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# Optical transmission through metallic nanoslit with symmetric or asymmetric surface-relief profile

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ABSTRACT

The enhanced optical transmission through metallic nanoslit with symmetric or asymmetric surface-relief profile is investigated based on rigorous electromagnetic theory by using the boundary integral method (BIM). Metallic nanoslits with different geometrical structure surfaces: asymmetric sinusoid surface-relief profile and symmetric sinusoid surface-relief profiles, are investigated. The transmission spectra are calculated and the corresponding intensity distributions of magnetic fields at the resonant wavelengths are numerically emulated and illuminated. The numerical results show that there are two transmission peaks – attributed to the nanoslit geometrical structure and the metallic material, respectively, and the normalized transmittance through the conventionally rectangular nanoslit will be enhanced largely when its surface profile is replaced by the smoothly surface-relief shape of the metallic nanoslit. It is indicated that anomalously high transmission is quite sensitive to the surface geometrical profile of the nanoslit and the incident direction of the light wave.

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## 1. Introduction

In recent years, with the development of microfabrication technology, various optical elements with feature size of nanometer are available. It is well known that the transmission of a sub-wavelength aperture of $d$ is very weak if the wavelength of the incident light $\lambda > 2d$ according to Bethe's [1] theory. This can be overcome by surrounding a single sub-wavelength aperture with a periodic structure such as a periodic corrugation, as reported by Ebbesen et al. [2]. The report exclaimed that the resonant transmission of light through an array of sub-wavelength slits in an otherwise opaque metal film has stimulated equally extraordinary properties. Surface plasmon polaritons (SPPs) are suggested to explain the phenomenon immediately [2]. Further research work [3] from the same research team is reported that the beaming light can be achieved and therefore it is possible to break the diffraction limitation. This has stimulated much theoretically and experimentally fundamental research since then. Further investigations show that enhanced transmission associated with the excitation of nanoslit waveguide resonances also exists through single sub-wavelength slit [4,5]. The phenomenon of enhanced transmission through sub-wavelength apertures in optically thick metal films is attributed to the presence of the defects in the metallic film, and therefore it provides an effective refractive index allowing the launching of SPPs like surface waves. The physical origin of enhanced optical transmission through metallic nanoslit in terms of SPPs has been challenged by different models, for instance, the composite diffracted evanescent wave (CDEW) model [6], the dynamical diffraction explanation [7], the negative role of SPPs [8], the Fano-type interpretation [9], the SPP and quasi-cylindrical wave (CW) [10], and the Fabry-Perot resonant cavities [11] etc. However, how much is the enhanced optical transmission through the metallic wavelength aperture with the same effective refractive index but different surface-relief shapes? Previous works are focused on the physical origin and extraordinary optical transmission through a rectangular metallic nanoslit with different effective refractive indices [12–15]. Few attentions are paid on the influence of different geometrical surface-relief profiles of the metallic nanoslit with the same effective refractive index on the optical transmission and the local-field enhancement. In this paper, we analyze the enhanced optical transmission (EOT) through sub-wavelength metallic slit with symmetric or asymmetric geometrical surface-relief profile by the use of rigorous Boundary Integral Method (BIM). The metallic nanoslits with different surface-relief profiles: asymmetric sinusoid profile and symmetric sinusoid profiles are designed and studied. The transmission spectra of the metallic nanoslit with various profile shapes and the intensity distributions of magnetic field at the resonant wavelengths for different metallic nanoslit structures are quantitatively compared. The influence of the surface-relief profile of metallic nanoslit with the same effective refractive index on the transmission spectra, the shifting of the resonant wavelengths, and

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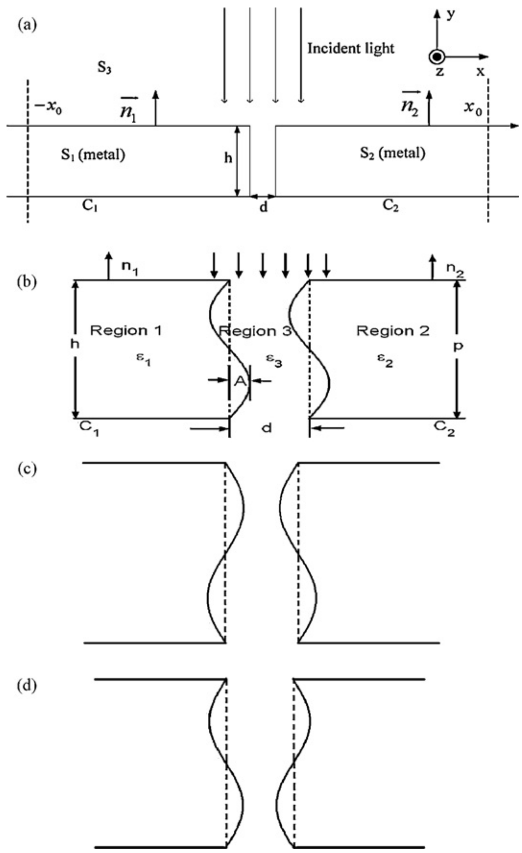


**Fig. 1.** The schematic view of the metallic nanoslit with different surface-relief profiles: (a) rectangular profile *a* as described by Eq. (3); (b) asymmetrical sinusoid surface-relief profile *b* as described by Eq. (4); (c) symmetrical sinusoid surface-relief profile *c* as described by Eq. (5); (d) symmetrical sinusoid surface-relief profile *d* as described by Eq. (6). *A* and *p* stand for the amplitude and the period of the sinusoid shape, respectively. *h* and *d* represent the depth and the width of the nanoslit, respectively. $\varepsilon_1$, $\varepsilon_2$, and $\varepsilon_3$ denote the dielectric coefficients of the medium in the Regions 1, 2, and 3, respectively.

the local-field enhancement through the metallic nanoslit is studied in detail.

This paper is organized as following: In Section 2, fundamental integral equations are briefly described and different surface-relief profile functions of metallic nanoslits with the same effective refractive index are predestinated. In Section 3, the numerical results are presented. The resonant wavelengths of the metallic nanoslits with different surface-relief profiles are investigated and the corresponding local-field enhancements of the nanoslits are illuminated. The influence of the surface-relief profile of the nanoslit on the optical transmission is analyzed in detail. In Section 4, the conclusions are drawn briefly.

## 2. Fundamental integral equations and formulas

The two-dimensional (2D) scattering problem consisting of two scatterers with their surface contours $C_1, C_2$ and their outward normal $\vec{n}_1, \vec{n}_2$ is displayed in Fig. 1(a). The metallic nanoslit composed by two metallic films is laid on the *xy* plane, and *z* is perpendicular to the section of the metallic films and is infinite. The whole space is divided into three regions: Region 1 ($S_1$) with dielectric constant $\varepsilon_1$, Region 2 ($S_2$) with dielectric constant $\varepsilon_2$ and Region 3 ($S_3$) with dielectric constant $\varepsilon_3$. The integral equations governing the total optical field distributions in whole space can be written as [16]:

$$\begin{aligned}
\psi^{\rm tot}(r_1) &= \int_{C_1}\left[\varepsilon_1 G_1(r_1, r_{C_1})\frac{\partial\psi^{\rm tot}(r_{C_1})}{\partial n_1} - \psi^{\rm tot}(r_{C_1})\frac{\partial G_1(r_1, r_{C_1})}{\partial n_1}\right] dl,\ r_1 \in S_1\\
\psi^{\rm tot}(r_2) &= \int_{C_2}\left[\varepsilon_2 G_2(r_2, r_{C_2})\frac{\partial\psi^{\rm tot}(r_{C_2})}{\partial n_2} - \psi^{\rm tot}(r_{C_2})\frac{\partial G_2(r_2, r_{C_2})}{\partial n_2}\right] dl,\ r_2 \in S_2\\
\psi^{\rm tot}(r_3) &= \int_{C_3}\left[\varepsilon_3 G_3(r_3, r_{C_3})\frac{\partial\psi^{\rm tot}(r_{C_3})}{\partial n_3} - \psi^{\rm tot}(r_{C_3})\frac{\partial G_3(r_3, r_{C_3})}{\partial n_3}\right] dl + \psi^{\rm inc}(r_3),\ r_3 \in S_3
\end{aligned} \tag{1}$$

where $G_i(r_i, r_{C_i}) = H_0^{(2)}(k_i r_i - r_{C_i})$ ($i$ = 1, 2, and 3) is Green function, $H_2^{(2)}$ is the zero-order Hankel function of the second kind. $k_i = (2\pi n_i)/\lambda_0$ is wave number in region $S_i$. $r_i$ represents position vector of a random point in Region 1, 2, or 3. $r_{C_i}$ denotes the point on the boundary $C_i$ ($C_3 = C_1 + C_2 + C_\infty$). $\psi^{\rm tot}(r_i)$ (total field) stands for $E_z(r)$ or $H_z(r)$ in the case of the TE or TM polarized incidence. In this paper, the TM polarized light is employed. Therefore, we can firstly determine the total optical field on the boundary by solving the boundary integral equations [16], and then obtain the total field distribution over the whole space from Eq. (1).

Now we describe the surface-relief structure of the metallic nanoslit with the same effective refractive index. The boundary function of metallic nanofilm can be described as

$$y = \pm\frac{h}{2} \quad |x| > \frac{d}{2}, \tag{2}$$

and different surface-relief functions of metallic nanoslits with the same effective refractive index can be predestinated as following: the rectangular surface-relief profile *a* (as shown in Fig. 1(a)) can be written as

$$x = \pm\frac{d}{2} \quad |y| \le \frac{h}{2}; \tag{3}$$

the asymmetric sinusoid profile *b* (as shown in Fig. 1(b)) can be described as

$$x = A\sin\left(\frac{2\pi}{p}y\right) \pm \frac{d}{2} \quad |y| \le \frac{h}{2}; \tag{4}$$

the symmetric sinusoid profile *c* (as shown in Fig. 1(c)) can be read as

$$x = \pm A\sin\left(\frac{2\pi}{p}y\right) \pm \frac{d}{2} \quad |y| \le \frac{h}{2}; \tag{5}$$

and the symmetric sinusoid profile *d* (as shown in Fig. 1(d)) can be given as

$$x = \pm A\sin\left(\frac{2\pi}{p}y + \pi\right) \pm \frac{d}{2} \quad |y| \le \frac{h}{2}, \tag{6}$$

where *d* and *h* denote the width and the height of the metallic nanoslit, *A* and *p* stand for the amplitude and the period of the sinusoid shape. The surface-relief profile in Eq. (6) can be understood as the same as that of in Eq. (5) except for different incident directions: $\theta = 0$ for Eq. (5) and $\theta = \pi$ for Eq. (6). The effective areas of the nanoslits with different surface-relief profiles are the same, so are their effective refractive indices.

To obtain the resonant spectrum, we define the normalized transmittance through the nanoslit by the Poynting vector $\vec{S}$ as:

$$T = \frac{\int_{-l+d/2}^{l+d/2}\langle\vec{S}_n^{\rm tot}\rangle_{y=y_0}dx}{\int_{-d/2}^{d/2}\langle\vec{S}_n^{\rm inc}\rangle dx}, \tag{7}$$

where $\vec{S}_n^{\rm tot}$ and $\vec{S}_n^{\rm inc}$ are the normal components of the time-averaged Poynting vectors of the total field and the incident field, respectively. *l* is the width of metal films. The integral in the nominator of Eq. (7) is the incident power. The normalized transmittance stands for a ratio of the transmitted power to the incident power. By calculating Eq. (7), we can well study the transmission properties of the light waves through the single nanoslit digging in the metallic film for various structural parameters quantitatively.

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