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Numerical investigation of the transmission enhancement through subwavelength hole array

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Abstract

The transmission characteristics of a metallic film with subwavelength periodic square hole arrays are investigated by using the three-dimensional finite-difference time-domain (3D-FDTD) method. The influences of the hole size, the refractive index of substrate, the refractive index of filled medium, the thickness of film as well as the incident angle on the characters of transmission spectra are studied. It is found that the transmission can be enhanced by filling the holes with higher refractive index medium. This enhancement can be explained by the collaboration of localized waveguide resonance with surface plasmon resonance.

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Keywords: Subwavelength metal structure; Enhanced transmission; Surface plasmon

1. Introduction

Recently, experiments which show the extraordinary high transmission of light through the metallic subwavelength hole array are of considerable interests [1,2]. When the size of hole is much smaller than the wavelength of incident light, it can be found that the maximum transmission is about 2–3 times higher than the hole porosity of the structure. This large transmission implies many potential applications. Furthermore, the underlying mechanism for the extraordinary transmission itself is also an intricate and meritorious research.

Many theories have been proposed to interpret this phenomenon. It is generally admitted that the enhanced transmission is mainly due to the coupling of surface plasmon resonance (SPR) excited on the upper and lower surfaces of the structure through evanescent waves [3–5]. The influence of the hole shape on the transmission are investigated [6–8]. On the other hand, Baibda et al. found that the transmission can be enhanced further by filling the central region of each circular hole with higher refractive index medium [9]. However, the mechanisms for this phenomena has not been clearly explained.

In this paper, the transmission of subwavelength square holes filling with higher refractive medium is investigated by using the three-dimensional finite-difference time-domain (3D-FDTD) method. The response of the transmission spectra to the hole size, the refractive index of substrate medium, the refractive index of filled medium, the thickness of film, and the incident angle are shown to elucidate the transmission mechanism. The near field distributions corresponding to the high transmission wavelengths are also given to help us to understand how the wave passes through the suwavelength hole array.

This paper is organized as follows: In Section 2, the theoretical model is described. In Section 3, the dependence of

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the transmission spectra on the thickness of film, the refractive index of filled medium as well as the incident angle are investigated. At last, a conclusion is drawn in Section 4.

2. Theoretical model

The dispersion properties of the metal must be considered here since the absorpbtion and permittivity of the metallic material are frequency dependent. The Drude model [9,10] is used to describe the dependence of the metallic permittivity on the frequency:

$$\epsilon_M(\omega) = \epsilon_0\left(1 - \frac{\omega_p^2}{\omega(\omega + i\gamma)}\right), \tag{1}$$

where ω is the angle frequency of the incident wave, ϵ_0 the permittivity of the vacuum, ω_p the plasma frequency of the metal, and γ represents the damping rate which characters the ohmic absorption loss. The metal gold (Au) is used in this paper, it's plasma frequency is $\omega_p = 1.236 \times 10^{16}$ and loss $\gamma = 1.4 \times 10^{14}$.

The propagation of the light in the metal is described by the Maxwell's equations, which are coupled with the oscillations of quasi-free electrons (Drude model) [10]:

$$\begin{aligned} \vec{\nabla} \times \vec{E} &= -\mu_0 \frac{\partial \vec{H}}{\partial t}, \\ \vec{\nabla} \times \vec{H} &= -\epsilon_0 \frac{\partial \vec{E}}{\partial t} + \vec{J}, \\ \frac{\partial \vec{J}}{\partial t} + \gamma \vec{J} &= \epsilon_0 \omega_p^2 \vec{E}, \end{aligned} \tag{2}$$

where $\vec{E}$ and $\vec{H}$ are the electric and magnetic field vectors, respectively. $\vec{\nabla}$ is the Nabla differential operator. $\vec{J}$ is a current density and equals to the time derivative of the metal polarization, i.e. $\vec{J} = \partial\vec{P}/\partial t$. μ_0 is the magnetic permeability of the vacuum.

The 3D-FDTD method is employed to simulate the interaction between the metal and incident wave. The structures are illumined normally by a TE-polarized plane wave pulse $(Ex, Hy, Hz \neq 0)$ centered at $\lambda = 600$ nm. The spectrum width of this pulse can cover the range desired in the calculation. The Fourier transform of the temporal response is used to obtain the spectrum. Then normalization of the spectrum by the incident wave and the hole porosity of the structure gives the zero-order normalized transmittance spectrum.

The schematic of the structure is shown in Fig. 1. The square holes with width d are arranged in the metal film with period p. When a plane wave is incident on the metal film, the SPR enhances energy transmission through the film for [4,11]

$$\vec{k}_0 \sin(\theta) \pm i\vec{G}_x \pm j\vec{G}_y = \vec{k}_{sp}, \tag{3}$$

where $\vec{k}_0$ is the wave vector of incident light and θ is the incident angle. $\vec{G}_x$ and $\vec{G}_y$ are the Bragg vectors of the square lattice and $|\vec{G}_x| = |\vec{G}_y| = 2\pi/\text{p}$. i and j are integers, which express the mode indices. $\vec{k}_{sp}$ is the surface plasmon vector:

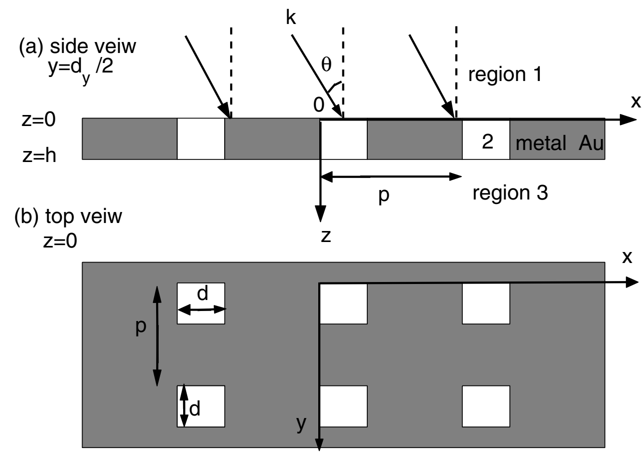

Fig. 1. Schematic of the metal Au structure. (a) xz cross section and (b) top view. The regions 2 in the holes can be filled with different medium.

$$|\vec{k}_{sp}| = |\vec{k}_0|\sqrt{\frac{\epsilon_{1,3}\epsilon_M}{\epsilon_{1,3} + \epsilon_M}}, \tag{4}$$

where ϵ_1 and ϵ_3 are the dielectric constants of the incident and substrate medium, respectively. ϵ_M is the dielectric constant of the metal.

For the normal incidence, the wavelengths of the excited SPR modes are given approximately by

$$\lambda_{max}(i,j) = \frac{p}{\sqrt{i^2 + j^2}}\sqrt{\frac{\epsilon_{1,3}\epsilon_M}{\epsilon_{1,3} + \epsilon_M}}. \tag{5}$$

3. Simulation results

In this Section, the array of square holes in the Au metal film is taken into account. The grating period $p = 430$ nm is fixed for the whole paper. The thickness of the film is h and the hole width is d. Firstly, the influence of the hole size on the transmission is investigated. The thickness of the Au film is selected as $h = 200$ nm and the dielectric constants in the regions 1, 2, 3 are $\epsilon_1 = 1.00, \epsilon_2 = 1.00$, and $\epsilon_3 = 2.31$, respectively. The sizes of the square holes are $d_x = d_y = 120$, 160, 200, 240, and 280 nm, respectively. The normalized zero-order transmission spectra are shown in Fig. 2(a). Two transmission peaks corresponding to the SPR modes $(1,0)$ and $(1,1)$ can be obviously seen. It can also be found that increasing the width of holes results a higher transmittance and broader peaks. These results agree with the experiment in Ref. [12] quite well. The red-shift trend with the increasing of the hole width is also the same with the experimental results. These results confirm the validity of the 3D-FDTD code adopted in this paper.

The enhanced transmission also depends on the SPR of the substrate interface. The influence of the substrate on the transmission spectrum is shown in Fig. 2(b). The hole width is selected as 200 nm and the thickness of the film is 200 nm, the upper side medium is air. When the dielectric constant of substrate increases, the new transmission peaks