Optics Communications 325 (2014) 105–110

Contents lists available at ScienceDirect

Optics Communications

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

Enhanced optical transmission in a plasmonic nanostructure perforated with compound holes and nanorods

Xiangnan Zhang, Guiqiang Liu *, Ying Hu, Zhengqi Liu *, Zhengjie Cai, Yuanhao Chen, Xiaoshan Liu, Guolan Fu, Gang Gu, Mulin Liu

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 13 January 2014
Received in revised form
11 March 2014
Accepted 7 April 2014
Available online 19 April 2014

Keywords:
Localized surface plasmons
Enhanced optical transmission
Surface plasmon polaritons
Compound hole and nanorod arrays

ABSTRACT

We propose a novel enhanced optical transmission plasmonic nanostructure composed of a metallic film perforated with a compound rectangular hole and nanorod array. The optical characteristics are investigated by the three-dimensional finite-difference time-domain (FDTD) method. An extraordinary enhanced transmission (transmittance over 96%) in the optical regime is obtained as a result of the excitation and hybridization of localized surface plasmon resonances (LSPRs), surface plasmon polaritons (SPPs), as well as the gap plasmon modes supported by the holes. The enhanced optical transmission can be effectively tailored by changing the geometrical parameters such as the length and width of inner cubic Ag nanorods, the gap of rectangular holes, the period of compound hole array, as well as the height of Ag film due to their effects on oscillating charges on metal surfaces. The structure could facilitate numerous important applications in highly integrated plasmonic filters and optoelectronic circuits.

1. Introduction

Since Ebbesen first found the enhanced optical transmission (EOT) properties through a thin metal film with periodic holes [1], EOT phenomena in metal films perforated with subwavelength hole arrays have attracted tremendous interests due to its widely applications in integrated optical circuits and optoelectronic devices. Many efforts have been performed to demonstrate the intrinsic physical mechanisms of EOT [2–5]. Surface plasmon polaritons (SPPs), coherent fluctuations of electronic charges bound at the metal–dielectric interface and exponentially decay into both sides, have been believed to be an important physical origin of EOT [6–8]. SPPs have promising applications in highly integrated optical devices, such as multi-channel wavelength demultiplexers, slow light systems, plasmonic filters, plasmonic waveguide systems, optical switching and so on due to that they can overcome the conventional diffraction limit and can manipulate light on subwavelength scale [9–11]. Many devices based on SPPs have now been realized theoretically and demonstrated experimentally. For example, a novel tunable multi-channel wavelength demultiplexer based on metal–insulator–metal plasmonic nanodisk resonators has been proposed by Wang et al. [10]. In addition, a significant slow light effect has also been found in a metal–insulator–metal waveguide system based on the plasmonic analogue of electromagnetically induced transparency [11].

Recently, localized surface plasmon resonances (LSPRs) have also been revealed to contribute to EOT [12–15]. Strong electron oscillations can be excited around the holes or nanoparticles, which propagate along the metal surface to the output port of metal films when the period of array matches the wavelength of surface plasmons excited on the metal nanostructures [16,17]. Different from SPPs excited at the interface of metal and dielectric, LSPRs are individual resonances occurring within the apertures or nanoparticles and the optical properties induced by LSPRs are more sensitive to the structural geometry factors [17,18]. Up to date, many metallic structures perforated with various hole arrays have been studied such as circles, cross-shapes, H-shapes, rectangles, X-shapes and so on [18–21]. In order to figure out the interaction between SPPs and LSPRs, many studies have been performed. For example, the properties of LSPRs can be tuned by the excitation of Wood's anomalies and SPP resonances [13,19]. The localized waveguide resonances, existing in the thin metal film perforated with a two-dimensional period array of holes, have also been found to contribute to EOT, where each air hole can be considered as a section of metallic waveguide with both ends open to free space and thus forms a low-quality-factor resonator [20]. The resonant frequency of the lowest-order cavity mode is the same as the cutoff frequency of the basic mode in these compound waveguides [20]. It is noted that complex apertures generally provide higher coupling efficiency to unpolarized light than simple

---

* Corresponding authors.
E-mail addresses: liugq83@163.com (G. Liu), liuz@jxnu.edu.cn (Z. Liu).

http://dx.doi.org/10.1016/j.optcom.2014.04.015
0030-4018/© 2014 Elsevier B.V. All rights reserved.

squares or rectangles and cause larger transmittance. For example, Ni et al. have experimentally realized a compound metal periodic array of subwavelength cross-shaped apertures and obtained great transmittance [22]. By numerically investigating the transmission properties of metal films with compound periodic subwavelength hole arrays, Liu et al. have obtained an obviously tailored EOT [14]. A tunable plasmon resonant cavity array in paired parallel nanowire waveguides has been theoretically demonstrated and experimentally fabricated by Bora et al., which showed high electric field confinement in the cavities and the tunability of plasmon resonances [13]. However, little attention has been focused on the structure with the combination of rectangular holes and metal nanorods, which may present especial EOT properties due to its compound nanohole cavities with parallel nanorods.

In this work, we theoretically investigated a thin metallic film perforated with compound rectangular holes and cubic metal nanorods based on the silica substrate. The optical properties of our proposed structure and electric field intensity distributions ($|E|^2$) were calculated by the three-dimensional (3D) finite-difference time-domain (FDTD) method. It is found that extremely enhanced transmission with maximum transmittance over 96% is obtained due to the excitation and near-field coupling of strong LSPRs, SPPs as well as the gap plasmon modes supported by the holes. The position and intensity of the EOT peak can be effectively tuned by changing the structural parameters because of their effects on the distribution of oscillating charges on metal surfaces. The highly tunable EOT phenomenon in our proposed structure has potential applications in optoelectronic circuits and optical filters.

2. Numerical model and simulations

The details of the proposed EOT structure are shown Fig. 1. It consists of a silver (Ag) film (olive) perforated with a two-dimensional square array of compound rectangular holes and cubic nanorods based on a silica (cyan) substrate. A unit cell including two identical cubic Ag nanorods surrounded by rectangular air holes in the Ag film is shown in the left graph in Fig. 1. The gap widths between adjacent nanorods and between the nanorod and the metal film are all denoted as d. The thickness of Ag film is h. The width and length of the cubic Ag nanorods are denoted by w and l, respectively. The period of the compound hole array is p. The compound hole array structure is normally illuminated by a linear plane wave with the electric field vector parallel to the x axis, which is launched on the upside of the structure away from the top Ag film 150 nm. The optical properties and corresponding electromagnetic field intensity ($|E|^2$) distributions were calculated by the FDTD method. The infinite structure was simulated with periodic boundary conditions along the x and y directions around the unit cell and perfectly matched layers along the z direction. Furthermore, meshes were refined until convergence and simulations ran long enough to resolve all the sharp features in the spectra. In this work, the calculations converge satisfactorily for a mesh size of 1 nm. The Ag permittivity can be described by Drude model: $\varepsilon_{\mathrm{Ag}}=1-\omega_p^2/[\omega(\omega+i\Gamma)]$, where ω_p is the plasma frequency ($\omega_{p(\mathrm{Ag})}=1.37\times10^{16}$ Hz) and Γ is the damping rate ($\Gamma_{(\mathrm{Ag})}=2.73\times10^{13}$ Hz) [23]. All transmission and reflection spectra were normalized by the incident light intensity.

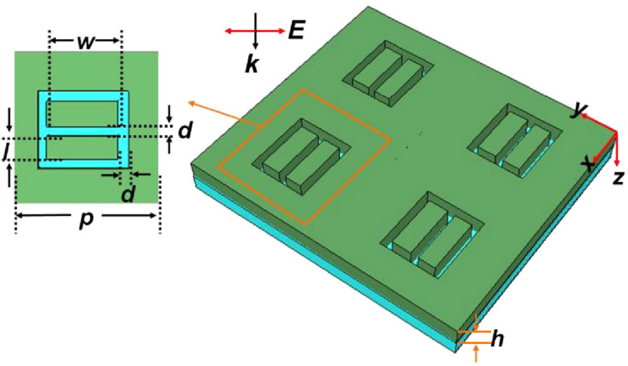

Fig. 1. Schematic graph of the proposed structure consisting of a thin Ag film perforated with a compound rectangular hole and nanorod array based on the silica substrate. The gap width of all holes is same in this structure.

3. Results and discussion

The periodic perforated metallic structures supporting the SPPs and LSPRs can bring out an enhanced zero-order optical transmission [24]. The Ag film with highly conductive characteristic has been widely used in optoelectronic applications. However, a pure Ag film with 20 nm in thickness is opaque to light as reported in our previous work [25]. Here, we investigated the transmission (black) and reflection (red) spectra of our proposed structure ($d=30$ nm, $h=50$ nm, $w=70$ nm, $l=30$ nm, and $p=288$ nm) and the results are shown in Fig. 2. One near-perfect transmission peak located at 650 nm can be clearly observed, corresponding to a near-zero reflection dip. The maximum transmittance (T) even reaches up to 96%, higher than those reported in many metal films perforated with various holes [18–21]. The bandwidth of the peak with $T\geq50\%$ is over 160 nm. As reported before [12,15], both LSPRs and SPPs have important roles in the EOT phenomenon and when they exhibit a similar energy, the holes become conductive to transmission. Therefore, this EOT phenomenon may be attributed to the excitation and coupling of LSPRs in the holes between inner nanorods and outer metal surface [12] and SPPs at the metal surface [15]. The compound holes in our proposed structure are with both ends open to free space and thus can be regarded as the compound rectangular resonant cavities. The localized waveguide resonances [20] or gap plasmon modes [13] may also contribute to EOT.

In complex metal structures, the extraordinary optical responses are sensitive to the geometry shapes, sizes and materials filled in the holes. In this work, we first investigated the transmission spectra and wavelength shift as a function of the length (l) of inner cubic Ag nanorods, as shown in Fig. 3. Here, the length l changes from 20 to 50 nm in intervals of 10 nm and other factors are invariable ($d=30$ nm, $h=50$ nm, $w=70$ nm, and $p=288$ nm). Clearly, an obvious red-shift of the transmission peak, accompanied by a slight increase in intensity, is observed in Fig. 3(a).

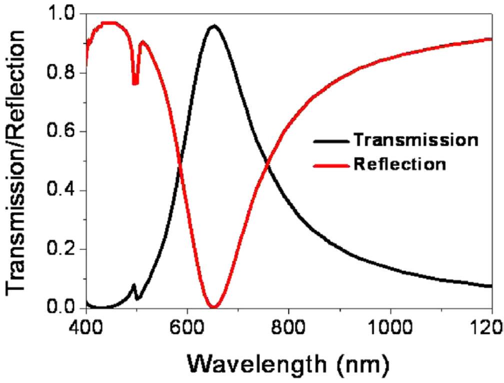

Fig. 2. Transmission and reflection spectra of the proposed structure. Here, $d=30$ nm, $h=50$ nm, $w=70$ nm, $l=30$ nm, and $p=288$ nm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)