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Enhanced transmittance of a dual pass-band metamaterial filter

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ABSTRACT

A broad pass-band metamaterial-based optical filter is experimentally and numerically studied. The designed structure consists of periodically arranged composite metallic arrays and dielectric layer that exhibits transmission responses composed of two flat pass-bands. The coupling of localized surface plasmon (LSP) modes results in the low-frequency pass-band, while the internal surface plasmon polaritons (ISPPs) between the upper and lower metal layers leads to the high-frequency pass-band. Structural parameters (L and R) are experimentally considered from the viewpoint of exploiting their effects on the pass-bands and resonance frequencies. The bandwidths of these pass-bands both can reach to maximums by optimization of these structural parameters. In addition, the two pass-bands can be modulated to be a single pass-band with a bandwidth of 10.7 THz by optimizing L and R simultaneously.

1. Introduction

In recent years, metamaterials and noble metallic sub-holes [1–3] have attracted extensive interest over a broad range of disciplines [4,5] because of their ability to display unique optical properties, including acting as perfect absorbers [6], invisibility cloaks [7,8], superlenses [9], and filters [10]. The initial attention of most researchers focus on understanding of the rich range of optical phenomena that occurs in metamaterial and researching the possibility of controlling electromagnetic waves using metamaterial-based devices. Researchers subsequently become interested in using and promoting a variety of interesting applications such as nanofabrication and detection, biochemical detection, and integrated devices [11,12]. Among these devices, optical devices attract a great deal of attention because of their important applications. These optical devices generally include modulators, compensators and resonant pass-band filters. In recent years, there has been growing demand for pass-band filters to ensure that high tolerances are maintained in multi-frequency operations. However, many pass-band filters can't scale well because their pass-bands are too narrow, which significantly limits the application of these pass-band filters [13–17]. It is important to design and provide a filter with broad and tunable pass-band, which should be fabricated in a practical manner. In this paper, we design and experimentally study a metal-dielectric-metal (MDM) sandwiched structure with the intention of producing a tunable dual-band filter. This type of optical device can provide a desirable pass-bands filter that can be used to select both an operating frequency band and a central frequency.

2. Design and numerical results

Many sub-wavelength hole arrays based on metamaterial have been studied by researchers. However, few of these arrays are designed in an attempt to produce a tunable dual pass-band filter. Zhong et al. [18] propose an optical metamaterial filter with a modified fishnet structure. A broad pass-band is obtained because of the coupling of the localized surface plasmon (LSP) modes between the upper and lower silver layers. However, the effect of the internal surface plasmon polaritons (ISPPs) on the pass-band is not considered. In this paper, to obtain a dual-band metamaterial filter, a modified sandwiched structure consisting of periodic square-loop slot and circular patch arrays is designed as the basic sub-structure of the pass-band filter, as shown in Fig. 1. Each unit cell contains two silver layers and one dielectric layer. SU-8 is chosen as the dielectric layer material and the dielectric constant is 2.56 [18,19]. Each unit cell has dimensions of P=4 μm, L=2.1 μm, R=0.8 μm. The thicknesses of the silver layer and the dielectric layer are h=0.05 μm and H=0.3 μm, respectively. The simulation is performed using Ansoft HFSS10.0 commercial software. Bottom and top layers of the unit cell in Fig. 1(a)-(b) are assigned to ideal conductor boundaries. Two ideal magnetic conductor planes have been used on the boundary normal to the x-axis and two ideal electric conductor planes have been used on the boundary normal to the y-axis [18,20]. Drude model is used to describe the property of silver at optical frequencies:

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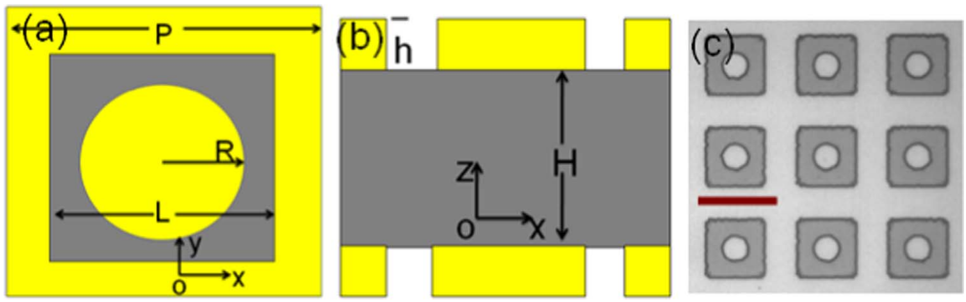

Fig. 1. (a) The top view of a unit cell. (b) The side view of a unit cell for two silver layers and one dielectric layer. The yellow part is silver layer, and the gray part is dielectric layer. (c) Optical microscopy images of samples. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

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

Here, $\omega_p = 1.37 \times 10^{16}\text{s}^{-1}$ is the plasma frequency and $\gamma_D = 9 \times 10^{13}\text{s}^{-1}$ is the collision frequency [18,21]. The chosen pattern exhibits excellent transmission performance in simulation and experiment. To validate the designed dual-band filter, samples are fabricated as follows: a thermally oxidized Si handle substrate is selected. A 0.05 μm-thick silver layer is evaporated on the substrate at a rate of 1.9 Å s^{-1} (ZZL-U400H) through electron beam evaporation. A 0.3 μm-thick dielectric layer is spin o on the first silver layer. The second 0.05 μm-thick silver layer is also evaporated on the dielectric layer. The fabricated metal/ dielectric/ metal metamaterial is subsequently removed from the Si handle substrate through using a buffered oxide etchant. Finally, the proposed array is patterned in the first and second silver layers by using a focused ion beam system [22]. The transmission spectra are measured by using the Bruker Optics Equinox 55 spectrometer at the normal incidence. A 3.5×3.5 mm^2 area samples are obtained. Fig. 1(c) shows optical microscopy images of the proposed dual-band metamaterial filter (Leica DM2700M).

To confirm the effective of the designed structure in this paper, the transmission spectra of the single loop structure is also calculated, as shown in Fig. 2(a)-(b). In the single loop structure case with one silver layer and one dielectric layer, a transmission peak is obtained at 13.9 THz with a maximum transmission rate of 87%, as shown in Fig. 2(a). However, in the case of a single loop structure with two silver layers and one dielectric layer, a transmission pass-band is obtained, as shown in Fig. 2(b). The central frequency of this pass-band is 14.0 THz, and the bandwidth is 1.85 THz. Fig. 2(a) and (b) show that a single pass-band can be obtained using the single loop structure. As discussed above, to obtain a dual-band metamaterial filter and enable modulation of the bandwidth, a silver circular patch is added to the single loop structure to form the designed structure shown in Fig. 1. The measured transmission spectra of the designed structure are shown in Fig. 2(c) and (d). In the case of the designed structure with one silver layer and one dielectric layer, a flat pass-band is obtained in the transmission spectrum from 12.8 to 14.9 THz with an average transmission rate of 81%, as shown in Fig. 2(c). The center frequency of the pass-band is 13.85 THz. A typical broad pass-band filter can thus be obtained by addition of a silver circular patch. In addition, in the case of the designed structure with two silver layers and one dielectric layer, the pass-band width increased from 2.1 to 3.2 THz, and the center frequency of the pass-band is 13.0 THz. Simultaneously, a new pass-band can be found from 20.6 to 25.0 THz with an average transmission rate of 88%, as shown in Fig. 2(d). For simplicity of reference in this study, the two transmission bands are called the low-frequency pass-band and the high-frequency pass-band, respectively. These results

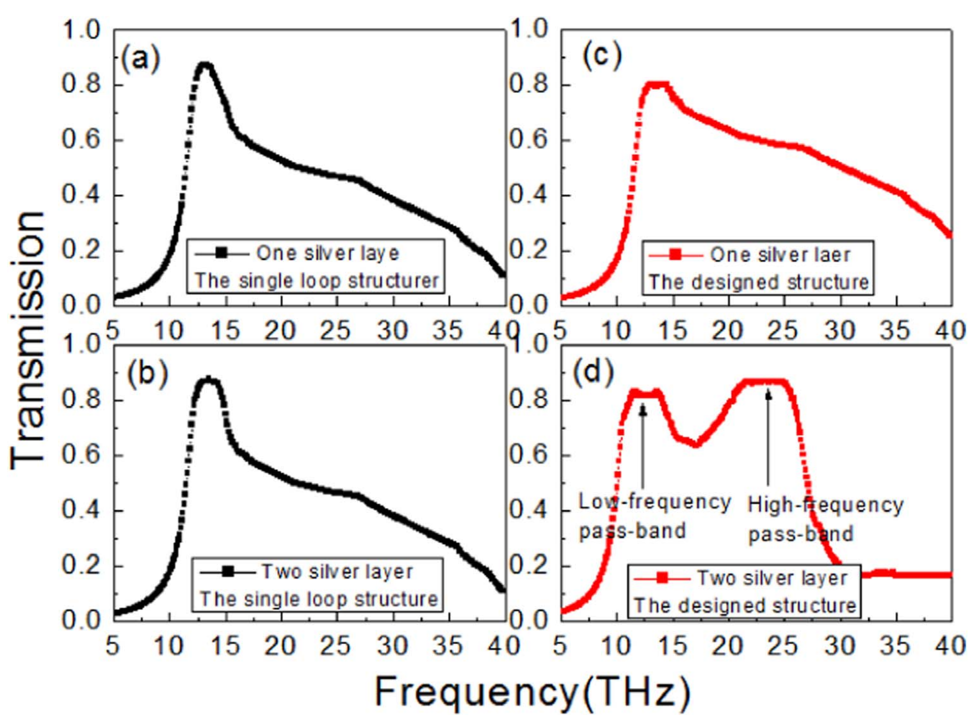

Fig. 2. The simulated transmission spectra of the single loop structure (black curve): (a) One silver layer, (b) Two silver layers. The measured transmission spectra of the designed structure (red curve): (c) One silver layer, (d) Two silver layers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).