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Enhanced transmission of a plasmonic ellipsoid array via combining with double continuous metal films

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ABSTRACT

We propose a tunable plasmon-induced transparency metal nanostructure which can be performed by double continuous metal films with a two-dimensional hexagonal periodic array of metal ellipsoidal nanoparticles in between them. The optical features of this structure are simulated by using the three-dimensional finite-difference time-domain (3D-FDTD) method. It is discovered that the structure shows an enhanced optical transmission behavior in the optical regime, and the optical response in this structure can be efficiently modified by varying the aspect ratio of ellipsoidal nanoparticles, the thickness of metal film, and the environmental refractive index, and the period of the plasmonic array. The structure proposed here may provide a new alternative approach to obtain transparent metal structures with potential applications in optoelectronic integrated circuits, plasmonic filters and sensors.

1. Introduction

Surface plasmons, electron charge density waves that can exist at a metal surface or at the interface between the metal and the dielectric materials [1], are emerging as a new research field to focus on the interaction of light with noble metal nanostructures and to manipulate light at the nanoscale level and have attracted much attention due to which they play a key role on the novel optical characteristics of the metal nanostructures. Recently, there has been significant interest in studying high-conducting metal films with plasmon-induced transparency [2–6] due to which this kind of structure owns the electrical and mechanical characteristics simultaneously which are very important for the rapid development of plasmonics in solar energy and optoelectronic applications. A typical approach has been brought out by introducing holes or slits in the metal films to obtain enhanced optical transmission [7,8] due to certain resonances of surface plasmon polaritons or cavity modes [7–14]. By introducing a periodic array of metal grooves, ridges or sphere nanoparticles on one or both surfaces, enhanced transmission has also been obtained via strong coupling of light with plasmons [15–20].

Metal ellipsoidal nanoparticles exhibit a dipolar surface plasmon resonance known as the Flöhlich mode [21] at a frequency that depends on the aspect ratio and dielectric function of ellipsoids and the environmental dielectric function. It is interesting and important to know how the metal ellipsoidal nanoparticles could be utilized to make transparent metal structure. However, to date, there is little attention focused on the enhanced transmission by using metal ellipsoidal nanoparticles. In this paper, we propose a novel plasmon-induced transparent metal structure, and focus on the cooperative effects of the nanometer-separated metal ellipsoidal nanoparticle array and the continuous metal film structure. The results show that the plasmonic resonance properties can be modified noticeably by changing the thickness of the continuous metal film, the aspect ratio and orientation of ellipsoidal nanoparticles, and the environmental refractive index. Near-perfect optical transparency (up to 80%) is obtained with the enhanced transmission intensity of 45 times than that of the double metal films without the metal ellipsoidal nanoparticle array, which would show great potential applications in optoelectronic integrated circuits, plasmonic filters and sensors.

2. Model design

The plasmon-induced transparent metal structure consists of double flat continuous gold (Au) films inserted with a two-dimensional Au ellipsoidal nanoparticle array as shown in Fig. 1(a). The long axes of ellipsoidal nanoparticles in this proposed structure are parallel to the z axis. The Au ellipsoidal nanoparticles are arranged into a two-dimensional hexagonal periodic array as shown in Fig. 1(b). The horizontal axis radius, vertical axis radius, aspect ratio of ellipsoidal nanoparticle, and the thickness of continuous Au film are denoted as a, b, r, and h, respectively.

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The aspect ratio is defined as $r=a/b$. The center distance of adjacent ellipsoidal nanoparticles along the x direction is represented by p as shown in Fig. 1(a). The gap distance (g) (edge-to-edge separation distance) between adjacent ellipsoidal nanoparticles is equal to $g=p-2a$. The optical responses and electric field intensity distribution patterns are calculated by the three-dimensional finite-difference time-domain (3D-FDTD) method [22]. The calculated region is truncated by using perfect matched layer (PML) absorbing boundary conditions on the top and bottom surfaces of the computational space along the z direction. The truncated positions are above (reflection) and below (transmission) the detector 50 nm. The left and right boundaries along the x and y directions are treated by the periodic boundary conditions. The grid size is refined until full convergence and simulations run long enough to resolve all sharp features in the spectrum. In this work, the grid size is 1 nm. A Gaussian single pulse of light with a wide frequency profile is sent up away the structure 500 nm as the incident light source. The incident light is normal to the continuous Au film along the negative z axis with the electric field parallel to the x axis as shown in Fig. 1(a). A detector is placed below the structure 300 nm or up the structure 800 nm to measure the transmission or reflection spectrum.

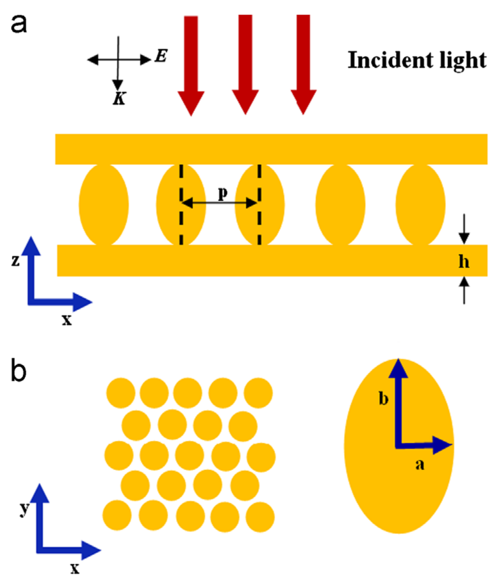

Fig. 1. Schematic diagram of the structure consisting of double Au films inserted with one Au ellipsoidal nanoparticle array in which the long axes of ellipsoidal nanoparticles are parallel to the z axis. (a) x–z cross section, (b) x–y cross section. Incident light is normal to the Au film along the negative z axis with the electric field parallel to the x axis.

The metal film and ellipsoidal nanoparticles are all made of Au, and the dielectric constant of Au is described by the Drude model [23]

$$\varepsilon_m(\omega)=\varepsilon_\infty-\omega_p^2/(\omega^2+i\gamma\omega) \quad (1)$$

where the parameter ε_∞ describes the dielectric screening introduced by the bound valence electrons of the positive ion cores and the second term is the contribution from the conduction electrons, ω_p is the plasma frequency and γ is the collision frequency, related to energy loss. In what follows, we will for simplicity assume $\varepsilon_\infty=1$.

3. Results and discussion

First, we study the optical properties of a continuous Au film with only one Au ellipsoidal nanoparticle array on its top surface via changing the aspect ratio and orientation of ellipsoidal nanoparticles under the illumination by the linearly polarized light as shown in Fig.1. Fig. 2(a) shows the transmission spectra of the structure in which the long axes of ellipsoidal nanoparticles are along the horizontal direction, *i.e*, x direction. The horizontal axis radius ($a=60$ nm) of ellipsoidal nanoparticles, the thickness ($h=20$ nm) of continuous Au film and the gap distance ($g=15$ nm) between adjacent ellipsoidal nanoparticles in this structure are kept invariable. For the pure Ag film with a thickness of 20 nm, according to our previous studies [3,6,24,25], it is almost opaque in the visible and near-infrared regions by itself alone. When one Au plasmonic array consisting of ellipsoidal nanoparticles with horizontal orientation is placed on the continuous Au film as shown in the inset in Fig. 2(a), enhanced transmission with a maximum transmission intensity up to 55% (corresponding to $r=2{:}1$) is clearly seen here, accompanied by an obvious red-shift as r increases from 1 to 2:1. According to the electric field intensity distribution patterns at the center wavelengths of $\lambda=618$ nm ($r=1$) and 678 nm ($r=2{:}1$) (the insets in Fig. 2 (a)), it is clearly seen that the electric field energy confined in the gaps between adjacent ellipsoidal nanoparticles as $r=2{:}1$ is much stronger than that confined in the gaps between adjacent spheres as $r=1$. Therefore, the phenomena observed in Fig. 2(a) are mainly the results of the increased near-field dipolar plasmon interaction of adjacent ellipsoidal nanoparticles with r increasing [26,27]. When the Au ellipsoidal nanoparticles are arranged into one array with their long axes along the z direction, *i.e*, vertical orientation (see the

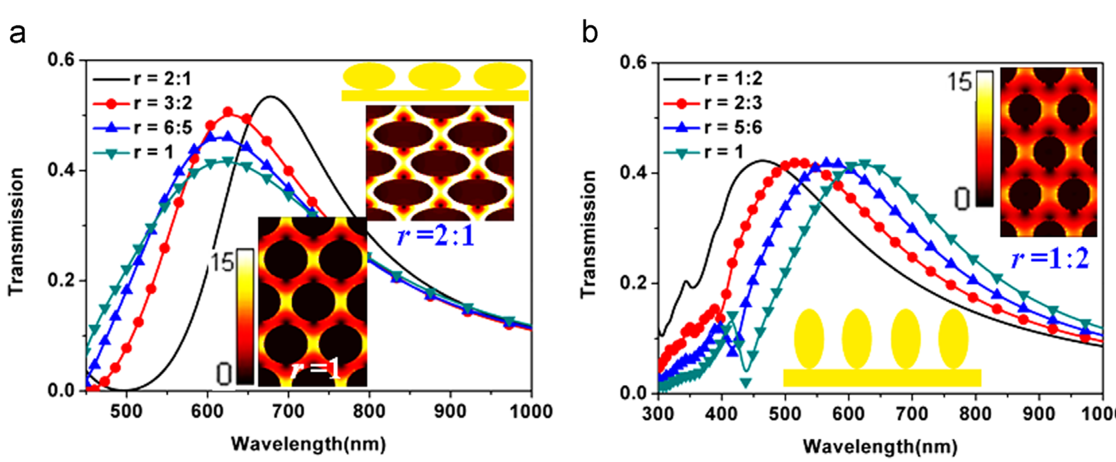

Fig. 2. Transmission spectra of the structure consisting of a continuous Au film with one Au ellipsoidal nanoparticle array on its top surface by varying the aspect ratio of ellipsoidal nanoparticles. Long axes of Au ellipsoidal nanoparticles in the array are along the horizontal (a) and vertical (b) directions. Insets: schematic diagrams of the simulated structures and corresponding electric field intensity distribution patterns at $\lambda=618$ nm ($r=1$), $\lambda=678$ nm ($r=2{:}1$), and $\lambda=460$ nm ($r=1{:}2$).