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Sensor based on Fano resonances of plane metamaterial with narrow slits

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ABSTRACT

The optical properties of a composite metamaterial composed of narrow slits and nano hole pairs have been investigated experimentally and numerically. The strength of the transmission peak originating from the interference between the coupled surface plasmon polaritons (SPP) of the narrow slit and the SPP modes of the hole array is modulated by the degree of symmetry breaking. Some SPP modes can be inhibited by controlling the spacer layer thickness. Our metamaterial has potential applications in sensing and weak signal detection.

1. Introduction

It is well known that a narrow grating has higher qualify factor coupled surface plasmon polaritons (SPPs), which is associated with the excitation of an electromagnetic mode with an SPP character on each surface (top and bottom) of the grating [1]. Thus, it could lead to many promising applications in both physical and biological fields, such as biosensing [2] and polarization filtering [3,4]. However, the existence of a substrate destroys the symmetry of the metamaterial about the z axis, and leads to weakening of the coupled SPP. In order to enhance the strength of the coupled SPP, multiple methods to enhance optical transmission through a single subwavelength slit have been proposed. For example, a single subwavelength slit flanked by a finite array of grooves in a thick metallic film was proposed for the visible light band [5] based on the diffracted evanescent wave theory for enhanced transmission [6–10]. In addition, the freestanding narrow grating was introduced in the micron band [11] as a mechanism for transmission enhancement based on the constructive interference between the coupled SPP of the upper and lower surfaces. However, the fabrication of the freestanding narrow grating is very difficult in the visible and near-infrared bands. To overcome this problem, Liu's group proposed a molecular concentration sensor based on the diffraction resonance mode of gold nanowire gratings and realized a sensor with a higher sensitivity [2]. In addition, because both the energies and widths of the Fano resonances are independently controlled by changing the distance and geometry between individual nanostructures [12–16], the sensitivity of a sensor is enhanced by introducing nanostructures with the Fano resonance phenomenon in a narrow grating. In this paper, first, we describe the design of a metamaterial whose unit cell consists of a narrow slit and two parallel rectangular holes. Second, we introduce an approach to realize a higher sensitivity during sensing. In this approach, the transmission strength is controlled by adjusting the distance between the slit and two rectangular holes in the unit cell. Finally, we show that an intermediate dielectric film inserted between the substrate and metal nanostructures can completely suppress the SPP coupled to the glass plane.

2. Experimental and theoretical methods

The geometry of our designed unit cell with a period P is shown in Fig. 1(a). It consists of a narrow slit and two identical parallel rectangular holes in an 80-nm-thick Au film. The width a of the slit is 45 nm. The length l and width a_1 of the rectangular hole are 180 nm and 100 nm, respectively. The distance s_1 between the two parallel rectangular holes is 80 nm. The distance s between the slit and the rectangular holes is 90 nm. The metamaterial is fabricated using a focused-ion beam (FIB) system

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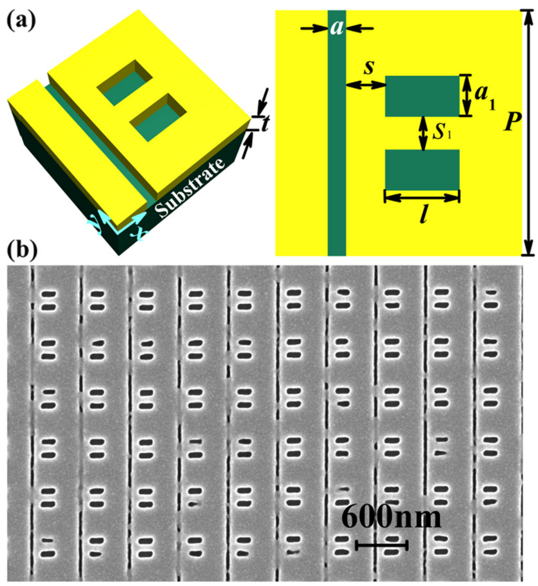

Fig. 1. (Color online.) (a) Unit cell with the corresponding structural parameters. (b) SEM image of a typical sample.

(Strata FIB 201, FEI Co., 30 KeV Ga ions, 11 pA beam current). The array consists of 116 × 116 unit cells covering an area of 70 × 70 μm^2. A typical scanning electron microscopy (SEM) image is shown in Fig. 1(b). x-Polarized light from a halogen lamp is normally incident on our sample. The zero-order transmission spectra are collected by an optical spectrum analyzer (ANDO AQ-6315 A). To understand the physical mechanism of the spectra formation, a numerical simulation is performed using a finite-difference time-domain method. In the simulation, the permittivity of gold described by a Drude mode with plasma frequency $\omega_p = 1.374 \times 10^{16}$ rad/s and collision frequency $\gamma = 1.224 \times 10^{14}$ rad/s [17], and the dielectric constant of the glass substrate is set to 2.1.

3. Optical characterization

Our metamaterial is composed of a 1D pure grating and 2D pure hole array. To study the physical mechanism, we simulated the transmission spectra of the 1D pure grating, 2D pure hole array, and our composite metamaterial. Fig. 2(a) shows the zero-order transmission spectra for the three types of nanostructures, i.e., 1D pure grating (olive curve), 2D pure hole array (blue curve), and our composite nanostructure with $s = 90$ nm (red curve). The other parameters are as previously specified. The sharp peak at about 870 nm corresponds to the coupled SPP of the grating/substrate interface for the 1D grating [1]. The coupled SPP of the grating/air interface disappears due to asymmetry along the z-axis for a thick metal film. For the 2D hole array, two sharp peaks at about 621 nm and 897 nm correspond to the SPP (1, 0) of the metal/air and metal/substrate interface [18–20], respectively. The peak at about 648 nm indicates the SPP (1, 1) of the metal/substrate interface. Based on the law of the momentum conservation [18–20], for the normal incidence case, the SPP wavelengths are given by

$$\lambda_{\mathrm{SPP}}(i, j) = \frac{P}{\sqrt{i^2 + j^2}} \sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \tag{1}$$

Here i, j are integers, ε_m is the real part of the dielectric constant of the metal, and ε_d is that of the dielectric. Based on Eq. (1), we obtain $\lambda_{\mathrm{SPP},G}(1, 0) = 893$ nm, $\lambda_{\mathrm{SPP},G}(1, 1) = 648$ nm and $\lambda_{\mathrm{SPP},A}(1, 0) = 616$ nm. The calculated results agree well with the simulation results. For our nanostructure, the overall transmission spectra show a clear resonant behavior at four different wavelengths, i.e., 618 nm, 645 nm, 871 nm, and 892 nm, which are shown as sharp peaks A–D in Fig. 2(a). Peaks A (618 nm) and B (645 nm) originate from a Fano resonance between the continuous spectra of the narrow grating and the discrete spectra (SPP (1, 0) of the metal/air interface and SPP (1, 1) of the metal/substrate interface) of the hole arrays. Peaks C (871 nm) and D (892 nm) originate from a Fano resonance [21–24] between the coupled SPP of the metal/substrate interface of the grating and the SPP (1, 0) of the metal/substrate interface of the hole arrays.

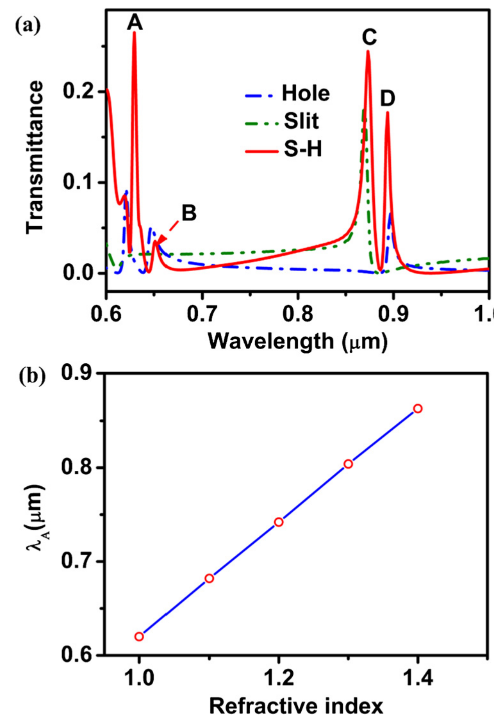

Fig. 2. (Color online.) (a) Zero-order transmission spectra corresponding to the pure hole array (blue dash-dotted curve), pure slit array (olive dash-bi-dotted curve), and composite metamaterial (red solid curve) with a distance $s = 90$ nm. (b) Spectral shift of peak A in the simulated zero-order transmission spectra as a function of the refraction index.

By varying the angle of incidence, we can calculate the angle-dependent transmission spectra. The simulated dispersion of the metamaterial with $s = 90$ nm is shown in Fig. 3. The degenerate modes are split due to symmetry breaking. For example, the lower branch at $k_x = 0$ is split into three peaks due to a Fano resonance. A thinner curve corresponds to peak B whose amplitude is smaller. A thicker curve corresponds to peak A whose amplitude is greater. When the incident angle increases, peaks A and B merge into one peak at about 3° and experience a red shift. The higher branch is split into two peaks due to a Fano resonance at about 900 nm. When the incident angle increases, one mode shifts down and the other mode shifts up in frequency. The blue-shifted peak at the higher branch and the red-shifted peak at the lower branch form an anti-crossing at about 10°. This phenomenon is analogous to that in [1]. Therefore, the hypothesis that the peaks originate from the SPP is further verified. To study further the physical mechanism of these peaks, the zero-order transmission spectra with the distance s are shown in Fig. 3(b). Peaks A, C, and D strengthen gradually as s increases, however, peak B is almost unchanged. Peak A reaches 30% when $s = 187.5$ nm and the metamaterial is symmetric about the y-axis. In contrast, peaks C and D merge into one peak with 60% transmittance intensity. Therefore, they originate from the Fano resonance due to the symmetry breaking. The phenomenon can be explained by the composite diffracted evanescent wave theory [6–10].