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Surface plasmon interactions between the grating with slanted sidewall and a metallic film

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ABSTRACT

Based on the finite difference time domain method, the optical properties and the plasmonic interactions between the grating with slanted sidewall and a thin gold film were investigated theoretically. We compare the similarities and differences of transmission, reflection, and absorption spectra of the composite system and the single grating with slanted sidewall. When the thicknesses of the two films and the slit widths are changed, the resonance peaks show blue-shifts, red-shifts, split, decrease and other physical phenomena. Based on the distributions of electric field component E_x, E_y and the total energy, we explain the physical mechanism of light passing through the grating/film nanosystem. The adiabatic nanofocusing of the system is also discussed.

1. Introduction

Surface plasmon (SP), based on the coupling between light and metallic nanostructures, are coupled oscillations of electrons and electromagnetic fields which propagate along the interface between a dielectric and a metal [1,2]. Plasmon provides a powerful means of confining light to dielectric/metal interfaces [3]. As a consequence of this binding, SPs can generate intense local electromagnetic fields and significantly amplify the signal derived from analytical techniques that rely on light, which indicates that SPs are suitable for a variety of nanophotonic applications. Therefore, in recent years many significant attentions have been paid to study of the surface plasmon resonance (SPR) in metallic nanostructure for their applications in surface enhanced Raman scattering (SERS) [4], negative refraction [5], enhanced optical transmission (EOT) [6], optical filters and sensors [7], optoelectronics [8], and other areas.

For a single nanostructure, the plasmonic properties such as nanoparticles and all kinds of nanoholes have been studied at full length. The results have shown that the plasmonic properties strongly dependent on the composition, size and the morphology of the nanomaterial [9,10]. However, when different kinds of individual nanostructures form a composite nanosystem, such as ring/disk nanocavities [11], nanoparticle array [12], nanotube/fim [13], etc, the plasmon modes can be modulated by additional plasmonic resonances, energy shifts and energy confinements created by the reciprocity of the single nanostructures. So, major efforts have been devoted to the design, fabrication, and patterning of metallic composite nanosystem.

Another important direction of research is to focus SPs to nanoscale regions with tapered metal geometries. Stockman [14] introduced theoretically a description of rapid adiabatic nanofocusing with a smoothly tapered metal nano-plasmonic waveguide without metal dissipation, which causes the local field intensity to increase by four orders of magnitude in energy density. Similarly, Gan et al. [15] proposed to use a tapered slit to achieve an intensity-enhanced spot in the tip of the slit. By adding two optimized grating structures to both sides of the nanoslit, they investigated the bidirectional sub-wavelength splitters for SPs in THz domain. Søndergaard et al. [16] experimentally investigated the field intensity enhancements (FE) ascribed to the SPs nanofocusing by the closed tapered shape at the V-groove bottom. They elaborated the EOT phenomenon through thin metal films with a periodic arrangement of tapered slits [16–18]. In addition, tapered waveguides are also employed to enhance the performance for optical switching of nonlinear plasmonic couplers operating at the nanoscale, overcoming the detrimental losses but preserving the subwavelength confinement [19].

In this paper, we extend our previous work [3,20] to study systematically the plasmonic interactions between grating with slanted sidewall (i.e. tapered slits) and a metallic film by using the finite-difference time-domain (FDTD) method. The enhanced

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transmission is associated with the surface plasmon resonance. We calculated the zero order transmission, reflection, and absorption spectra and show that the plasmon resonances depend strongly on the thicknesses of the two films and the slit width. And the underlying physics is also discussed by the simulated electric field distributions. Finally, we introduce the adiabatic nanofocusing of the system.

2. Model and theory

Fig. 1 depicts schematically a metallic grating with slanted sidewall and a metallic film in each unit cell. The grating/film nanosystem is placed in air. In all cases, light is incident normal to the structure with the $\vec{E}$ field polarized along the y axis. The lattice parameter $a_0=200$ nm is kept constant in all the simulations. Geometric variables h and h_1 represent the thicknesses of the left and right film, respectively. The broad slit width and the narrow slit width are labeled as a and b. While the layer spacing ($d=160$ nm) is kept the same.

The two-dimensional FDTD method was used to simulate the results [21,22]. We simulate the structure with an FDTD cube of size $L_x \times L_y = 800\text{ nm} \times 200\text{ nm}$. The spatial and temporal steps are set at $\Delta x=\Delta y=1$ nm, and $\Delta t=\Delta x/2c$ (c is the velocity of light in vacuum). Perfectly matched absorbing boundary conditions are applied at the left and right surfaces of the computational space along the x direction, whereas periodic boundary conditions are applied on other boundaries along the y direction. In our simulation, the nanosystem consists of gold. For this metal, the Drude model is used to describe the dependence of the metallic permittivity on the frequency [23]:

$$\varepsilon(\omega)=1-\frac{\omega_p^2}{\omega^2+i\omega\gamma_p} \tag{1}$$

where ω is the angle frequency of the incident wave, $\omega_p=1.374\times10^{16}\ \mathrm{s}^{-1}$ is the bulk plasma frequency of the gold, and $1/\gamma_p=245fs$ represents the electron relaxation time.

The electric field at the metal-dielectric interface is given by [24]

$$E=E_0 e^{i\left(k_{//}r_{//}-k_y|y|-\omega t\right)} \tag{2}$$

here

$$|k_{//}|=\frac{\omega}{c}\sqrt{\frac{\varepsilon_m\varepsilon_d}{\varepsilon_m+\varepsilon_d}} \tag{3}$$

When the thickness of a thin metal film denoted as H, the dispersion of SPs is modified due to the interface between the SPs of the two surfaces and is obtained from [25]:

$$\left(\frac{k_{y1}}{\varepsilon_1}+\frac{k_{ym}}{\varepsilon_m}\right)\left(\frac{k_{ym}}{\varepsilon_m}+\frac{k_{y2}}{\varepsilon_2}\right)+\left(\frac{k_{y1}}{\varepsilon_1}-\frac{k_{ym}}{\varepsilon_m}\right)\left(\frac{k_{ym}}{\varepsilon_m}-\frac{k_{y2}}{\varepsilon_2}\right)\exp(-2\alpha_{ym}H)=0 \tag{4}$$

where ε_1, ε_2 and ε_m are the dielectric functions of the dielectrics on the two sides and the metal, respectively. Moreover, $k_{y1,2,m}^2=\varepsilon_{1,2,m}\omega^2/c^2-k_{//1,2,m}^2$, and $i\alpha_{ym}=Im(k_{ym})$. Obviously, $\varepsilon_1=\varepsilon_2=1$ in this paper. For relatively thick metal films, the two SPs dispersions are essentially decoupled.

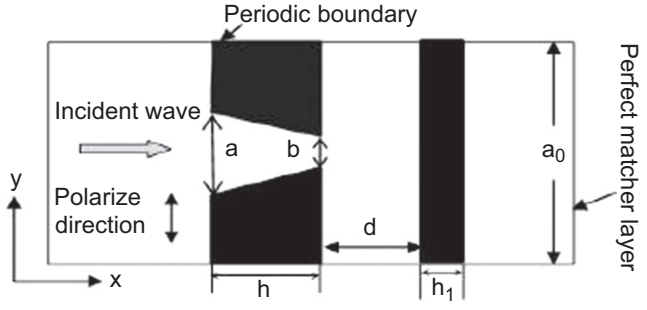

Fig. 1. xy cross section of the computational domain consisting of a single unit cell of the grating with slanted sidewall and a film. A normal incident light wave polarized along the y direction illuminates the arrays along the x direction. Periodic boundary conditions are imposed on the surfaces perpendicular to the gold films, while perfect matched layers are imposed at the left and right surfaces.

3. Results and discussion

For comparison, in Fig. 2, we first show the zero order transmission, reflection, and absorption spectra of the single gold grating with slanted sidewall as a function of wavelength with $h=200$ nm, i.e. the condition is $h_1=0$. The absorption spectra were obtained via $A=1-T-R$, where A, T, and R express the absorbance, transmittance, and reflectance, respectively. Fig. 2 shows three distinct transmission resonance peaks, and there have strong absorption and reflection drops at the transmission wavelengths. This means absorptions and reflection are very small because the electromagnetic wave is mostly transmitted at these wavelengths. We can also see there appears a narrow forbidden band gap in the ultraviolet region between 0.24 μm and 0.33 μm. At wavelengths within a bandgap, the density of SP modes is zero, thus no SP modes can be supported. The strongest transmission at the wavelength of 0.6225 μm achieves 0.93, which indicates the surface plasmon resonances are intensively at this wavelength.

We will investigate the effects of the thicknesses of the two films h and h_1 separately. Fig. 3 shows the zero order transmission, reflection, and absorption spectra of the grating/film nanosystem as a function of wavelength with thickness of the film: (a) $h_1=8$ nm, (b) $h_1=20$ nm, (c) $h_1=30$ nm, (d) $h_1=40$ nm. Parameters are $h=200$ nm, $a=30$ nm and $b=20$ nm, respectively. It is observed the transmission spectrum of grating/film nanosystem resemble with that of the grating. However, in contrast to Fig. 2, the intensities of transmission peaks in 0.2 μm and 0.6 μm regions decrease obviously until they vanish when the thickness of right gold film is added. At the same time, the intensities of absorption peaks increase remarkably. The absorption around the 0.6 μm region is almost up to 100% when the thickness of right film beyond 20 nm. The attenuation effect of the electromagnetic

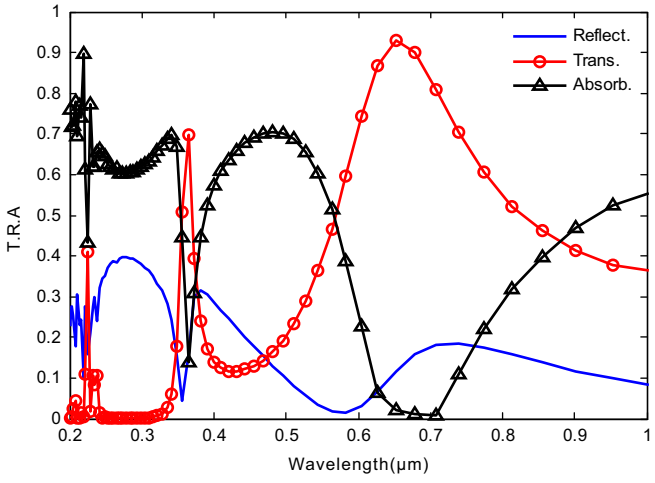

Fig. 2. Transmission, reflection, and absorption spectra of the single gold grating with slanted sidewall with $h=200$ nm, $a=30$ nm, $b=20$ nm.