Optics Communications 316 (2014) 111–119

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Multispectral optical enhanced transmission of a continuous metal film coated with a plasmonic core-shell nanoparticle array

Gui-qiang Liu, Ying Hu, Zheng-qi Liu*, Zheng-jie Cai, Xiang-nan Zhang, Yuan-hao Chen, Kuan Huang

Laboratory of Nanomaterials and Sensors, College of Physics and Communication Electronics, Jiangxi Normal University, Key Laboratory of Optoelectronic and Telecommunication of Jiangxi Province, Nanchang 330022, China

ARTICLE INFO

Article history:
Received 25 September 2013
Received in revised form
29 November 2013
Accepted 2 December 2013
Available online 12 December 2013

Keywords:
Surface plasmons
Continuous metal films
Multispectral optical enhanced transmission
Plasmonic nanoparticle arrays

ABSTRACT

We propose and show multispectral optical enhanced transmission in the visible and near-infrared region in a continuous metal film coated with a two-dimensional (2D) hexagonal non-close-packed plasmonic array. The plasmonic array consists of metal/dielectric multilayer core-shell nanoparticles. The excitation of near-field plasmon resonance coupling between adjacent core-shell nanoparticles, plasmon resonance coupling between adjacent metal layers in the nanoparticle, and surface plasmon (SP) waves on the metal film are mainly responsible for the multispectral optical enhanced transmission behavior. The multispectral optical enhanced transmission response could be highly modified in the wavelength range, transparent bandwidth and transmission intensity by varying the geometry parameters including the gap distance between adjacent plasmonic nanoparticles, the size of metal core and the thickness of dielectric layer between the metal layers. In addition, the number of optical enhanced transmission bands increases with the number of metal layers in the plasmonic nanoparticle. The proposed structure shows many merits such as the deep sub-wavelength size, multispectral optical enhanced transmission bands as well as fully retained electric and mechanical properties of the natural metal. These merits may provide promising applications for highly integrated optoelectronic devices including plasmonic filters, nanoscale multiplexers, and nonlinear optics.

1. Introduction

Manipulation of light with metal nanostructures at the nanoscale exhibits significant advantages in nanophotonic applications involving surface enhanced Raman scattering [1], electromagnetically induced transparency [2,3], and negative index metamaterials [4–6]. Optical enhanced transmission in metal nanostructures have been proposed [7–12] via the excitation of surface plasmon (SP) waves or Fabry–Pérot modes in single metal films with sub-wavelength periodic apertures [13–17] and has also been predicted via strong near-field light-matter interaction by using plasmonic period arrays with more compact sizes [18–22], which would open the possibility of achieving ultra-compact functional optical components in highly integrated optical devices. However, the vast majority of metal nanostructures reported previously support only a single plasmonic resonance.

Recently, plasmonic structures, such as multi-diffractive gratings [22], nanoantennas [23], and resonator-waveguide systems [24–26], have been proposed to exhibit multiple plasmon resonances induced by the plasmon coupling. Especially, multispectral optical enhanced transmission has been obtained in a periodic metal cylinder array or a compound structure of metal cylinder/hole array [27,28] and in a continuous metal film with periodic metal cylinders on their top [29] via the excitation of multiple SP resonant modes. Multi-peak transmission has also been found in a bull's-eye-shaped metamaterial due to the combination of dark modes and electromagnetically induced transparency [30]. Multiple plasmon resonances in one metal structure would provide potential applications in constructing complex optical devices such as multi-wavelength sensors and plasmonic filters [22–30]. However, due to the large periodic grating structures employed in these studies, multiple plasmon resonances mainly originate from SP waves on the metal film, localized SP modes on the nanoparticles and their cooperative effects; the interaction between adjacent nanoparticles is rather weak to be neglected in such structures and their cooperative effects on the plasmon resonances are still unexplored.

In order to meet the requirements of the higher integrated optoelectronic potential applications, the much more compact structures are desired. So far, great interesting and considerable attention have been focused on sub-wavelength plasmonic nanostructures. Novel optical features including surface enhanced absorption and Raman scattering have been explored in the non-close-packed metal nanoparticle arrays [31–33]. Strong

* Corresponding author. Tel./fax: +86 791 812 0370.
E-mail address: lzhq86025@163.com (Z.-q. Liu).

0030-4018/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.optcom.2013.12.011

managements in the light trapping and absorption have been found in the sub-wavelength near-field plasmonic coupling nanostructures [34–37]. For example, near-perfect enhanced light transmission or anti-reflection behaviors in the continuous metal film structures have been achieved due to the excitation of strong near-field plasmon resonant coupling by the nanometer separated metal nanoparticle array [18–22]. Multispectral plasmon resonances have also been achieved in a hybrid nanostructure composed of a triangle and a nanorod(*s*) with nanometer separated distance through the cavity resonant modes [38] and in the coupled meta-atoms consisting of a two-slot antenna based complementary metamaterial layers with a small gap by the hybridized plasmonic modes [6] due to the appearance of strong near-field interaction. These studies show new approaches for investigating the near-field coupling effects in such nanostructures and attract much attention for their potential applications in ultra-compact optical devices. Metal/dielectric core-shell nanostructures exhibit many novel optical properties such as Fano resonances, enhanced optical absorption and local electric field enhancement due to the plasmon hybridization mode in such structures [39–41]. However, to the best of our knowledge, the structural tunability of multispectral optical enhanced transmission response has never been studied in detail for plasmonic multilayered core-shell nanoparticles.

Inspired by the strong near-field plasmon coupling in non-close-packed nanoparticle arrays and the plasmon hybridization mode in multishell metal–dielectric nanostructures, in this work, we investigate the multispectral optical enhanced transmission response in the continuous metal thin film with a two-dimensional (2D) hexagonal non-close-packed multilayer metal/dielectric core-shell nanoparticle $(Ag/(SiO_2/Ag)_m$ $(m \geq 0$, integer)) array and show the multispectral optical enhanced transmission response in the visible and near-infrared region in such structures. Hybridized near-field plasmonic resonant coupling between adjacent metal layers (including the metal core and metal shells) in the nanoparticle, and also between adjacent plasmonic core-shell nanoparticles, cooperated with the coupling between these near-field plasmon resonances and the excitation of SP waves on the metal film are responsible for the multispectral optical enhanced transmission response in this proposed nanostructure. Our investigation also shows that the number of transmission bands is closely related to the number of metal layers in the plasmonic core-shell nanoparticle. Moreover, the proposed structure also shows other merits such as deep sub-wavelength size and fully retained electric and mechanical properties of the natural metal. These may provide promising applications not only in constructing high-compact optoelectronic devices including multi-wavelength plasmonic filters, multiplexer devices, and biosensors, but also in designing high power superluminescent light emitting diodes [42,43].

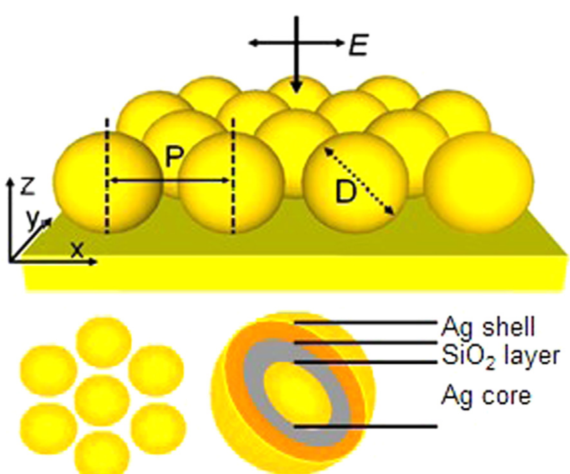

Fig. 1. Schematic diagram of the structure consisting of a continuous Ag film with a plasmonic array of multi-layer metal/dielectric core-shell nanoparticles. Insets: hexagonal lattice structure (left) and tri-layer $(Ag/SiO_2/Ag)$ core-shell nanoparticle (right).

2. Structural design and simulation

The multispectral optical enhanced transmission metal nanostructure consists of a continuous metal film with a 2D hexagonal non-close-packed periodic array of metal/dielectric multilayer core-shell nanoparticles on its top, as shown in Fig. 1. Metal (silver, Ag) and dielectric (silica, SiO_2) materials are arranged alternately in the nanoparticles with the metal spheres serving as the cores. The multilayered plasmonic $Ag/(SiO_2/Ag)_m$ $(m \geq 0$, integer) core-shell nanoparticles are easy to be synthesized [40,41,44]. The proposed structure in this work can be easily obtained by the well-developed standard metal film deposition method [45] and the self-assembling of nanoparticle array [46]. The thickness of the continuous Ag film is 20 nm. Six important parameters as displayed in Table 1 are considered in this work. These parameters include the period (P) of the array, the distance (H) between the array and the metal film, the radius (R) of Ag cores, the thickness (t) of SiO_2 dielectric layer, the number (N) of metal layers in the nanoparticles, and the environment refraction index (n). The gap distance (G) is denoted as the edge-to-edge separation distance between adjacent plasmonic nanoparticles, *i.e.*, $G=P-D$. The optical responses and electric field distribution patterns are calculated by the three-dimensional finite-difference time-domain (3D FDTD) method [47]. The infinite array is simulated through using periodic boundary conditions along the x and y directions around the unit cell and perfectly matched layers along the z direction. Furthermore, meshes have been refined until fine convergence and simulations run long enough to resolve all sharp features in the spectra. For adjacent nanoparticles with the separation distance of 5 nm, the calculations converge satisfactorily for a mesh size of 1 nm [48]. A Gaussian single pulse of light with a wide frequency profile is sent up away the top of the structure 350 nm as the incident light source. The incident light placed on top is normal to the Ag surface (along the z axis) with the electric field vector parallel to the x axis. The detector is placed away from the top and bottom structure 500 nm and 300 nm to measure the transmission and reflection spectra, respectively. All transmission/reflection spectra in our systems are normalized by the intensity of incident light.

The metal layers in the core-shell nanoparticle and the metal film in this hybrid structure are mainly used to produce plasmon-induced

Table 1
Six important and changeable parameters closely related to the optical response of the proposed structure being considered in this work.

Simulated parameter	Period of the plasmonic array	Distance between the array and the metal film	Radius of Ag cores	Thickness of dielectric layer	Layer number of metal	Environment refraction index
Symbol	*P*	*H*	*R*	*t*	*N*	*n*