A high figure of merit localized surface plasmon sensor based on a gold nanograting on the top of a gold planar film*

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We investigate the sensitivity and figure of merit (FOM) of a localized surface plasmon (LSP) sensor with gold nanograting on the top of planar metallic film. The sensitivity of the localized surface plasmon sensor is 317 nm/RIU, and the FOM is predicted to be above 8, which is very high for a localized surface plasmon sensor. By employing the rigorous coupled-wave analysis (RCWA) method, we analyze the distribution of the magnetic field and find that the sensing property of our proposed system is attributed to the interactions between the localized surface plasmon around the gold nanostrips and the surface plasmon polarition on the surface of the gold planar metallic film. These findings are important for developing high FOM localized surface plasmon sensors.

Keywords: localized surface plasmon biosensor, figure of merit, nanogratings, gold film

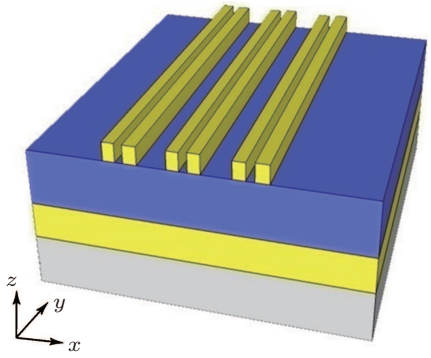
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1. Introduction

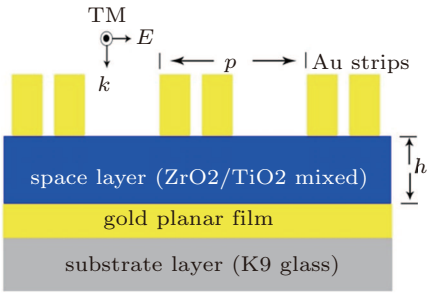
In the past decades, localized surface plasmons (LSPs) supported by a metallic nanostructure have attracted much attention in both fundamental and applied science[1] for use as optical filters[2] and in surface enhanced Raman spectroscopy (SERS).[3,4] The optical property of LSPs in a nanostructure is very sensitive to the refractive index of the local environment, which can be widely applied to biosensors,[5,6] the detection of biomolecules,[7,8] safety-related concerns,[9] and chemical reactions.[10] It allows the controlled fabrication and manipulation of metallic structures on the nanoscale, but the spectra bandwidth of optical resonace localized around an individual metallic particle is usually broad – more than 100 nm. The broad linewidth can degrade the sensing property of the nanostructure.[11,12] For example, the figure of merit (FOM) of nanoparticles reported previously has rarely reached 6.[13] To overcome this disadvantage, we propose a structure consisting of a gold nanograting separated from a gold planar film by a space layer and each unit of the gold nanograting has two strips. The LSP mode of the gold nanograting may couple to the surface plsmon polarition (SPP) mode on the surface of the gold planar film, which can help to reduce the linewidth of the spectrum of the LSP sensor.[14,15] Then the FOM of the LSP sensor can be improved.

2. Sketch of the structure's configuration

Our proposed structure is shown in Fig. 1. Each unit of the gold grating has two strips, the distance between the strips is 80 nm, the width of the strip is 65 nm and the height is 105 nm, the period of the nanograting is p. The refractive index of the space layer is 2.21 (ZrO_2/TiO_2 mixed) and the height of the space layer is h. The thickness of the gold planar film is 80 nm and the refractive index of the substrate (K9 glass) is 1.52.



(a)



(b)

Fig. 1. (color online) (a) Schematic geometry of the sensor, and (b) the Y-cut section of the structure.

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3. Theoretical analysis of the structure

We calculate the optical properties of this structure by two-dimensional rigorous coupled-wave analysis (RCWA). In our model, the dielectric constant of gold is evaluated by the Drude–Lorentz model[16] to fit the experimental data, a TM plane wave is adopted as the normally incident light.[17] The transmission, reflection, and absorption spectra of the structure are shown in Fig. 2(a). There are three peaks at the wavelengths of 484.5 nm, 775.2 nm, and 909.6 nm in the absorption spectrum. In order to analyze the mechanism of the absorption enhancement of light, the distributions of the magnetic field, $|H|$, at the three resonance peaks have been calculated and are shown in Figs. 2(b)–2(d) respectively. In Fig. 2(b), the light field is concentrated on the top side of the strips, the first peak is mostly attributed to the LSP mode on the top side of the strips. In Figs. 2(c) and 2(d), the LSP mode in the gap between the strips and the SPP mode on the surface of the gold planar film both exist. It is apparent that, through the gold nanograting, the SPP mode can be excited on the surface of the gold planar film.[18] In Fig. 2(c), at the wavelength of 755.2 nm, the LSP mode in the gap between the strips and the SPP mode on the surface of the gold planar film couple together, but the LSP mode is predominant in this case. However, in Fig. 2(d), one can see that the SPP mode on the surface of the gold planar film is predominant at the wavelength of 909.6 nm.

To find the origins of the two resonance peaks, the spectrum of the nanograting without gold planar film is calculated. In Fig. 3(b), there are two transmission valleys around the wavelengths of 496 nm and 705 nm, then we calculate the distributions of the magnetic field, $|H_y|$, at the valley wavelengths. In Fig. 3(c), at the wavelength of 496 nm, the light field is mostly concentrated on the top side of the two strips, the first transmission valley is attributed to the LSP mode on the top side of the strips. In Fig. 2(d), at the wavelength of 705 nm, the light field is concentrated in the gap between the two strips, which can be attributed to the excitation of the LSP mode in the gap between the two strips. The contrast between the distributions of the magnetic field, $|H_y|$, in Figs. 2(b), 2(c), 3(c), and 3(d) shows that the first two peaks in Fig. 2 are attributed to the LSP mode around the strips.

By comparing the two spectra in Figs. 2(a) and 3(b), the spectrum linewidth of the structure with gold planar film is much narrower than that without gold planar film. The coupling between the LSP mode of the gold strips and the SPP mode of the gold planar film is conducive to reducing the linewidth of the LSP sensor.

The second and third peaks shown in Fig. 2(a) are both related to the LSP mode in the gap between the strips and the SPP mode on the surface of the gold planar film. To verify which mode is predominant for the second and third peaks, the period p of the grating is changed from 180 nm to 450 nm.

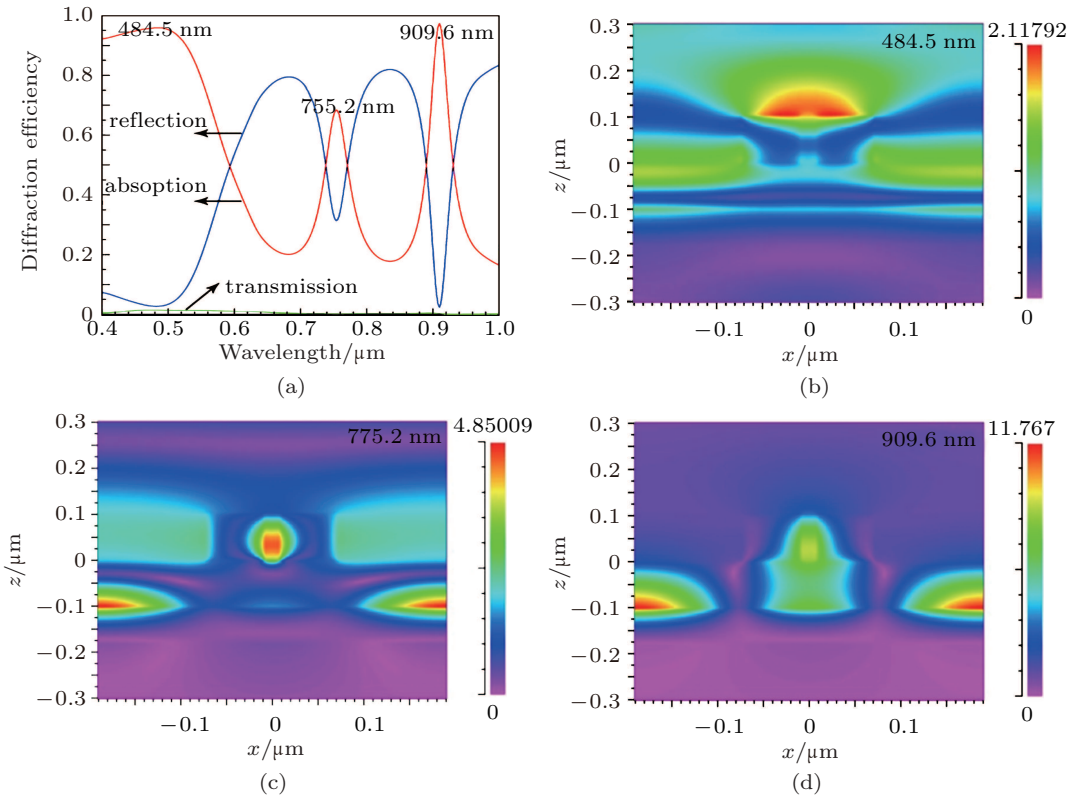


Fig. 2. (color online) (a) Reflection, absorption, and transmission spectra of the structure (a), and the spectral lines of H_y of the three absorption peaks ((b)–(d)).

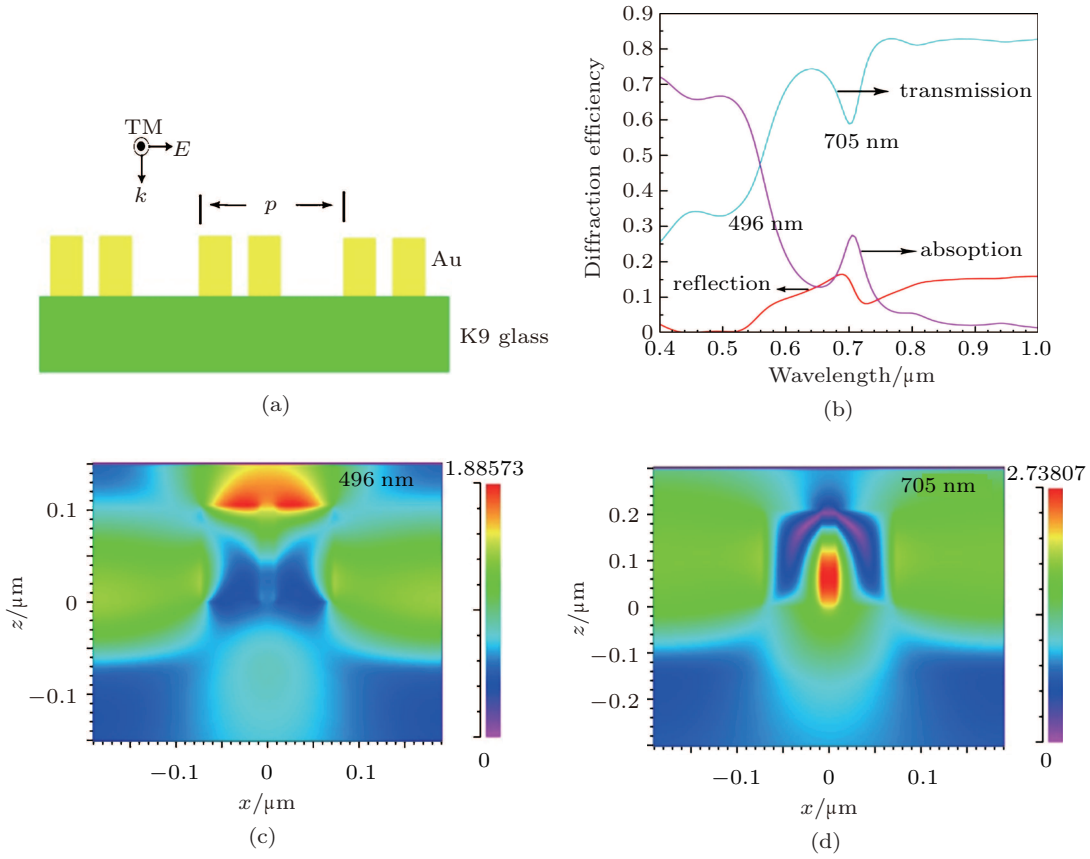


Fig. 3. (color online) (a) The Y-cut of the nanograting without gold planar film. (b) The reflection, absorption, and transmission spectra of the structure. (c) and (d) The spectral lines of H_y of the two transmission valleys at the wavelengths of 496 nm and 705 nm.

In Fig. 4(a), the left peak is insensitive to the period p, and it is attributed to the LSP mode. When p is not large, the coupling between each unit of the nanograting will lead to some redshift of the left peak; as p increases, the coupling becomes weak and the left peak no longer shifts. For the right peak, it exhibits redshift with p increasing and it is attributed to the SPP mode. We can conclude that LSP mode and SPP mode are the predominant mechanisms for the left peak and the right peak, respectively, which is consistent with the analysis of the field distribution in Figs. 2(c) and 2(d).

Moreover, the height dependence of the absorption spectrum for the nanograting is also investigated. The period p of the grating is set to be 380 nm and h is changed from 50 nm to 120 nm. The absorption spectra are shown in Fig. 4(b), when the space layer is very thin, the left peak is notable and the LSP mode in the gap between the strips is predominant. As h increases, the right peak becomes gradually notable, the left peak becomes weak and the SPP mode on the surface of the gold planar film is predominant. By changing the parameter h, we can determine which peak is more prominent.

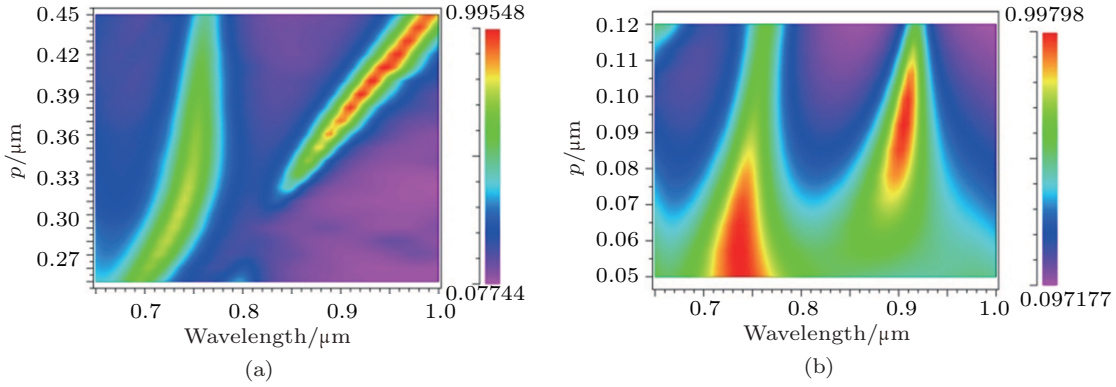


Fig. 4. (color online) (a) Absorption spectra of the structure when p is changed from 180 nm to 450 nm, and (b) the absorption spectra of the structure when h is changed from 50 nm to 120 nm.

4. Sensing performance of the structure

The two narrow valleys of the reflection spectrum in Fig. 2(b) are calculated to study the sensing performance of the structure, by controlling p and h of the structure as discussed above. The valleys of the reflection spectrum can be modified. When $p = 400$ nm and $h = 100$ nm, the refractive index sensitivity and the FOM of the structure are calculated. We can find in Fig. 5(a) that with the refractive index around the grating changing, the valley wavelengths show redshifts. The two valley wavelengths are both sensitive to the refractive index change. S is the refractive index sensitivity, which is defined as $S = \Delta\lambda/\Delta n$ (λ is the valley wavelength of the reflection spectrum and n is the refractive index around the grating). The FOM is defined as follows: FOM $= S/\text{FWHM}$ (FWHM is the full width at half maximum of the resonance peak). In Fig. 5(b), the sensitivity and FOM of the left valley of the spectrum are calculated. The sensitivity of the LSP sensor is 317 nm/RIU and the FWHM of the left reflection valley is 38 nm. Then the FOM of the LSP sensor is almost 8.3. It is very high at present, because the FWHM of the spectrum is large for most LSP sensors.[13]

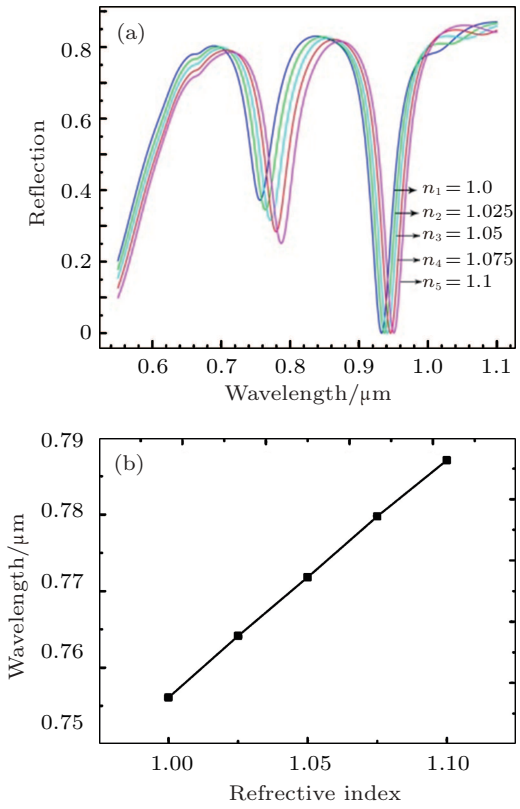


Fig. 5. (color online) (a) Variations of reflection valley with wavelength for some different refractive indexes around the gold nanograting. (b) The resonance wavelength of the first valley versus the refractive index around the gold nanograting.

5. Conclusions

In the present paper, we propose a high FOM LSP sensor, whose FOM is almost 8.3. The LSP sensor is very promising for the future, because it can be integrated onto a chip and it can detect a single molecule. However, for most LSP sensors, their sensitivity values are much lower than those of SPP sensors, so if we want to improve the LSP sensor, we can reduce the FWHM of the resonance spectrum to obtain a high FOM. By coupling the LSP mode in the gap of the gold nanograting with the SPP mode on the surface of the gold planar film, we have achieved an LSP sensor with a narrow linewidth. Our structure may open up a new way of improving the performance of LSP sensors, which can enhance the FOM of the LSP sensor.

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