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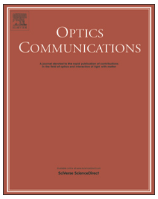

Energy conversion within infrared plasmonic absorption metamaterials for multi-band resonance

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ABSTRACT

The energy conversion within the cross-shaped plasmonic absorber metamaterials (PAM) was investigated theoretically and numerically in the infrared range based on the Poynting's theorem of electromagnetic energy. From the microscopic details, the heat generation owing to the electric current accounts for the majority of the energy conversion, while the magnetic resonance plays a negligible role. The PAMs possess three distinct resonant peaks standing independently, which are attributed to the polarization sensitive excitation of plasmonic resonance. Field redistribution and enhancement associated with multiplex resonant electromagnetic wave passing through the PAM medium provided insight into the energy conversion processes inside the nanostructure. The research results will assist the design of novel plasmon enhanced infrared detectors with multiple-band detection.

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1. Introduction

The electromagnetic wave absorption of the recently emerging plasmonic absorber metamaterials (PAMs) [1] have been demonstrated to potentially enable electromagnetic wave detection at nearly any frequency, ranging from the terahertz to infrared [2,3] and even visible light range [4,5]. Such broad bandwidth performance results from the interaction of electromagnetic waves with nanostructures, which produces the exertion of the electromagnetic fields on the nearly free electrons of the metal in combination with strong field confinement, thus leading to the extraordinary collective electron–photon oscillations that can occur within nanostructures [6]. The plasmonic absorber metamaterials with either broad spectral features or narrow band response are both equally necessary. Particularly in the mid-infrared region, the narrow spectral response is significant in obtaining a large field enhancement over the volume of interest [7,8]. By accurately tuning such frequency response, multispectral micro-bolometers and wavelength-tunable thermal radiation sensors can be produced [9,10].

To produce imaging devices in the mid-infrared spectral region, one key problem is the conversion of electromagnetic energy into other types of energy, such as the photocurrent [11,12], mechanical energy [13], and thermo-mechanical energy [14]. All these mechanisms of the energy conversion are divided into two groups: the generation of photo-current and the generation of photo-heat. Heat generation produces a mechanical response [13] or a thermal conduction response [15]. That is, photo-thermal effects play a critical role in the detection of electromagnetic radiation [16].

One dual cross-shaped plasmonic absorber metamaterials has been developed recently to obtain multiple-band absorption spectrum at mid-infrared region [17]. Three distinct absorption peaks were attributed to the polarization sensitivity excitation of the plasmonic resonance. In this paper, the energy-conversion process was investigated theoretically using the Poynting theorem, in which the Ohmic loss and dielectric loss were calculated to estimate the amount of heat energy produced. The heat-generation within the PAM was studied numerically. The strong field confinement and redistribution inside the structure of the PAM were investigated for use in a subsequent thermal-detection design.

2. PAM structure and optimization

The proposed PAM, as shown in Fig. 1, is a metal–dielectric–metal scheme that exhibits the properties of electromagnetic selectivity and resonance [18]. The typical dielectric layer, as an energy dispersive medium, is sandwiched between the top metallic periodic arrays and the bottom conducting ground metallic plane. The top layer consists of an array of dual cross-shaped

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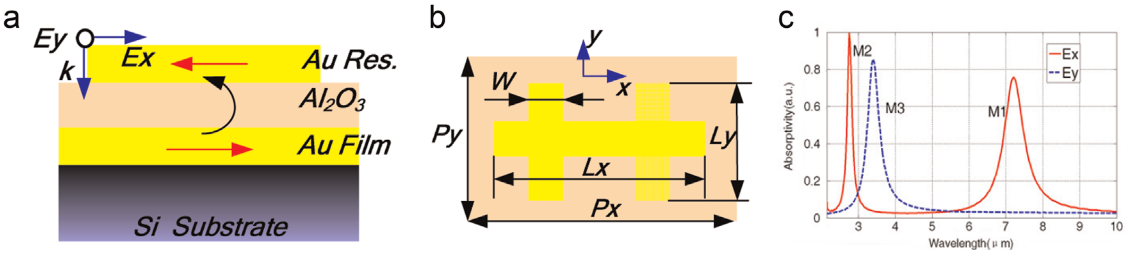

Fig. 1. Schematic of side view (a) and the top view (b) for the dual cross-shaped plasmonic absorber metamaterials. Optimal dimensional sizes are $Lx=1.6$ μm, $Ly=0.8$ μm, $w=0.3$ μm, $px=2.0$ μm, $py=1.2$ μm. Thickness of top metal resonators, dielectric layer, and ground metal layer are 0.1 μm, 0.05 μm, and 0.1 μm. (c) Normalized resonance absorption spectrum. The resonant response peaks ($M1=7.20$ μm and $M2=2.75$ μm) are excited by *Ex* polarized incident light and the third mode ($M3=3.40$ μm) by *Ey* incident light.

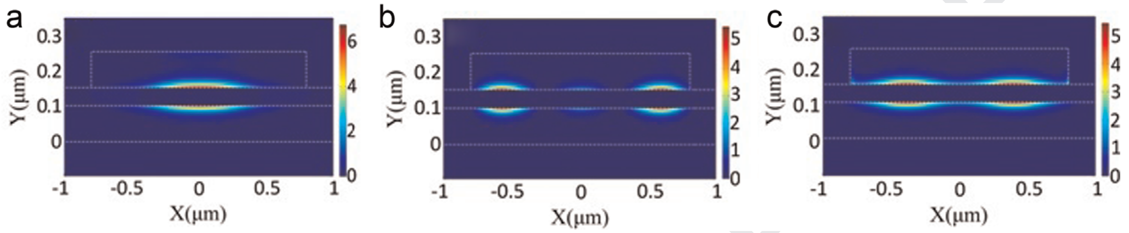

Fig. 2. Time-averaged energy density distributions (in the *x*–*z* cross-sectional plane along the central axis where $y=0$) at resonance wavelengths of (a) 7.20 μm, (b) 2.75 μm, and (c) 3.40 μm. The color bars represent the magnitude of the power density (Unit: $\times 10^{19}$ W/m^3). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

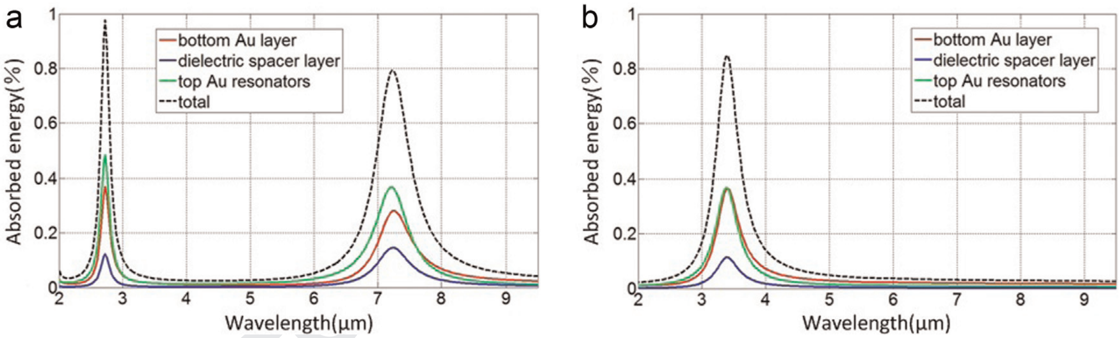

Fig. 3. Energy absorption spectrum within the specified volumes for the (a) *Ex*-incident condition and (b) *Ey*-incident configuration, which take into account the electrical Ohmic loss in the metallic layers and the dielectric layer. Red line denotes the absorption within the bottom gold layer. Blue line denotes the absorbance in the dielectric layer of Al$_2$O$_3$. Green line represents the absorbance in the top metallic resonator layer. Black dotted line is the total absorbance energy spectrum. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

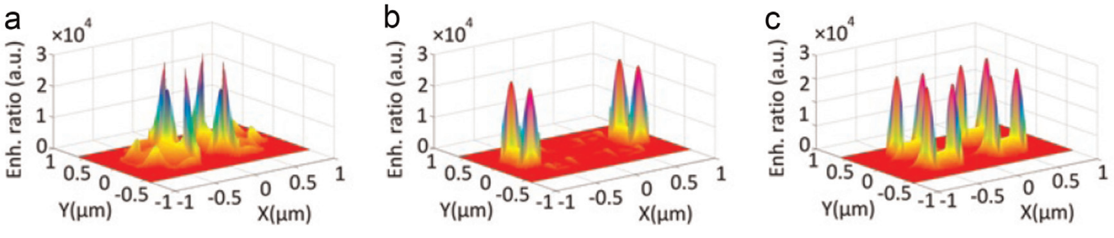

Fig. 4. Concentration and redistribution of the electromagnetic Poynting Field ($|P|^2$) within one unit cell excited by resonant wavelengths of (a) 7.20 μm, (b) 2.75 μm, and (c) 3.40 μm.

resonators, and the bottom layer is a continuous thick metallic film. The dimensioning is shown in the figure. The structure and dimensions were carefully designed to approach the resonance condition in mid-infrared region. When both transmission and reflection are zero at specified frequency, the absorbance would approach to unit one, which means nearly perfect absorption. Zero reflectance has been considered to satisfy the impedance match with the surrounding media at specific frequency bands [18,19]. In conjunction with the transmission blocking of the thick metallic film, the incident electromagnetic energy was effectively confined within the dielectric layer, thereby enabling nearly perfect absorption. In our work, gold was utilized for both the top array of resonators and the bottom conducting film. Aluminum oxide (Al$_2$O$_3$) was chosen for the dielectric medium.

The PAM structure was optimized using commercial finite-difference time-domain (FDTD) software (Lumerical Company). The permittivity of gold was modeled using a Drude expression with a plasmonic frequency of 1.32×10^{16} rad^{-1} and a collision frequency of 1.2×10^{14} rad^{-1} [20]. The transmittance $T(\omega)$ and reflectivity $R(\omega)$ were obtained from the simulations. The incident

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