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Giant-enhancement of extraordinary optical transmission through nanohole arrays blocked by plasmonic gold mushroom caps

Qing Zhang [a,b], Pidong Hu [c], Chengpu Liu [b,*]

[a] Department of Physics, College of Sciences, Shanghai University, Shanghai 200444, China
[b] State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Shanghai 201800, China
[c] Department of Physics, East China University of Science and Technology, Shanghai 200237, China

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ABSTRACT

An improved plasmonic hole array nanostructure model with the holes blocked by gold mushroom caps is proposed and it can realize a giant transmission with efficiency up to 65%, 182% larger than the unblocked nanohole array, due to the strong coupling between caps and holes, which plays the role of a cavity antenna. Moreover, the numerical investigation confirms that it provides more consistency with the practical experimental situations, than the nanodisk model instead. As expected, the light transmission sensitively depends on the geometric parameters of this new nanostructure; as the cap-hole's gap or cap's diameter vary, there always exists an optimal transmission efficiency. More interesting is that the corresponding optimal wavelength decreases with the gap's increment or the diameter's decrement, particularly in an exponential decaying way, and the decay rate is obviously influenced by the cap's parameters.

1. Introduction

The extraordinary optical transmission (EOT) of light through an array of periodic holes in metal films has been of great interest to researchers working in the nano-optics and plasmonics fields [1,2]. The extraordinary property means, at the resonance wavelength of a nanohole array, the light transmission efficiency can exceed 100%, in contrast to the standard aperture theory, when compared to the light incident on the nanoholes [3] due to the occurrence of surface plasmon polaritons (SPPs). Simultaneously there also exist highly localized surface plasmon resonance (LSPR) wave in the vicinity of the nanoholes, which enables many important applications [4–13], such as sunlight harvesting [5,6], macroscopic color holograms [7], full color filter [8], color printing [9], surface-enhanced Raman scattering [10] and sensing [11–13].

It has been experimentally demonstrated that the EOT depends sensitively on the dielectric functions of the metal film and the dielectric material, the spacing between the nanoholes, the holes lattice arrangement, and the propagation direction of the excited SPP modes [14,15]. It can be controlled by incorporating periodic structures surrounding the subwavelength holes [16].

Recently, numerical simulation has predicted that covering the subwavelength silts by metallic nanostrips forming horizontal nanocavity antennas can significantly enhance the optical transmission [17]; Li et al. reported experimentally an unexpected light transmission enhancement when the subwavelength holes blocked by opaque metal disks [18], based on a new kind of plasmonic nanostructure, termed as “disk-coupled dots on pillar antenna array” (D2PA) [19]. Here we propose one mushroom cap model instead of the simplified nanodisk model, because the former is more accurate than the latter in comparison with experimental results, which is a reasonable judging from the scanning electron microscopy (SEMs) images [18]. Of course, the difference between theory and experiments could come from many resources, such as fabrication accuracy, shape uniformity, measurement condition, simulation parameters, etc. However, the following simulation results confirm that the mushroom cap model provides more consistency with the practical experimental situations, than the nanodisk model instead. The transmission can be tuned by changing the mushroom cap's diameter, as well as the gap between the caps and the holes. After an optimization, a giant light transmission with efficiency up to 65%, 182% larger than the unblocked nanohole array, is realized. The simulation related to transmission spectra and electric field distributions confirms that an interaction of SPPs associated with LSPPs between nanocaps and nanoholes, which plays the role of a cavity antenna, results in new transmission resonances [20]. Such an

* Corresponding author.
E-mail address: chpliu@siom.ac.cn (C. Liu).

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improved device blocked by nano-mushroom caps will find more potential and significant applications in nanoplasmonics.

2. Methods

A three-dimensional (3D) finite difference time domain (FDTD) method [21,22] is used to investigate the optical transmission property for a light propagating through a sub-wavelength metallic holes array, as shown in Fig. 1. In this paper, we consider three cases: (i) the holes are open without any blockers (Fig. 1a), (ii) the holes are completely blocked by flat metal circle disks with diameter (*D*) size larger than that of the holes (Fig. 1b), and (iii) the holes are blocked by mushroom caps with flat, circle bottom and diameter D. The Au film is covered on the dielectric materials (SiO_2) substrate, and the SiO_2 pillar array get through the holes. The flat metal disks or the mushroom caps lies on the top of the SiO_2 pillar. The diameter of either disk or cap is larger than that of the hole and as well the pillar. The fabrication method and process of the nanodisk structure can get details from papers [18,19]. However, with a careful investigation to the scanning electron microscopy (SEMs) picture of the nanodisk blocked array [18], the top shape profile of the disk should not be simply considered to be flat, using a mushroom-like cap instead of circle disk would be more practical. This holes array has 52 nm high pillars and 40 nm thickness in both top gold blockers and bottom perforated gold film, and a 200 nm pitch between the 70 nm diameter holes (the periodic structure is a $200 \times 200\ nm^2$ square). The two type blockers both have a diameter of 85 nm (15 nm larger than the holes' size). In FDTD simulation, the gold mushroom cap can be characterized as a half-ellipsoid with a fixed 40 nm thickness.

In the FDTD simulation, a single cell containing a periodic structure (gold nanoholes covered by nanodisks or mushroom caps) is simulated with two different boundary conditions to calculate the interaction between light and an infinite periodic structure. The *x*- and *y*-axes are set to periodic boundary conditions while the *z*-axis to perfect match layer (PML) boundary condition. The mesh sizes are 2 nm in all directions (much smaller than the gap's size, which is in the range of 10–50 nm). The dielectric function of gold is used from CRC [23] and that for SiO_2 is provided by Palik [24]. A p-polarized plane wave source is used to illuminate this nanostructure from the bottom substrate side. After the plane wave passes through the holes array, the transmission spectrum of the light is investigated in detail as shown in the following.

3. Results and discussion

First, the transmitted spectrum simulated by the FDTD method based on the nanodisk model (Fig. 1(b)) is obtained using the same experimental parameters in [18], as shown in Fig. 2 (dashed line). This spectrum clearly shows two transmission peaks and one dip between them. The first peak is due to the SPP excitation at the perforated gold film with periodical holes array, and the second peak with much higher enhancement is caused by the LSPR of the gold holes coupling with the gold disks.

The corresponding experimental result (solid line) [18] in Fig. 2 is also shown for comparison. The simulated spectrum is wholly below the experimental measurement, that is, both the efficiency and position of the transition peak have differences: (1) The position of the second peak for the nanodisk calculation is with a red-shift by around 40 nm compared with that for the experimental spectrum; (2) the maximum transmission efficiency for the simulated spectrum is only 30%, which is much smaller than that for the experimental result, 47%.

Why these larger differences occur? In fact, with a careful investigation to the scanning electron microscopy (SEMs) picture of the nanodisk blocked array, the top shape profile of the disk

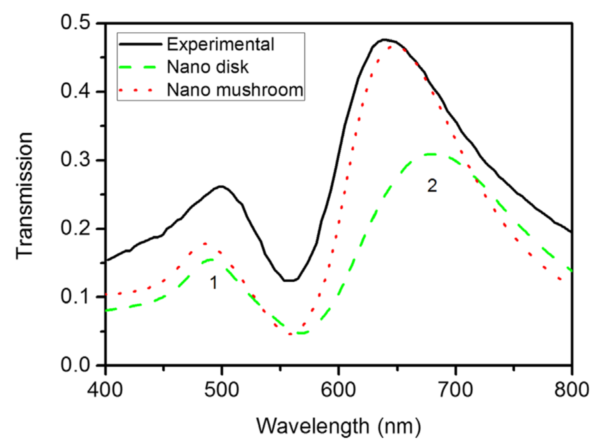

Fig. 2. The simulated transmission spectra for different blocker models compared with the experimental transmission spectrum (solid line) [18]. Simulated spectrum (dashed line) adopts the nanodisk model (Fig. 1b), and the simulated spectrum (dotted line) uses nano-mushroom cap model (Fig. 1c) instead. The holes array's thickness is 40 nm and the holes' diameter 70 nm; the SiO_2 pillar's height is 52 nm and the gold nanodisks have a diameter of 85 nm.

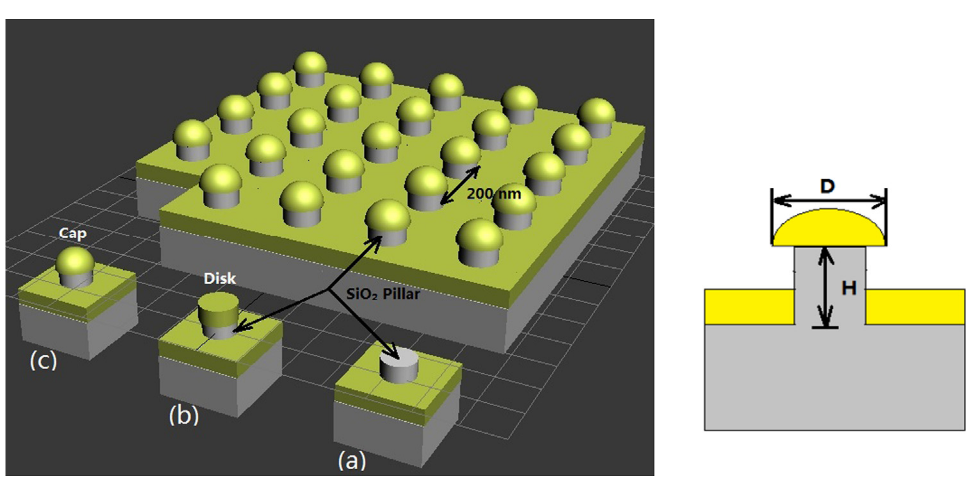

Fig. 1. Schematics of subwavelength metallic holes array in Au (gold) film without or with two types of blockers. The substrates are transparent fused silica (SiO_2) with pillars supporting the blockers. (a) Without blocker on the top of pillars; (b) nano-disks as blockers; (c) nano-mushroom caps as blockers.