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A broadband transparent window in a continuous metal film coated with double layer hybrid dielectric gratings

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ABSTRACT

In this letter, we propose a highly conductive and transparent structure which consists of two high-low index dielectric gratings placed on two sides of a continuous metal film. A broadband transparent window with over 550 nm wavelength width and 80% transmission is achieved in both visible and near-infrared regions. The excitation of hybrid plasmons cavity resonances in the structure generates multiple transmission peaks. Three different transmission peaks overlap to yield a broad transparent window with proper parameters. In addition, the transmission spectrum can easily be modified by tuning structural parameters. Its excellent performance makes our proposed structure a promising candidate for optoelectronics, such as the highly conductive transparent electrodes, displays and solar cells.

1. Introduction

The material with high electronic conductivity and near-perfect optical transparency would be significant for the applications in optoelectronics. Since Ebbesen et al. first presented extraordinary optical transmission through a metallic film perforated with subwavelength hole arrays in 1998 [1], metal metamaterials which combine high transmission and conductivity become a promising candidate in the transparent electrodes and solar cells [2–5]. In order to make a metal film transparent, a typical approach is to introduce holes or slits in the metal film which could provide efficient coupling of input and output light by exciting the surface plasmons [6–11]. However, the introduction of holes or slits weaken the metal film's electrical conduction and mechanical feature inevitably, which limits their applications.

Recently, more attentions have been drawn to enhance transmission of continuous metal films. Non-close-packed plasmonic nanoparticle arrays have been theoretically coated on double sides of the metal film [12–14] or inserted between double continuous metal films [15–17]. Extremely enhanced transmission is achieved due to the excitation of near-field plasmons resonance between adjacent nanoparticles and the plasmons cavity modes between different layers. A seamless metal film covered by a dielectric layer and metallic grating at one or two sides which can provide magnetic plasmons resonance, has been demonstrated to achieve transparent metal in both visible and near-infrared regions [18–20]. Dielectric grating deposited on the thin metal film could enhance transmission due to the excitation of guided mode resonance or Fabry–Perot resonance [21–23]. The combination of two or more modes can also produce a transparent metal film [24–26]. However, the drawbacks including limited transmittance intensity and bandwidth lead to critical limitation in the applications.

In this letter, we propose a hybrid dielectric 2D grating which consists of high index dielectric (Si) strips and low index dielectric (SiO_2) strips stacked on the two sides of a continuous gold film. Based on the hybrid surface plasmons cavity resonance exciting by the hybrid dielectric grating, our proposed structure could achieve a broad transparent (transmission over 80%) window with a bandwidth more than 550 nm in both visible and near-infrared regions. With the excellent performance, it has great application prospects in optoelectronics, such as the highly conductive transparent electrodes, displays and solar cells.

2. Structure and model

Hybrid dielectric gratings (HDG) with a high index dielectric (Si) and a low index dielectric (SiO_2) placed on the two sides of a continuous gold film, as schematically shown in Fig. 1(a)–(b). The top and bottom gratings are symmetric relative to the middle film. The width of the grating, thickness of the Si and SiO_2 are denoted as w, t_1 and t_2, respectively. P represents the period of the grating. A continuous gold film with thickness $h = 20$ nm is chosen, which is thick enough to produce a highly conductive free electron density [18].

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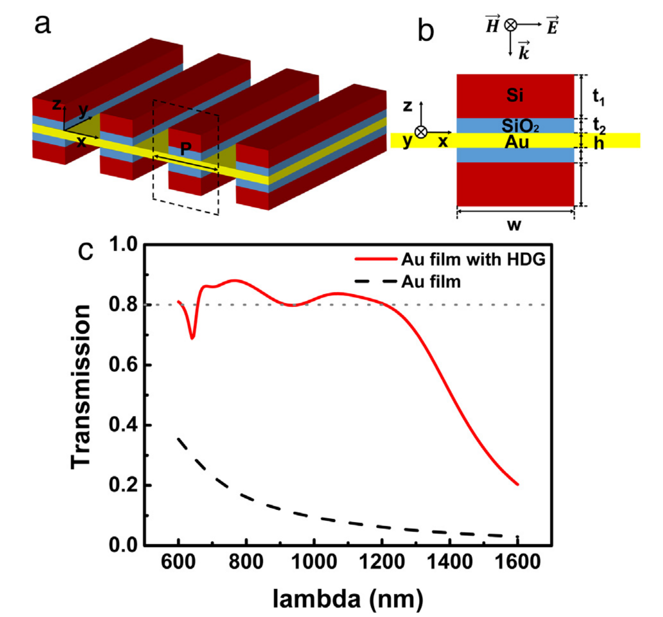

Fig. 1. (a) 3D schematic diagram of the proposed structure with two hybrid dielectric gratings placed on Au's surfaces. (b) Cross section of a grating unit. (c) Transmission spectrum of the proposed structure (red solid line) and Au film (black dash line), with parameters set as: $h = 20$ nm, $t_1 = 100$ nm, $t_2 = 25$ nm, $w = 280$ nm and $P = 580$ nm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

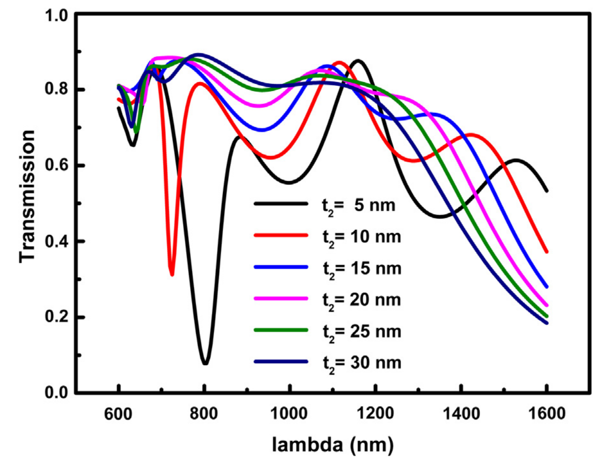

Fig. 2. Transmission spectra for different t_2 (thickness of SiO_2), while other parameters fix as: $h = 20, t_1 = 100$ nm, $w = 280$ nm and $P = 580$ nm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

We used Finite-Difference Time-Domain (FDTD) method to simulate the electromagnetic response and investigate the mechanism of transparency in the structure. In the simulation, the permittivity of gold is extracted from experimental data [27]. And the refractive index of SiO_2 and Si is set as 1.4 and 3.5, respectively. TM plane wave were injected from z direction with magnetic component polarized along the y axis. PML (perfect matched layer) boundary condition is used in z direction, and period boundary is used in x direction to represent the periodicity of the structure.

3. Results and discussion

Fig. 1(c) shows the transmission spectrum of the proposed structure at the TM normal incidence (red solid line). The parameters are set as $t_1 = 100$ nm, $t_2 = 25$ nm, $w = 280$ nm and $P = 580$ nm. As we can see, the transmission spectrum exists a broad transparent window from 650 to 1200 nm with a transmission over 80%. For comparison, we also plot the transmission spectrum for a bare Au film (black dash line) and the transmission is less than 20% in our considered spectral region. So the appearance of transparent window is attributed to the introduction of HDG on the Au film.

In order to investigate the physical mechanism of the transparent window in our structure, we study the effect of t_2 on high transmission, as shown in Fig. 2. It shows the simulated transmission spectra for different t_2 with other parameters being the same as the previous. The broad transparent window splits into three transmission peaks when t_2 is less than 20 nm. And all the three transmission peaks are red-shifted by decreasing the t_2. Taking $t_2 = 5$ nm for an example, we clearly observe three transmission peaks centered in the vicinity of 885, 1160 and 1530 nm. Our attentions will be paid to these peaks because that would help us to further corroborate the mechanism behind the broad high transmission phenomenon.

To characterize this feature, we next investigate the electromagnetic field distributions at the peaks wavelength. The results of electric field distributions for $t_2 = 5$ nm with wavelengths 885 nm (peak 1), 1160 nm (peak 2) and 1530 nm (peak 3) are plotted in Fig. 3. For all three peaks, the electric fields are mainly concentrated in the low index dielectric grating strips (Fig. 3(a)–(c)), indicating a plasmons cavity resonance in the structure. The plasmons cavity modes at both sides of the metal film have been excited, exhibiting the light energy can through the metal film because of the strong coupled between up and down structures. Next, we regard the up and down as a whole structure. If we define the order of cavity resonance as the number of standing wave nodes, peak 2 (peak 3) is the fundamental plasmons cavity resonance, and peak 1 is a third-order plasmons cavity resonance. We could find that E_z in the up and down SiO_2 are in phase at peak 2, while there are out of phase at peak 1 and peak 3, as shown in Fig. 3(d)–(f). So we identify that the symmetrical SPP goes back and forth between the ends of the cavity, forming a Fabry–Perot resonance at peak 2. On the contrary, peak 1 and peak 3 are formed by anti-symmetrical SPP mode.

Next, we pay our attentions to verify the hybrid plasmons cavity resonance (FP resonance) model. We calculate the eigen-modes which propagate along x axis in the proposed cavity (five layer's structure: Si–SiO_2–Au–SiO_2–Si, parameters are set as: $t_1 = 100$ nm, $t_2 = 5$ nm, $h = 20$ nm), using finite element method (FEM). Because of the coupled between up and down structure, it exists two hybrid SPP mode (symmetrical SPP mode and anti-symmetrical SPP mode, the E_z distribution shown in Fig. 4(a) and (b), respectively) The effective mode index of symmetrical SPP mode (n_s) and anti-symmetrical SPP mode (n_a) is shown in Fig. 4(c). The real part of n_s and n_a both decrease monotonically as the wavelength increases. The imaginary part of n_s is much less than the imaginary part of n_a at the considered wavelength region, meaning a low propagation loss in the symmetrical SPP mode. Thus the transmission of the symmetrical SPP cavity resonance should be larger than the transmission of the anti-symmetrical SPP cavity resonance, in agreement with the results shown in Fig. 2. According to the FP resonance condition [28], the relationship of the resonance wavelength (λ) and cavity width (w) can be expressed as:

$$\frac{2\pi}{\lambda} \cdot n_{eff} \cdot (2w) + \varphi = m \cdot 2\pi \quad (1)$$

where φ is the phase shift due to reflection at the edges of the cavity, m is the order of the cavity mode and n_{eff} is the effective mode index of the propagation mode in the structure. Fig. 5 shows the transmission as a function of wavelength and cavity width with other parameters set as: $t_1 = 100$ nm, $t_2 = 5$ nm, $h = 20$ nm and $P = 3w$. The white dash line and black dash line which calculated by Eq. (1), represent symmetrical and anti-symmetrical SPP cavity resonance, respectively. Here we choose $w/P = 3$, due to the dependent relationship between duty ratio and φ. As we can see, the results from simulation and calculated by FP resonance