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A strategy for polarization-independent ultra-narrowband filters by sub-wavelength all-dielectric meta-materials

Xiaoshan Liu, Guolan Fu, Mulin Liu, Zhengqi Liu*

Institute of Optoelectronic Materials and Technology, Jiangxi Key Laboratory of Nanomaterials and Sensors, Jiangxi Key Laboratory of Photoelectronics and Telecommunication, School of Physics, Communication and Electronics, Jiangxi Normal University, Nanchang 330022, China

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ABSTRACT

Ultra-narrowband light filtering is with wide applications in display, image and optical measurement devices. Here, we theoretically propose and show a new and simple strategy for achieving notch filters by sub-wavelength all-dielectric meta-materials (ADMMs). The ADMM is comprised of a triple-layered high/low/high-index dielectric structure. Similar to the plasmonic resonances existed in the metallic meta-materials, strong optical field resonances have been observed in this ADMM. Dual-band reflective notch filtering phenomenon is achieved. Spectral bandwidth down to 3 nm and the spectral contrast reaching 97% are obtained. Moreover, the polarization-independent response is simultaneously achieved in this ADMM. Furthermore, high spectral tunability for the observed ultra-narrowband filtering is obtained via tuning the structural parameters.

1. Introduction

Narrowband filters are desirable for optical measurement devices such as detection and sensing, displaying and imaging devices. The way for achieving narrowband filters has long been pursued. A typical way is to use the dielectric gratings, which can provide monochromatic diffraction and filtering. Nevertheless, the large grating period size and the polarization-dependent response inevitably limit its further application for high-resolution and polarization insensitive displaying and imaging [1]. Recently, although periodic dielectric structures such as the three-dimensional photonic crystals [2–4] and two-dimensional colloidal crystals [5,6] have been demonstrated with structural coloring response, the filtering behavior was observed to be with a broad bandwidth [5]. On the other hand, plasmonic filtering phenomena have been observed in the plasmonic resonant materials based on the great efforts made in the past decades [1]. For instance, based on the periodic metallic nanoparticles arrays, plasmonic filters for image sensing applications [7] and color generation via plasmonic nanostructures [8,9] have been demonstrated. However, the inherent ohmic losses in the resonant metallic materials eventually lead to a broadband spectrum for these filters. In our previous work [10], sharp resonant spectrum has been theoretically demonstrated in a non-close-packed plasmonic crystal via the strong near-field coupling effects. Nevertheless, the requirement of high precise fabrication technique limits these structures to be fabricated in large-scale at low-cost.

In this work, we for the first time theoretically design and show a simple strategy for achieving ultra-narrowband filters based on the all-dielectric meta-materials (ADMMs) in which the silicon (Si) patches are used to act as the resonators [11]. The triple-layer structure shows strong optical resonances and interaction with the incident light similar to the plasmonic resonances in the conventional meta-materials. Owing to the lossless dielectrics used in this platform, ultra-high spectral contrast of 97% with the reflectance peak of 99.9% is achieved in the notch filtering window. The bandwidth is even down to single-digit level. These novel features hold the predicted ADMM-based filter with wide applications in the optoelectronics such as the display, image and detection devices [1,12].

2. Materials and method

Schematic of the ADMM-based filter is shown in Fig. 1(a). In this work, dielectric material is assumed to be the Si. The structural parameters of the length (L), width (W) of the patch and the period (P) of the hexagonally packed array are set to be 400 nm, 100 nm, and 500 nm, respectively. The thickness values of the top Si patch, the middle SiO_2 patch and bottom Si cavity film are 30 nm, 40 nm, and 100 nm, respectively. The refractive index n of the Si is 3.5. Three-dimensional finite-difference time-domain method has been employed to theoretically measure the optical properties and behaviors of the field [13]. The calculation unit cell

* Corresponding author.
E-mail addresses: zliu@jxnu.edu.cn, lzhq86025@163.com (Z. Liu).

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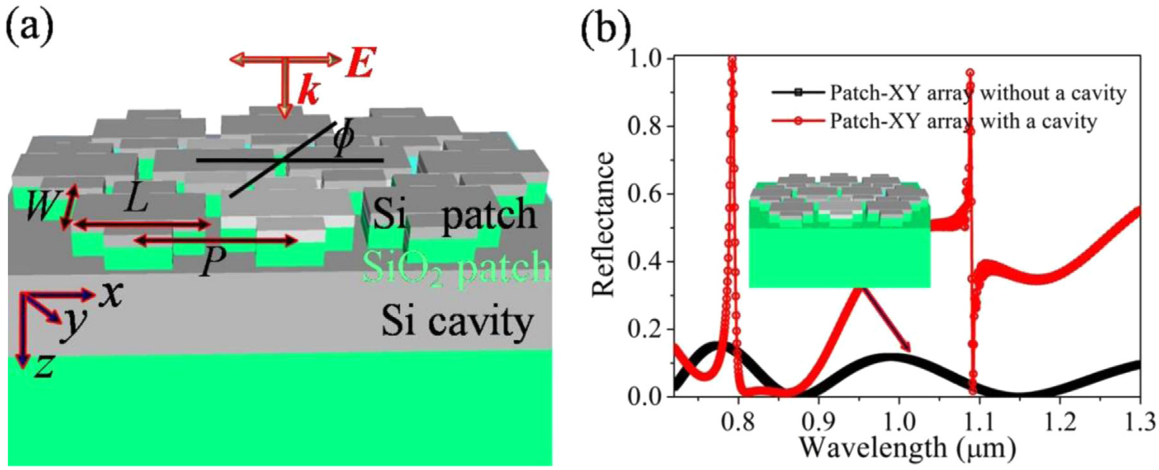

Fig. 1. (a) Schematic of the ultra-narrowband filter platform consisting of a triple-layer Si–SiO_2–Si structure on the quartz. (b) Reflectance response of the patch-*XY* array without the Si film cavity (black line) and the array with the Si film cavity (red line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

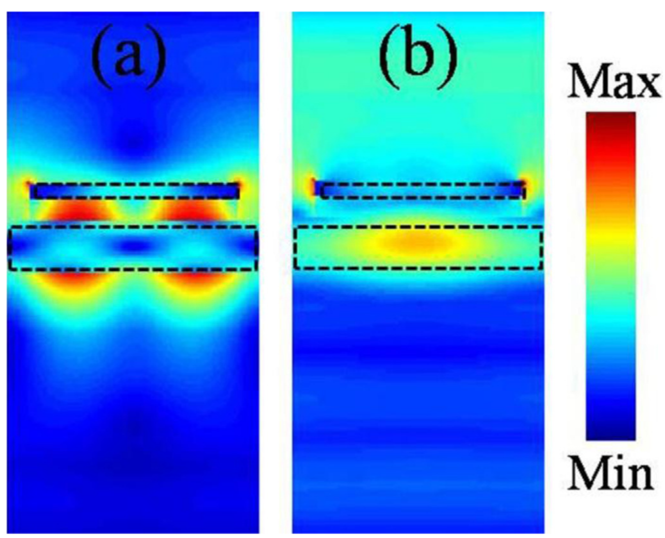

Fig. 2. (a),(b) Normalized electric field intensity distributions of the ultra-narrowband filter at the wavelength of 0.793 μm and 1.088 μm, respectively.

is with one center patch-*XY* and four quarter patches. Periodic *x*- and *y*-boundaries were used for reproducing the periodic array and perfect matching layer along *z*-boundaries was used for scattering cancellation [14]. For the experimental procedure, the ADMMs can be realized by fabricating resonators in the Si device layer of a silicon-on-insulator wafer. The Si patches array can be formed by using the standard photolithography [15,16] or focused ion beam milling techniques together with a lift-off process [17,18].

3. Results and discussion

Fig. 1(b) shows a dual-band sharp reflective spectrum of the ADMM-based filter consisting of the patch-*XY* array coated on the Si cavity film with a SiO_2 sandwich layer (Fig. 1(a)). Ultra-narrowband high reflectance (R) behavior is obtained for a dual-band spectrum at the wavelength of 0.793 μm (R=0.999) and 1.088 μm (R=0.958). The bandwidth values for these two filtering bands are 14 nm and 3 nm, respectively. The spectral contrast defined as the $R_{max}-R_{min}/(R_{max}+R_{min})$ is up to 97.0% at 0.793 μm. At 1.088 μm, the spectral contrast is also exceeding 96%. The spectral Q-factors reach 57 and 363 for these two filtering bands, which is much larger than the conventional plasmonic resonances with the Q-factor of about 10 [19]. In contrast to the only one resonant peak in the composite ADMMs in the previous reports [20,21], the dual-band spectrum with ultra-high spectral contrast and high-Q factors can provide multiple high-performance notch filtering. A

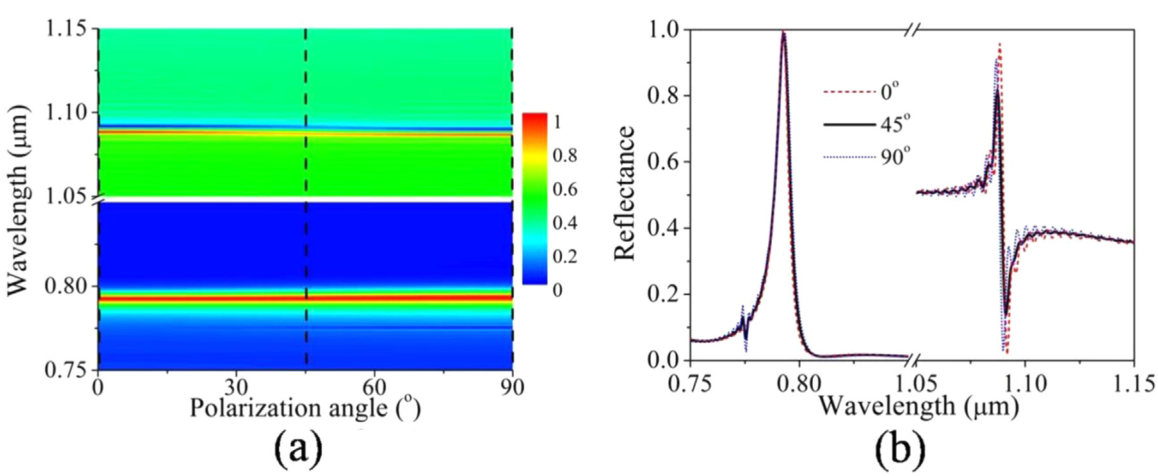

Fig. 3. (a) Plotted reflectance evolution mapping of the ultra-narrowband filter under a tuning polarization angle from 0° to 90°. (b) Reflectance spectrum of the filter under certain polarization angles.