stacks or three-dimensional structure metamaterials [16,17]. The proposed modified fishnet structure reveals excellent transmission performance in simulations. In practice, the designed metamaterial filter can be fabricated by employing focus-ion-beam milling or electron-beam lithography [18]. All of dimensional parameters are shown in Table 1. The silver layer follows the Drude model:

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2 - i\omega\gamma_D} \qquad (1)$$

Here, $\omega_p = 1.37 \times 10^{16} s^{-1}$ is the plasma frequency, $\gamma_D = 9 \times 10^{13} s^{-1}$ is the collision frequency [19].

3. Optical properties of the broad pass-band metamaterials filter

Across the pass-band in Fig. 1(c), the pass-bandwidth is 5.0 THz and the greatest variation of transmission energy is less than 3.6% through the full pass-band. In order to facilitate, we define the pass-band as $\Delta f = f_2 - f_1$ to characterize such a unique resonant pass-band transmission top [20]. Such an optical metamaterials filter with so stable and high value of pass-band is superior to previously reported structural metamaterials [21,22]. To understand the physical mechanism behind the pass-band in Fig. 1(c), we retrieve the effective refractive index, permeability and permittivity by applying S parameters retrieval methods based on the unit cell shown in Fig. 1 [23]. We can get insight into the influence of electromagnetic responses across the pass-band through these effective medium parameters. As shown in Fig. 2(a), two strong magnetic resonance modes in Re(μ) part can be observed and the Re(μ) increases from $\mu_{eff} = -0.08$ at 14.8 THz to $\mu_{eff} = +0.13$ at 19.8 THz, with a zero crossing at 16.7 THz. Meanwhile, two anti-resonances of Re(ε)are excited by magnetic resonance modes [24] which result in a nearly linear variation of Re(ε) increases from $\varepsilon_{eff} = -0.15$ to $\varepsilon_{eff} = +0.17$. These performance behaviors of multiple parameter which are discussed above result in the effective refractive index increasing from $n = -1.9$ to $n = 1.7$. As shown in Fig. 2(a), the Re(μ) and Re(ε) follow a similar slope from 14.8 THz to 19.8 THz which indicates the ε_{eff} and μ_{eff} are balanced throughout the hole pass-band, such that the effective impedance can be given by

Table 1
All dimensional parameters of the designed structure.

Parameter	P	L	a	b	c	H	h
Value(nm)	2200	1200	210	110	80	450	50

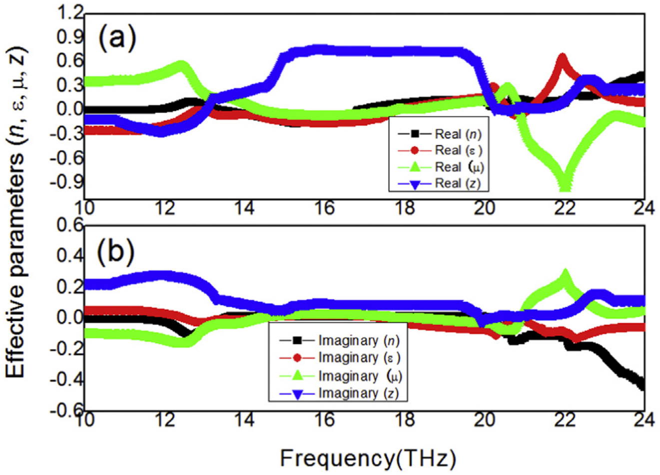

Fig. 2. Simulated optical properties and effective medium parameters of the designed structure metamaterials (n, ε, μ, z), (a) Real, (b) imaginary.

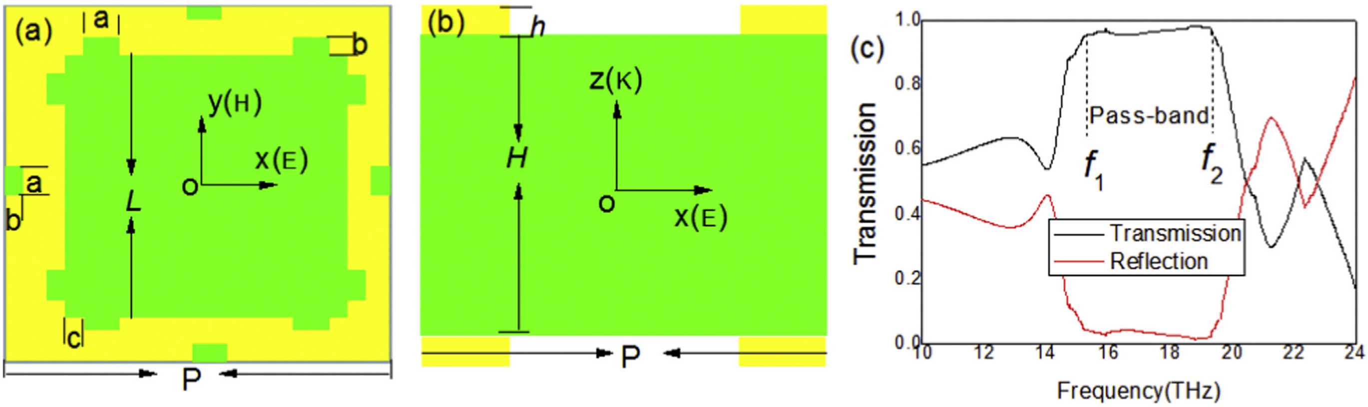

Fig. 1. (a) The top view of a unit cell; (b) the side view of a unit cell on the xoz plane. The yellow part is silver layer, and the light green part is SU-8 dielectric layer. (c) The simulated transmission and refraction spectra of the designed structure.

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