Extraordinary optical transmission through metal gratings with single and double grooved surfaces*

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We investigate the transmission properties of a normally incident TM plane wave through metal films with periodic parabolic-shaped grooves on single and double surfaces using the finite-difference-time-domain method. Nearly zero transmission efficiency is found at wavelengths corresponding to surface plasmon excitation on a flat surface in the case where the single surface is grooved. Meanwhile, resonant excitation of surface plasmon polariton (SPP) Bloch modes leads to a strong transmission peak at slightly larger wavelengths. When the grating is grooved on double surfaces, the transmission enhancement can be dramatically improved due to the resonant tunnelling between SPP Bloch modes.

Keywords: metal grating, surface plasmon, transmission
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1. Introduction

Extraordinary optical transmission (EOT) through sub-wavelength metal gratings has a wide range of potential applications in areas such as optical displays, near field microscopy, photolithography and bio-photonics.[1−4] Since this phenomenon was first reported by Ebbesen *et al.*[1] ten years ago, many efforts have been devoted to exploring the EOT through metallic gratings with various sub-wavelength structures such as periodic slit arrays, hole arrays, annular apertures and corrugated metal films,[5−8] and in different wavelength regions from microwave to ultraviolet.[9,10] Investigation of the various factors involved in the transmission mechanism, especially the role of the surface plasmon (SP) in periodic structures, has become a major topic. For periodic slit arrays, Porto *et al.*[11] proposed the coupled surface plasmon resonant mode and the waveguide mode to interpret the EOT. However, Cao and Lalanne[12] used the rigorous coupled-wave method and arrived at the conclusion that SP reduces the transmission efficiency. Xie *et al.*[13] supported the argument of Cao and Lalanne based on the finite-difference-time-domain (FDTD) method. There is still no consensus in the effect of SP excitation on the transmission efficiency.

Most of the previous work was concentrated on the transmittance of metallic gratings with narrow slits.[5,11] Both cavity mode and SP excitation contribute to the extraordinary transmission for slit arrays, and the physical interpretation can be rather complicated. On the other hand, EOT has also been observed through corrugated optically thin metal films without apertures,[14−21] in which propagating cavity modes cannot be excited. The transmission mechanism is related to tunnelling between surface plasmon polariton (SPP) Bloch modes. The surface-grooved continuous metal film should be the favourite structure for investigation of SP-assisted mechanisms. To our knowledge, most of the used structure is continuous metal film with a periodic set of rectangular ridges on both film interfaces.[19,21] Furthermore, the effect of geometry shapes and parameters of surface ridge on the transmission spectrum needs further research.

In this paper we consider the structure shown schematically in Fig. 1. It consists of a continuous silver film of thickness h with periodic parabolic-shaped grooves (T is the grating period, and d is the groove depth) on one or both surfaces. The film is illuminated by a transverse-magnetic (TM) wave at normal incidence from the top side. Based on the above struc-

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ture, we investigate the influence of groove depth and film thickness on the transmission properties by using the FDTD[22] method. We find that nearly null transmittance occurs when the wavelength of the incident wave matches the SP excitation wavelength on a flat surface. Maximum transmission is found at a slightly larger wavelength. The extraordinary optical transmission results from an SPP Bloch mode excitation and tunnel coupling process.

2. Theoretical model

We consider one-dimensional silver gratings with three types of constructions: type I, a metal grating having a grooved surface on the top interface (Fig. 1(a)); type II, a metal grating having a grooved surface on the bottom interface (Fig. 1(b)); and type III, a metal grating having the same grooved surfaces both on the top and bottom interfaces (Fig. 1(c)). For type III, theprofiles of the top and the bottom surfaces are symmetric about the plane $z = 0$. In our simulations we assume that both the top and bottom media are air. The host material is silver with frequency-dependent permittivity ε_m given in Ref. [23]. The surface profile used in the current study is periodic and specified by

$$z = f(x) = a(x + T/2)(x - T/2) \quad -T/2 \le x \le T/2. \tag{1}$$

The periodicity $T = 500$ nm is set to be a constant. There are two reasons why we use this model: first, the grooves can be made narrow or shallow by simply changing a, which is similar to models studied in Refs. [24] and [25]; and second, since there is no direct channel for incident light to pass through, there should be no propagating modes between the top and the bottom surfaces, a situation rather more similar to the hole array experimental model of Ebbesen *et al.* than the slit array model of Porto *et al.*

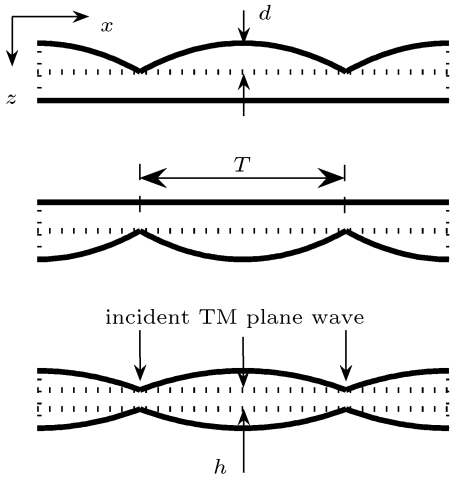


Fig. 1. Schematic of the studied gratings: a metal film with periodic parabolic-shaped grooves on the top (top row), bottom (middle row) and both surfaces (bottom row).

3. Results and discussion

We firstly explore the properties of a silver grating with structure type I. The thickness of silver substrate is chosen as a constant ($h = 25$ nm). Characteristics of transmission spectra for different groove depths d are presented in detail, as shown in Figs. 2 and 3.

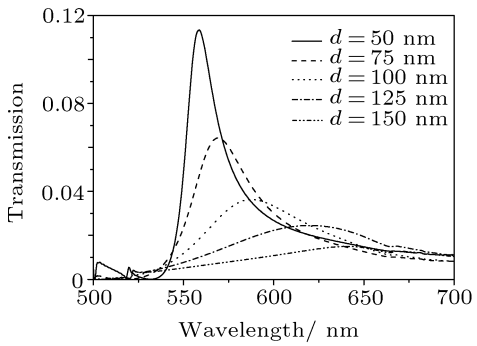


Fig. 2. Transmission spectra of structure type I with $T = 500$ nm, $h = 25$ nm and different groove depths as marked.

In the transmission spectrum curve of the $d = 50$ nm film, there is a sharp peak at wavelength $\lambda \approx 559$ nm. With the increase of the groove depth, the transmission peak drops dramatically, and its width spreads and the central position is red-shifted. On further increasing the groove depth, as shown in Fig. 3, the transmission peak gradually disappears in the long wavelength range and two new peaks appear again in the neighbourhood of $\lambda \approx 522$ nm, which is the SP excitation wavelength on a flat surface given by

$$\lambda_{sp} = T\mathrm{Re}\left[\left(\frac{\varepsilon_m}{1+\varepsilon_m}\right)^{1/2}\right], \tag{2}$$

for a periodicity of the grating of $T = 500$ nm. The broadening, decreasing and red-shift of the transmission peak at $\lambda > 522$ nm show up periodically with the increase of groove depth, indicating a quasi-periodic dependence of transmission efficiency on the groove depth. The most striking feature of Fig. 3 is the nearly zero transmission efficiency at $\lambda \sim \lambda_{\mathrm{sp}}$ when

$d > 100$ nm. The SP wavelength on a smooth surface always falls in the band-gap of the SPP modes excited on a periodically corrugated metal surface, and the transmission is zero since there are no modes available for tunnelling.

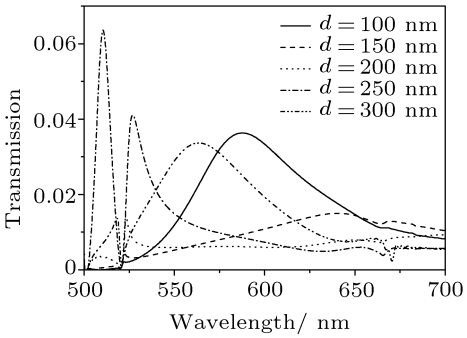


Fig. 3. The same as Fig. 2 but for deeper grooves.

The underlying physics can be understood as follows. For deep grooves, coupled SP (CSP) modes will be resonantly excited when the incident wave matches the frequency of a standing wave SP mode

$$2kd - \Delta\varphi = m2\pi, \tag{3}$$

where k is the wave vector of CSP, and $\Delta\varphi$ is the phase change in the groove. It then builds up strong fields localized in the grooves. The thickness of substrate film $h = 25$ nm is small enough so that the light can tunnel through the film and an electromagnetic (EM) field is then built up on the bottom interface, thus leading to photon tunnelling transmission through the metal film. For a given wavelength, there are multiple groove depths at which CSP modes are excited (for different m). Therefore the transmission peak shows up periodically with the increase of groove depth. The period between two successive resonant depths is equal to half the effective wavelength of the CSP. For a given m value, with the increase of groove depth the resonant condition requires the decreasing of effective wave vector k, therefore resulting in the red-shift of the transmission peak. The drop and broadening is caused by diffractive and absorption losses.

When gratings have a reversed structure, namely grooves are on the bottom surface (type II), the transmittance is slightly improved compared to that of structure type I with the same surface profile. Figure 4 shows the transmission efficiency for structure type II. By fixing the thickness of metal cladding $h = 25$ nm, the transmission spectra for different groove depths are presented. There are two sharp peaks located at $\lambda \approx 523$ nm and $\lambda \approx 561$ nm for the film with $d = 50$ nm. By varying the groove depth, the transmission spectra show a quasi-periodic dependence on groove depth and nearly zero transmission appears at $\lambda \approx 530$ nm.

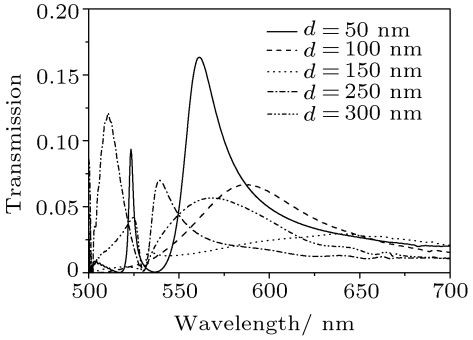


Fig. 4. Transmission of type II for different groove depths.

For the gratings with grooves on the bottom interface, the incident radiation evanescently penetrates through the metal cladding. In the meantime, it excites SPP modes on the bottom surface and builds up strong EM fields in the grooves, which finally emits the radiation downwards into the air. In contrast to type I, whose exiting surface is a flat plane, type II has a corrugated exiting surface, which favours EM field radiation into the air. It causes the transmission peak to be larger than that of type I. The non-reciprocity of the transmission under the reversal of the modulated structure has practical applications, such as micro/nanodevices diagnostics.

So far we have considered gratings with grooves on only one of the surfaces. The results indicate resonant tunnelling transmission through a metal film via exciting SPP Bloch modes (for $d < 100$ nm) or localized SPP modes (CSP for $d > 100$ nm). Besides, we find that the transmission efficiency is always nearly zero for wavelengths corresponding to SP excitation on the flat surface in the case of $d > 100$ nm. In the following part, we will investigate the transmission features for gratings with grooves on double surfaces. Figure 5 shows the calculated transmission spectra of the TM plane wave passing through metal gratings illustrated in Fig. 1(c), with $T = 500$ nm, $h = 25$ nm and different groove depths. We can see that there is a remarkable peak enhancement of transmission and no null transmission efficiency exists for all groove depths. For example, in the case of $d = 50$ nm, the maximal transmissions through structure type I and II are ~ 0.11 and ~ 0.16, respectively (see Figs. 2 and 4),

while for structure type III, the maximum of transmittance is ~ 0.62, almost enhanced by four times. As can be seen from the plots in Fig. 5, the spectrum consists of two sharp peaks when $d = 25$ nm. The short wavelength peak shifts to the long wavelength side when the groove depth increases, while the position of the long wavelength peak is almost unchanged. With further increase of d, the two peaks merge together and shift to a long wavelength. Because the separation between the bottoms of the grooves on two opposite surfaces is very small ($h = 25$ nm), the SPP modes on both surfaces are nearly equally excited and the tunnel coupling creates a pair of new modes. The SPP modes on the bottom surface are excited by tunnelling transmitted field with energy weaker than that on the top surface. Therefore the pair of new modes has unequal magnitude as indicated in Fig. 5 as a smaller short wavelength peak and a larger long wavelength peak. For the structure of type III, the top grooves favour the tunnelling of light to the bottom, and bottom grooves favour the reradiating into transmitted light. Therefore the transmittance is remarkably enhanced compared with that of types I and II having the same surface profile.

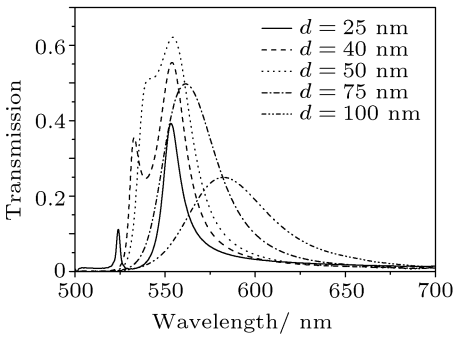


Fig. 5. Transmission of type III for different groove depths.

By fixing the groove depth $d = 25$ nm, the transmission spectra at different film thickness are shown in Fig. 6. It is shown that the transmission peaks depend strongly on the metal film thickness h. As in the case of $h = 75$ nm, the spectrum consists of two small peaks and the peak wavelengths are very close. With the decrease of film thickness, the two peaks increase rapidly and move in opposite directions, preserving the sum of the energies (given as $\hbar\omega = \hbar 2\pi c/\lambda$) of these two resonances. This phenomenon indicates the tunnel coupling between the SPP modes on the top and bottom surfaces.

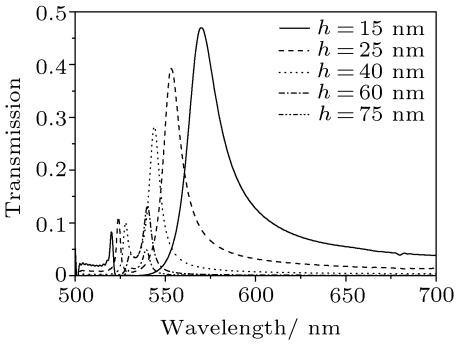


Fig. 6. Structure parameters: $d = 25$ nm, but for different film thicknesses.

For deeper grooves $d = 75$ nm, the transmission spectrum varying with the film thickness is also presented in Fig. 7. As we can see, a single peak appears and it becomes prominent. Its position remains unchanged with the decrease of film thickness h. At this condition, the coupling between the two SPP modes on the opposite surfaces is weak and the photon tunnelling process dominates.

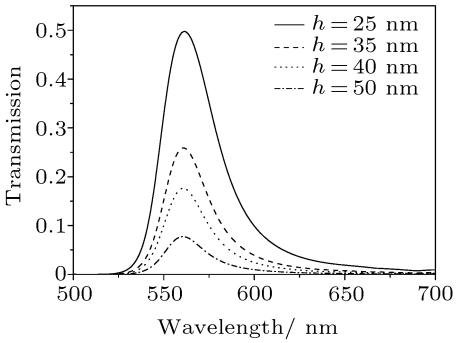


Fig. 7. The same as in Fig. 6. but with $d = 75$ nm.

4. Summary

In summary, we have investigated the transmission properties of metal gratings with parabolic-shaped grooves on single and double surfaces. By modelling a silver grating with grooves on one of the surface, we found that the excitation of SP on a smooth surface leads to nearly zero transmittance for gratings with deep grooves. Resonant tunnelling through the metal film via exciting the SPP Bloch modes or CSP modes is the prime mechanism responsible for the EOT. When both surfaces of the grating are grooved, no extreme transmission suppression exists. The grooves on the top surface favour the tunnelling of light through the film to exciting SPP modes

on the bottom surfaces, which finally radiates into the air. We revealed that, via coupling of SPP modes localized in the grooves on both interfaces, TM plane waves may tunnel through the metal film with a large efficiency.

The results presented in our paper indicate that such structures having parabolic-shaped grooves on single or double surfaces are promising photonic elements for potential applications such as optical filters. We hope that our results are helpful for understanding the EOT observed experimentally by Ebbesen *et al.* and that they also lead to novel device applications.

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