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Broadband enhanced transmission in a film-array plasmonic structure through the plasmon coupling effects

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ABSTRACT

Enhanced optical transmission in metal structures has received much attention due to the interesting physics and important applications in optoelectronic devices. Here, we propose and demonstrate the broadband enhanced optical transmission of a cooperative plasmonic structure consisting of double SiO_2 films inserted with double parallel nanoparticle arrays composed of metal and dielectric spheres by the three-dimensional finite-difference time-domain (FDTD) method. Based on the bright mode and dark mode rule, the proposed structure shows a greatly enhanced broadband transmission through the hybridization of the plasmon resonant coupling effects of adjacent metal spheres, the surface plasmon waves at the interface between the metal array and the dielectric material and the optical cavity modes formed by the double dielectric films. The full width at half maximum (FWHM) of this broadband optical transmission with a highest transmission up to 85% is more than 400 nm. The broadband optical transmission can be efficiently tailored by varying the lattice period of the arrays and the distance between the metal and dielectric arrays. This proposed structure with subwavelength size may provide potential applications in optoelectronic devices such as broadband transparent and conductive devices, slow light devices, and highly sensitive sensors.

1. Introduction

Light can be controlled in metal nanostructures through the surface plasmon resonance effects [1–4]. Since Ebbesen et al. first presented extraordinary optical transmission through a metallic film perforated with hole arrays in 1998 [5], metal structures and metamaterials with high transmission and conductivity have received significant attention for their great potential applications in highly integrated semiconductor devices and optoelectronic devices [6–12]. The enhanced optical transmission of metal films with apertures such as holes or silts has been achieved by some certain resonances like the Fabry–Pérot (FP) resonances or surface plasmon resonances [13,14]. With the advances of electron beam lithography, focused beam etching, atomic force microscopy and nanoimprint technique, many novel metal nanostructures can be realized. Based on these advanced technologies, novel metal nanostructutres with extraordinary optical transmission have been demonstrated and realized experimentally [15–18], which could provide promising applications in constructing structures with smaller sizes owing to their inherent properties of strong field confinement and overcoming the diffraction limit in the micro- and even nanodevices [19–22]. For example, by structuring the continuous metal film with appropriate corrugations or periodic modulation on its surface(s), enhanced optical transmission has been achieved experimentally due to the leakage of surface plasmon polaritons (SPPs) in the metal substrate [23]. Furthermore, the bandwidth of the enhanced optical transmission may be easily tuned by altering the parameters of structures [24]. Now, considerable research has been carried out to achieve enhanced transmission in metal plasmonic structures due to their various promising applications including slow light devices, highly sensitive sensors, nonlinear elements and so on [25–30]. Broadband enhanced transmission with high transmittance in a metal plasmonic structure is very important for potential applications in some optoelectronic devices such as flat panel displays and solar cells. A metal thin film structure with a nanohole array showing a high transparency in a wide wavelength range from ultraviolet to infrared has been proposed by Du et al. [31]. Recently, Zhang et al. has designed a counter-intuitive mechanism of constructing an ultrathin broadband transparent subwavelength device in the near infrared regime with two perfect blackbodies [32]. However, some metal structures with enhanced broadband optical transmission

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are too complex to fabricate or expensive to put into practical applications, such as a possible broadband slow light device using a 41-layer approach [26], a surface resonance biosensor based on a lot of gold cubes [27].

We have studied the greatly enhanced optical transmission with narrow bands through the strong near-field plasmon resonance coupling of adjacent plasmonic nanoparticles in the nanostructures with subwavelength sizes [33,34]. Singh et al. have demonstrated that by manipulating the coupling between a bright mode and a dark mode, where the bright mode is strongly coupled to the incident electromagnetic field, while the dark mode is not directly coupled to the field, broadband enhanced transmission could be obtained [35,36]. Inspired by these studies, we propose a novel cooperative plasmonic structure consisting of two dielectric silica (SiO_2) films inserted with double parallel periodic copper (Cu) or silver (Ag) and SiO_2 spherical nanoparticle arrays in this work. By the strong coupling of bright mode in the top metal nanosphere array to the input field, the coupling between the dark resonators and the bright resonators, as well as the coupling of dark mode in the bottom dielectric nanosphere array to the output field, a broadband enhanced transmission is achieved with the full width at half maximum (FWHM) more than 400 nm and maximum light transmission exceeding 85% in the visible and near infrared regions. The hybridization of plasmonic gap modes and resonant cavity modes play an important role in the enhanced optical transmission in our design and can be used to tune the resonant frequency of the system [37]. The proposed structure here could be fabricated through the self-assembling of nanoparticle array and reverse imprint lithography [38,39]. What is more, the broadband enhanced transmission behaviors can be efficiently tailored by changing the parameters of this novel structure. These indicate that our proposed structure could have potential applications in optoelectronic devices such as plasmonic filters, sensors, and solar cells.

2. Model design

The proposed structure in this work consists of two flat SiO_2 films inserted with double parallel two-dimensional metal (Cu or Ag) and dielectric (SiO_2) nanosphere arrays (both parallel to the x direction) as shown in Fig. 1. The metal spheres consisting of Cu or Ag are piled on the SiO_2 spheres in this structure. The radii of these two kinds of spheres are equal to each other and are denoted as r here. The thickness of the two dielectric films and the distance between the metal array and the dielectric array are denoted as l and h, respectively. The radii r of these nanospheres and the thickness of dielectric films (l) are fixed to 30 nm and 20 nm, respectively. The same lattice constants of these two periodic arrays are denoted as a and can be tuned in this work. The optical properties and the electromagnetic field intensity distribution ($|E|^2$) patterns of this proposed structure are performed by using the three-dimensional finite-difference time-domain (FDTD) method [40] with a Gaussian single pulse of light illumination along the z-axis in the negative direction as shown in Fig. 1. The infinite arrays are simulated using periodic boundary conditions along the x and y directions around the unit cell including one complete and four-quarter nanospheres in the xoy plane and perfectly matched layers along the z direction. Furthermore, meshes have been refined until convergence and simulations run long enough to resolve all the sharp features in the spectra. The incident light on the up side of the structure is normal to the surface of dielectric film (along the z axis) with the electric field parallel to the x axis. All transmission/reflection spectra are normalized by the incident light intensity.

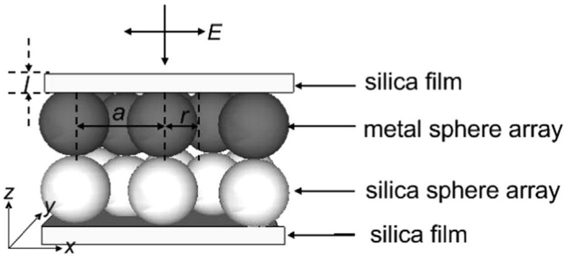

Fig. 1. Systematic graph of the structure consisting of two silica films inserted with a metal nanosphere array touching a silica nanosphere array.

The Drude model is employed to describe the dielectric constants of metal materials noted by [41] as follows:

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

with the plasma frequency ω_p (Cu)$=2\pi \times 1914$ THz, ω_p (Ag)$=2\pi \times 2175$ THz, and the collision frequency related to energy loss γ (Cu)$=2\pi \times 8.37$ THz, γ (Ag)$=2\pi \times 4.36$ THz [42] which are determined through fitting the experimental data [43]. The dielectric screening is generated by bound valence electrons of the positive ion cores and the effect of conduction electrons, which is denoted by ε_∞. Here, we simply assume $\varepsilon_\infty = 1$.

3. Results and discussion

The phenomenon of enhanced optical transmission can be realized via destructive interference between the superradiant and subradiant plasmonic modes or by breaking the symmetry of metamaterial system at microwave, terahertz, and optical frequencies [23–34]. Two different metal materials such as Cu and Ag are employed in this work to study the optical properties of the proposed broadband enhanced transmission structure. Firstly, we calculate the transmission, reflection and absorption spectra of the structure with a Cu sphere array closely in contact with the SiO_2 sphere array ($h=0$), as shown in Fig. 2. The reflection and transmission behaviors of our structure are calculated by the FDTD method and the absorption can be obtained by $A = 1 - R - T$, where A, R and T describe the absorption, the reflection and the transmission, respectively. A broadband enhanced transmission with high light transmission accompanied by a narrow absorption dip and much weaker reflection at the wavelength (λ) of 642 nm is clearly observed here. The FWHM of this broadened band exceeds 400 nm with a highest T up to 85%, much broader than those found in the plasmon induced enhanced transmission substructures and periodic grating structures [12,44], which

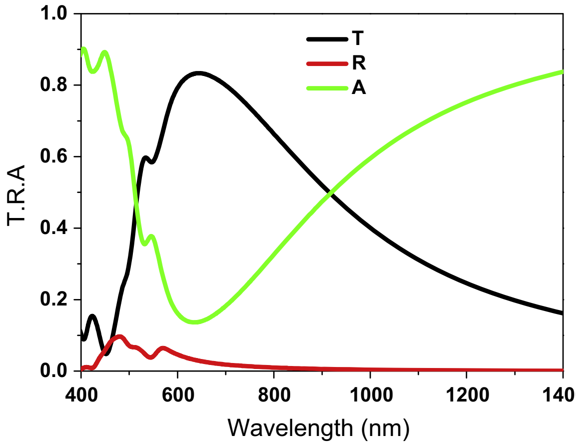

Fig. 2. Transmission, reflection and absorption spectra of the structure consisting of double flat SiO_2 films inserted with double parallel two-dimensional Cu and SiO_2 nanosphere arrays. Here $h=0$, $r=30$ nm, and $a=82.5$ nm.