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Tunable bandwidth of pass-band metamaterial filter based on coupling of localized surface plasmon resonance

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ABSTRACT

A broad pass-band compound structure metamaterial is designed which consists of periodic two metallic particles and hole arrays. The operating bandwidth of the designed structure reaches to $\Delta f \approx 33.8$ THz. Physical mechanisms are analyzed and validated based on calculated electric field distribution that the interaction and coupled of LSP modes between two metallic particles leads to the bandwidth increased and resonance frequency blue-shifted, while the interaction and coupled between metallic particle and metallic arrays results in the reduced of the pass-band. The pass-band can be expanded through reducing the permittivity of dielectric layer or reducing the width of the metallic particle (a). The effect of the angles of incidence on the pass-band is also analyzed for normal, 15°, 30° and 45°.

1. Introduction

Metamaterials have attracted a great attention in recent years for theirs unique electromagnetic propagation applications, due to their ability to offer a wide range of electromagnetic operations that are not available in natural materials [1–4]. The initial attention of researchers focuses on comprehending rich optical phenomenas of metamaterials and searching the possibility of controlling electromagnetic waves through metamaterials devices. Then researchers are interested in exploiting and promoting various applications in nano-fabrication and -detection, biochemical detection, integrated devices, and so on [5–7]. Several types of metamaterial applications have been reported so far, such as perfect absorbers, invisibility cloaks, spectroscopy and medical imaging, super-lens, optical filters [8–12]. The specific geometry and arrangement of nano-scale inclusions that are typically aligned in a periodic lattice which can effect the unique optical properties of these metamaterials [13]. The resonant properties of these inclusions would result in signal distorting and lead to narrow operational bandwidths [3,10,14,15], which would limit the application of these metamaterials in practical optical devices. The recent studies on metamaterials based on plasmonic structures gain enormous interesting in a broad range of disciplines [5,16–18], especially the nanofabricated metallic hole arrays and particle arrays. The interaction and coupling of light with periodic metallic particle arrays or hole arrays can result in plasmon resonance, especially the localized surface plasmon (LSP) resonance and surface plasmon polariton (SPP) resonance. Moreover, there is a growing demand for pass-band metamaterials to ensure high tolerances well in multi-frequency operations in the THz region. However, many pass-band metamaterials cannot scale well because of the pass-band is too narrow. Therefore, new strategies should be developed to increase the pass-band of metamaterials. In 2013, Zhi et al. [19] reported a pass-band and low-loss optical metamaterials whose pass-band reaches to $\Delta f \approx 15$ THz. In this paper, we modify the fishnet structure in literature [19] to expand the pass-band through adding two metallic particles in holes arrays to obtain a new compound structure metamaterial. The

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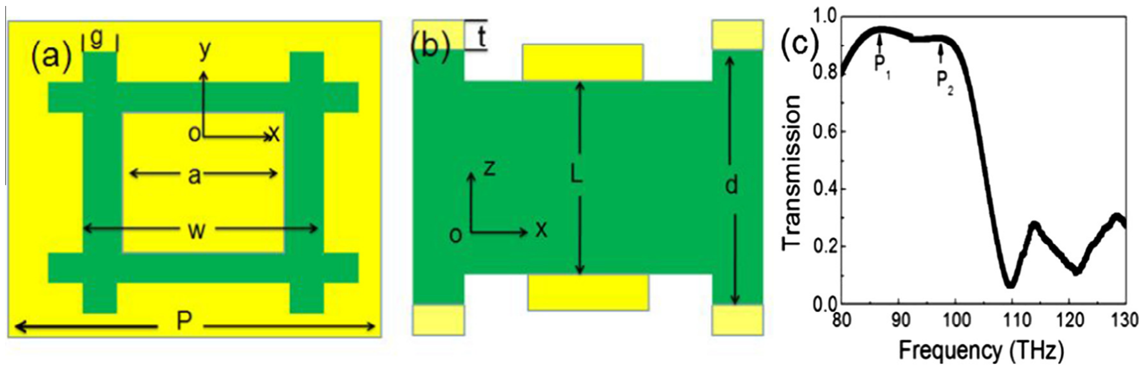

Fig. 1. (a) The top view of a unit cell; (b) the side view of a unit cell on the *xoz* plane. The yellow part is Au layer, and the green part is polyimide dielectric layer. (c) The simulated transmission spectra of compound structure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
All dimensional parameters of the compound structure.

Parameter	*P*	*g*	*w*	*a*	*t*	*d*
Value (nm)	2113	198	990	700	30	450

availability of bandwidth enhancement is verified by optimization structural parameters.

2. Compound structure and the theoretical modeling

The compound structure is shown in Fig. 1(a) and (b), which consists of periodic metallic particles and hole arrays. Each unit cell is constructed from a metal–dielectric–metal (MDM) sandwiched arrays and two metallic particles. Two gold layers is separated by a 450 nm thick dielectric spacer. The dielectric spacer is selected for polyimide layer, SiO_2 layer, SU-8 layer, and Al_2O_3 layer, respectively [20–23]. The metallic layers and metallic particles are selected to be Au in this paper and the dielectric function of Au layer follows the Drude model:

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

here $\omega_p = 2\pi \times 2175$ THz and $\gamma_D = 2\pi \times 6.5$ THz [24]. In our simulation, two ideal magnetic conductor planes and two ideal electric conductor planes are applied on the boundary normal to the *x* axis and *y* axis [25]. *L* is the longitudinal interval between two metallic particles. Dimensional parameters are shown in Table 1.

3. Numerical simulation and theoretical analysis

The compound structure is simulated through using Ansoft's HFSS 13.0 which is an useful software in calculating periodic structure under vertical incidence [24]. This software is capable of wideband simulation of periodic structures with regular shape through considering only one unit cell of periodic structure. Bottom and top layers of the unit cell in Fig. 1(a) and (b) are assigned finite conductivity boundary, with conductivity equal to that of Au in order to simulate the Au ground plane. Fig. 1(c) shows the transmission spectra of the compound structure. Two distinct transmission peaks are observed at $f_1 \approx 86.4$ THz and $f_2 \approx 100.0$ THz in Fig. 1 (c). A broad pass-band with $\Delta f = f_2 - f_1 = 13.6$ THz is obtained and the average transmittance reaches to 97.3%. In this paper, for the sake of convenience, these peaks are named as "P_1 peak" and "P_2 peak".

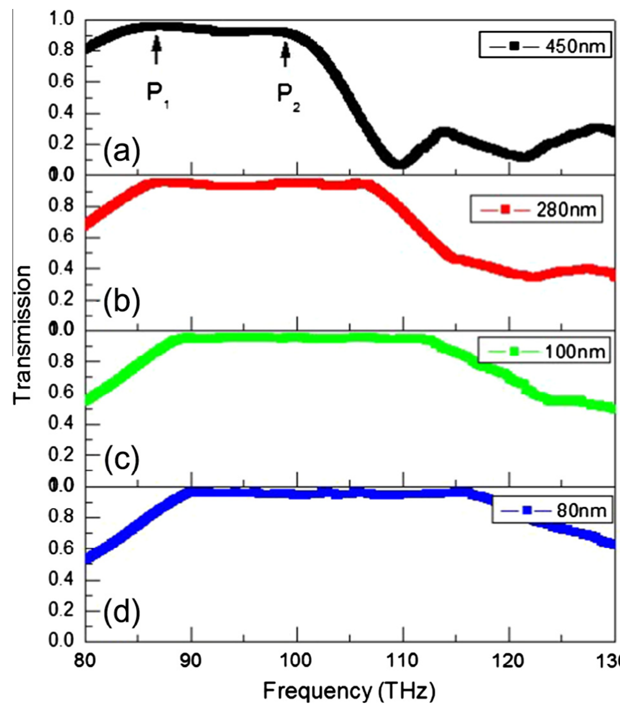

Fig. 2. Transmission spectra of compound structure at different values of *L* when *a* = 700 nm.

Fig. 2 shows the transmission spectra of compound structure with *L* reducing and the pass-bandwidth is 13.6 THz, 17.9 THz, 23.0 THz, and 26.1 THz, respectively. As *L* decreases, two metallic particles close to each other, the pass-band is expanded and resonant frequencies of "P_1 peak" and "P_2 peak" blue-shifted.[1] To get insight into the physical mechanism behind the transmission spectra in Fig. 2, the electrical field distribution on the *xoz* plane is also obtained and shown in Fig. 3(a)–(h). These peaks are associated with different resonance modes, as shown the electric field distribution in Fig. 3(a) and (b). The"P_1 peak" associates with the resonance of LSP mode [Fig. 3(a)] around the lower metallic particle and the lower edges metallic arrays. The coupled and interaction between the lower particle and the lower edges of metallic arrays is observed. On the other hand, the"P_2 peak" mainly results from the resonance LSP mode around the upper metallic particle and the upper edges

[1] For interpretation of color in Fig. 3, the reader is referred to the web version of this article.