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Numerical studies on absorption characteristics of plasmonic metamaterials with an array of nanoshells☆

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ABSTRACT

A numerical study was carried out for absorptance of light with wavelength in the range of 400–900 nm at normal incidence on a 3-layer plasmonic metamaterial, consisting of an array of Au nanoshell structures on the top and a Au layer at the bottom with a Al_2O_3 layer in between. The Finite-difference time-domain method with appropriate dielectric functions is used to obtain numerical results for the absorptance of light in the plasmonic metamaterial. It was found that the geometric configuration of the nanoshell could change the wavelength of the surface plasmon resonance without lowering the absorptance. The core material in the nanoshell has little effect on absorptance or on the resonance wavelength. The distance between nanoshells affects absorptance greatly but affects plasmon resonance wavelength only slightly.

1. Introduction

A blackbody is a perfect absorber that soaks up all the light incident on its surface without any transmission or reflection [1]. However, a blackbody is only an idealized model which is not easy to achieve in reality. For the past several decades, plasmonic metamaterials (artificial materials) have allowed the manipulation of light with its extraordinary absorption properties [2–4]. These artificially structured materials are in much demand to-date in many technology fields, such as photodectors [5,6], thermal images [7], nanoscale photonic modulators [8], and absorbers for photo-thermal and thermal-photovoltaic solar energy conversion [9–15], etc. According to Otto [16] and Kretschmann [17], arrays of discrete sub-wavelength resonators on the surface of plasmonic metamaterials are needed for the absorption of visible or near-infrared electromagnetic range [18–20]. Under the effect of plasmon resonance, the nanoscale metal elements can greatly enhance the electric field strength (up to 10^{14} times) on the surface of a metal [21], thus significantly enhancing the absorption of light on a metal surface.

Traditionally, the Maxwell theory can provide a detailed description of the interaction between the electromagnetic wave and a thin film [22], including the surface plasmon resonance. The finite-difference time-domain (FDTD) method developed by Yee [23] can give accurate numerical results instead of an analytical solution on absorption and scattering of electromagnetic waves. Based on different numerical methods, many theoretical predictions on absorption and scattering of thin films about the surface plasmons have been obtained [24–28].

Previous studies for absorptance of light in plasmonic metamaterials, however, focus mostly on solid rectangular nanoparticles [1,29] and tri-layer nanostructures [30]. Very few have studied plasmon resonance of light in a plasmonic metamaterial with nanoshell structures, although it has been shown that nanoshells [31] have a unique optical property for tunable plasmon resonance, which can be used to match with the wavelength requirement for a specific application. In this paper, we will focus our attention on the absorptance of light and plasmon resonance wavelength in a plasmonic metamaterial with nanoshell structures. It will be shown that changes in the nanoshells' thickness can change plasmon resonance wavelength without affecting the absorptance of light greatly, while changes of separation distance between nanoshells have little influence on plasmon resonance wavelength but affect the absorptance of light greatly. Results of this study will help to design absorbers for nearly total absorption of electromagnetic wave at a specific wavelength.

2. Description of the simulation model

An artificially structured plasmonic metamaterial usually consists of three layers with metal nanoparticles on the top layer, a metal thin film

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at the bottom, and separated by a dielectric layer in the middle [30]. In Section 2.1, we describe the 3D geometric structure of such a three-layer plasmonic metamaterial with an array of nanoshells on the top, where a physical model for numerical simulation is presented. Then, Maxiwell's equations for calculation of radiative properties of metamaterial are presented in Section 2.2.

2.1. Models of plasmonic metamaterials

Consider a three-layer metamaterial consisting of an array of Au nanoshells on the top, a thin dielectric Al_2O_3 layer in the middle, and an Au layer on the bottom as shown in Fig. 1(a). The light source (a plane wave) is at normal incident on the plasmonic metamaterial from the top. Two virtual planes, shown as horizontal lines, are used for calculations of the transmission and reflectance of light. A unit cell of the periodic structure, shown as a red rectangular block in Fig. 1(a), is chosen as the computational domain. Its 3D enlarged view is presented in Fig. 1(b), where the vertical axis is located at the midway between the adjacent nanoshells. Both the Al_2O_3 layer and the Au layer have a square cross-section (L by L) as viewed from the top with a thickness of H_1 and H, respectively. The nanoshell also has a square cross-section (L_1 by L_1) with a height of h, and with a thickness of h_1 and L_2 in the directions parallel and perpendicular to the incident light, respectively. For brevity, we shall refer to the nanostructure layer, the Al_2O_3 layer, and Au layer, as the nanostructure, Al_2O_3, and Au layers, respectively.

2.2. Numerical modeling

The interaction between the electromagnetic field and a non-magnetic plasmonic metamaterial can be described by Maxwell's equations as follows:

$$\nabla \times \vec{H} = \varepsilon_0 \varepsilon_r \frac{\partial \vec{E}}{\partial t} \quad (1)$$

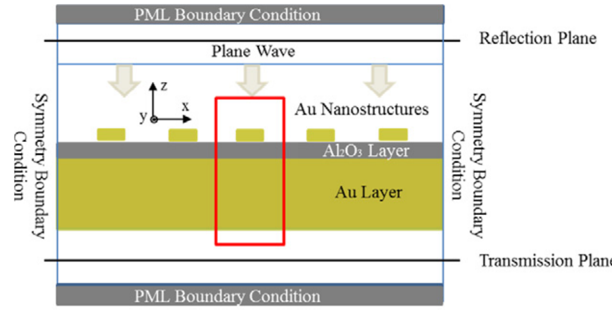
$$\nabla \times \vec{E} = -\mu_0 \frac{\partial \vec{H}}{\partial t} \quad (2)$$

where $\vec{H}$ and $\vec{E}$ are magnetic and electric fields, respectively, while ε_r is the complex dielectric function, and ε_0 and μ_0 are the permittivity and permeability in vacuum. For numerical simulations, we take the optical properties of the evaporated gold and SiO2 given by Olmon et al.[32] and Palik [33], respectively, and set the dielectric function of Al_2O_3 equal to 1.75 [1]. Simulations were carried out for the computational domain shown in Fig. 1(b) with perfectly matched layer (PML) boundary conditions in the z direction. Symmetry and anti-symmetry boundaries for x and y directions, respectively, are adopted to reduce simulation time and computer memory.

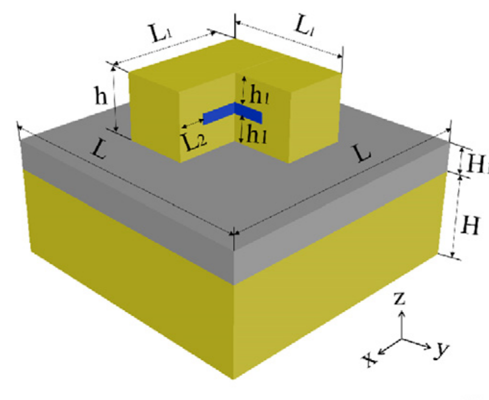
After obtaining numerical solutions on the electric and magnetic fields, E and H, given by Eqs. (1) and (2) by the FDTD method, the spectral reflectance or transmittance of the structure can be calculated by

$$T_\lambda = \frac{\int S(x,y)dxdy}{Q_{\lambda,i}} \quad (3)$$

where Q is the incident power per unit area and $S(x,y) = \frac{1}{T}\int_0^T |\vec{E} \times \vec{H}| dt$ is the time-averaged Poynting vector [34,35], where T is the time period we are concerned with. Eq. (3) can be used to calculate the power transmitting the virtual reflectance ($\boldsymbol{R}$) plane and the transmittance ($\boldsymbol{T}$) plane shown as horizontal lines in Fig. 1(a).



(a) 2D view of a 3-layer plasmonic metamaterial with an array of nanoshells on the top



(b) 3D computation domain of a periodic structure

Fig. 1. The physical model of a plasmonic metamaterial and geometric parameters of nanoshells, note that in (b), the nanoshell is intentionally shown for three quarters only.

The absorptance $\boldsymbol{A}$, defined as the ratio of the power dissipation in the plasmonic metamaterial over the incident power, can be computed from

$$\boldsymbol{A} = 1 - \boldsymbol{R} - \boldsymbol{T} \quad (4)$$

3. Results and discussion

In this section, computations for absorption properties of the plasmonic metamaterial with nanoshells shown in Fig. 1(b) surrounded by air (with $\varepsilon_r = 1$) were carried out for light with wavelength in the range of 400–900 nm. Fig. 1(b) shows that the 3-layer plasmonic metamaterial has a total of 7 geometric parameters, including 3 parameters (L, H_1, H) for the Al_2O_3 layer and the Au layer, and four parameters (L_1, h, L_2, h_1) for the nanoshells. In the following, calculations of absorptance and plasmon resonance wavelength of the metamaterial having $H_1 = 12$ nm, $H = 80$ nm, $L_1 = 50$ nm, $h = 30$ nm with different values of L, L_2, h_1 and filled with different core materials were carried out.

3.1. Nearly total absorptance of a metamaterial with nanoshells

Computations were first carried out for a metamaterial having nanoshells with the following geometric parameters: $L = 120$ nm, $H_1 = 12$ nm, $H = 80$ nm, $L_1 = 50$ nm, $h = 30$ nm and $h_1 = L_2 = 10$ nm. Numerical results for absorptance, reflection, and transmission of light for the metamaterial with nanoshells filled with air are presented in Fig. 2(a) and (b). As seen from Fig. 2(a), the maximum absorptance of light in this plasmonic metamaterial is more than 99% at the wavelength