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Surface plasmon resonance transmission filters at 1053 nm based on metallic grating with narrow slit*

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Metallic gratings with narrow slits can lead to special optical properties such as strongly enhancing the transmission and considerably strengthening the polarized effect. A narrow-band filter suitable for application in optical communication is designed by sandwiching a metallic grating between two identical dielectric films. The maximum transmission can reach 96% after optimizing the parameters of films and grating at a central wavelength of 1053 nm. It is the first time, to our knowledge, that such high transmission has been reported since the discovery of the extraordinarily high transmission through periodic holes or slits; moreover, the extremely polarized effect is also found in P mode of this symmetric grating.

Keywords: metallic grating, surface plasmon, extraordinary transmission
PACC: 4110H, 4225

1. Introduction

It has been discovered that the light can be extraordinarily enhanced by tiny holes periodically distributed in a thin metal film.[1] Such an effect is proposed to arise from the interaction of the light with the electronic resonances in the interface between metal films and dielectric materials, thereupon it could be applied to some important areas such as photolithography[2] and optical spectroscopy.[3]

The similar transmission effects can also be found in metallic grating with narrow slits.[4] Moreover, it was possible to obtain the extraordinary transmission even without any hole or narrow slit.[5] It is the periodicity of interface that contributes to the enhancement of surface plasmon tunnelling.[6] The phenomenon should be treated as the surface-plasmon-assisted resonant tunnelling (SPART)[5] rather than the light penetration through the narrow slits or holes.

The extraordinary transmission of periodically distributed tiny slits or holes can be theoretically predicted if the geometry is appropriately designed and the material is chosen suitably. Over 75% transmission is demonstrated at a central wavelength of 800 nm, with the thick metal film perforated with periodic holes.[7] Nearly 75% of high transmission at a wavelength of 900 nm is also attained with the periodically corrugated metal film.[5] As high as 80% transmission is predicted with metallic grating in an infrared range.[8] Although the extraordinary transmission is shown through periodic sub-wavelength structures, the energy is somewhat low, which greatly prevents the structures from extending to being functioned as filters, especially in a visible or near infrared range.

In this paper, the metallic grating with very narrow slits is chosen to enhance the transmission. The Fourier modal method (FMM), a powerful approach to the grating diffraction problem, is used to simulate the light diffraction of metallic gratings.

2. Theory design

The structure considered here (Fig.1(c)) is comprised of dielectric cover with refractive index $n_{\rm C}$, a rectangular metal grating of thickness $d_{\rm G}$ with ridge complex refractive index $n_{\rm M}$ and groove refractive index $n_{\rm R}$, two dielectric layers of thicknesses $d_{\rm H}$ and $d_{\rm L}$ with the refractive indices $n_{\rm H}$ and $n_{\rm L}$ respectively and dielectric substrate with refractive index $n_{\rm s}$. The metallic grating period is T, and the fraction occupied by ridge material is the filling factor F. For conve-

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nience, some parameters are fixed: $n_{\rm C}$ and $n_{\rm S}$ are 1 and 1.45 respectively, $F = 0.85$, angle of incidence of P polarized light is 0^0, and $d_{\rm G} = 150\,{\rm nm}$. It should be noted that F is so large that a very narrow slit can form. The grating thickness should be several times as large as skin depth of metals because slits are unnecessary to achieve significant transmission if the films are too thin. Typical skin depth is on the order of 20 nm for noble metals in a visible and near IR region. So the thickness of 150 nm is appropriate in this region. The choice of the metal depends on the wavelength to be used because the dielectric constant of the metal is wavelength dependent. Ag is the ideal metal to obtain the high transmission in this region. The optical constants of Ag in the 200–2000 nm wavelength are taken from Ref.[9] and interpolated at every given wavelength using a cubic spline.

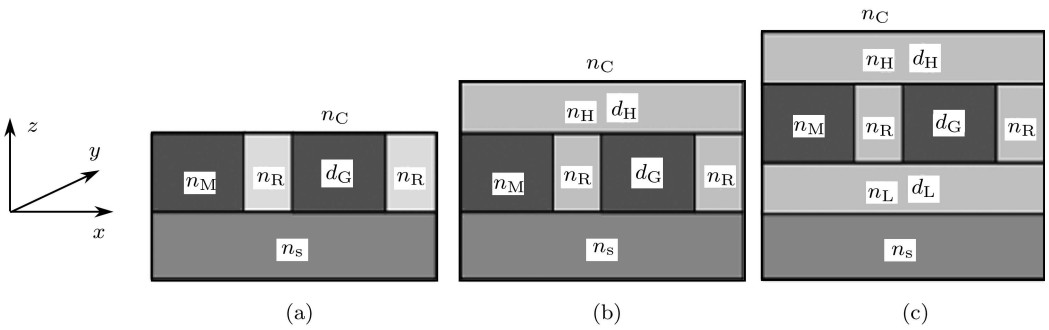


Fig.1. (a) Original structure of metal grating. (b) Original metal grating with low dielectric materials. (c) Symmetric metal grating.

To show the advantages of our novel structure for extraordinary enhancement of surface plasmon (SP) field in the optical communication region, we start from the modal structure (Fig.1(a)) taken from Ref.[8]. The transmission peak can be roughly predicted from the SP dispersion relation.[10] The peak $\lambda_{\rm max}$ in the normal incidence can be approximately given by

$$\lambda_{\rm max} = T{\rm Re}\left(\frac{\varepsilon_{\rm m}\varepsilon_{\rm d}}{\varepsilon_{\rm m}+\varepsilon_{\rm d}}\right)^{1/2}, \qquad (1)$$

where $\varepsilon_{\rm m}$ and $\varepsilon_{\rm d}$ are the dielectric permittivities of the metal and the dielectric, respectively. Expression (1) acts as the starting point in analysing the transmittance spectrum.

An extraordinary transmission peak can be found from the solid line in Fig.2. The central wavelength of the transmission peak is near 1053 nm if the period is set to be 700 nm. It should be noted that the transmission is enhanced by the SP mode between the metal and the substrate. The transmission is only about 20%, far below the energy predicted in the IR spectrum region,[8] which prevents this structure from being used in the visible or near IR spectrum region. The SP resonant wavelength on the sides of metal and substrate can be even further enhanced by matching the SP resonant energies on both sides of metal layer,[6] and so we add a matching layer of thickness $d_{\rm H} = 200\,{\rm nm}$ with $n_{\rm H} = 1.38$ (close to the index of substrate) and fill the grove with the same material as that illustrated in Fig.1(b). It is apparent from the dash line in Fig.2 that the transmission can be greatly enhanced by using the matching layer, for which the reason is that the strong influence on a SP mode is associated with the opposite surface through changing the dielectric constant of upper surface material.

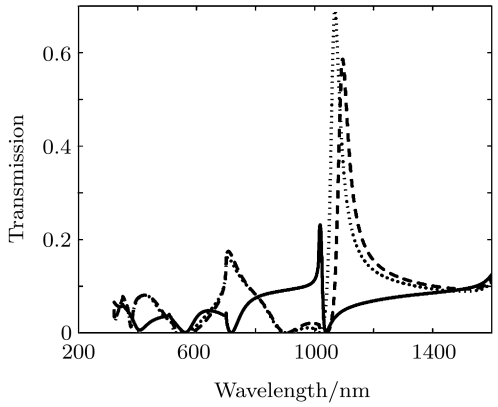


Fig.2. Transmission spectra for original structure of metal grating (solid line) (a), original metal grating with low dielectric materials (dash line) (b), and symmetric metal grating (dot line) (c).

Once we recognize that the extraordinary transmission is related to the resonant excitation of SP modes between metal and dielectric surfaces, an even strong transmission spectrum can be obtained if the modes with the low optical loss ($\alpha_{\rm SP}$) are excited[5]

$$\alpha_{\rm sp} = \frac{4\pi}{\lambda}{\rm Im}\left[\left(\frac{\varepsilon_{\rm m}\varepsilon_{\rm d}}{\varepsilon_{\rm m}+\varepsilon_{\rm d}}\right)^{1/2}\right]. \qquad (2)$$

As shown in Figs.3(a) and 3(b), the lower the dielectric refractive index is, the less the optical loss will be. Transmission will be further enhanced if a low refractive material is adopted as the substrate. We sandwich another dielectric material with refractive index 1.38 between the metal and the substrate, and such a structure is illustrated in Fig.1(c). It is shown from Fig.2 that the transmission is further enhanced (see the dotted line).

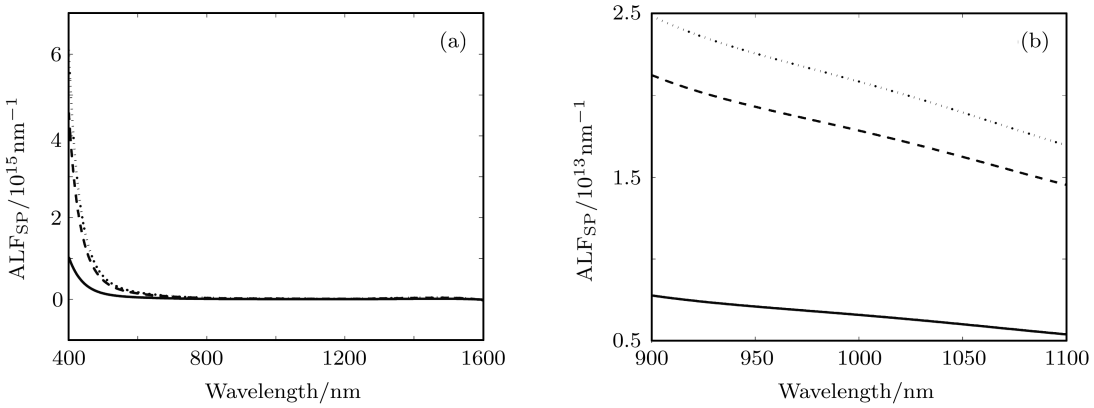


Fig.3. (a) Optical losses of Ag for three materials: air (solid line), MgF_2 (dash line) and SiO_2(dot line), and (b) magnified part of Fig.3(a).

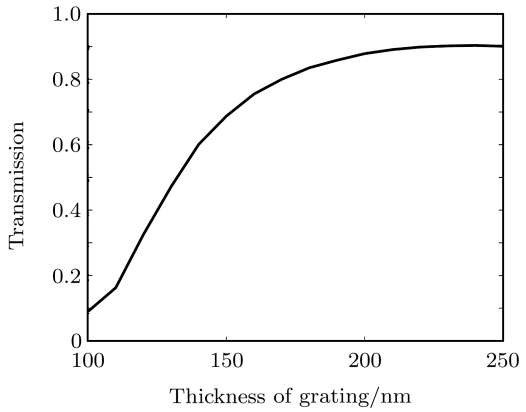


Fig.4. Variation of maximum transmission of zero order with grating thickness.

So far, the geometric structure of the metallic grating is obtained by introducing the low refractive material into the original modal structure used for enhancing the transmission in IR region. Next, we analyse the effect of grating depth on the transmission of spectrum in the case where the transmission will not increase apparently if the thickness of the grating becomes too much large, which may induce the effect of SP modes coupling between upper and lower surfaces of the metal grating. As is well known, the slit transmission has a quasi-periodic dependence on both the grating thickness and the period of the grating.[11] The transmission varies very slightly since our calculation is conducted in a small range of grating thickness, in which the transmission can arrive at a very high value. It should be noted that the transmission will not necessarily decrease since the most of energy mainly concentrates not on the metal but in the slit of the grating, thus the optical losses cannot increase when the thickness of grating is improved. We then tune the thickness of the grating to 200 nm for the further enhancement of transmission. Note that the $d_{\rm L}$ and $d_{\rm H}$ are fixed at 200 nm for the calculation of transmission spectrum indicated by the dot curve in Fig.2. If the thicknesses of these layers are chosen appropriately, the transmission of the symmetric metallic grating can further be improved. The peak transmission is enhanced to over 94% at wavelength about 1100 nm if the thicknesses, $d_{\rm L}$ and $d_{\rm H}$, are chosen to be 510 and 300 nm respectively.

The period of the grating, roughly determined from formula (1), should be adjusted so that the maximum transmission peak can be accurately changed to the given central wavelength 1053 nm. Therefore, the transmission spectrum can be tuned by adjusting the period, which is illustrated in Fig.5.

Finally, the transmission of 96% at a central wavelength of 1053 nm is shown in Fig.6. The period is adjusted to 533 nm, the transmission effect is even stronger than that shown in Ref.[12]. In addition, it is amazing to know from Fig.7 that the extinction ratio can reach 134 dB at the central wavelength, which is

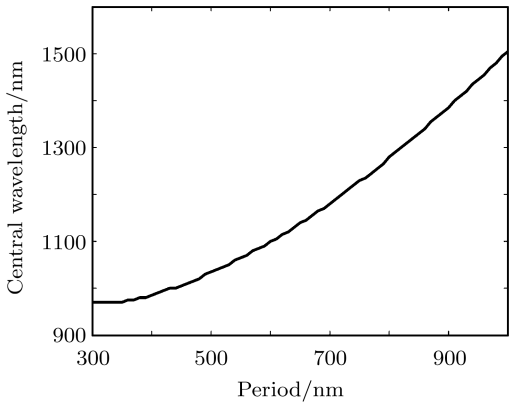


Fig.5. Variation of central wavelength of symmetric grating with period.

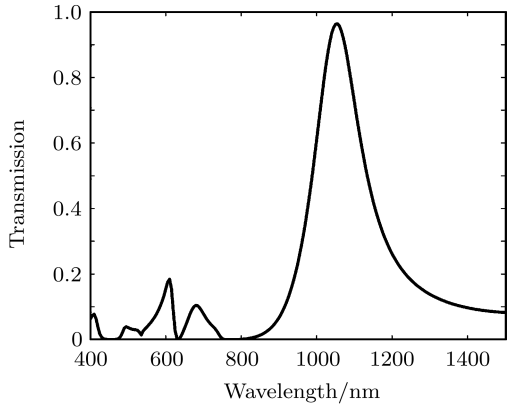


Fig.6. Transmission spectrum of symmetric grating.

five or six times higher than those of ordinary optical filters. The extremely polarized effect is demonstrated in P mode of the symmetric grating.

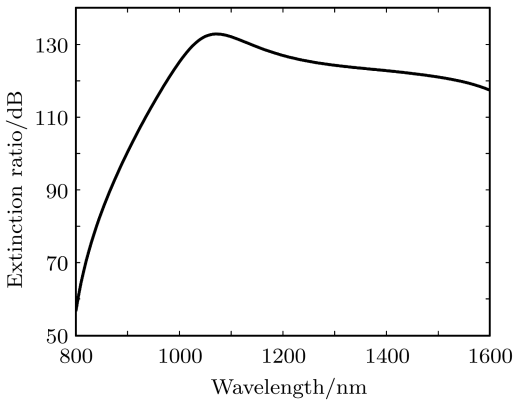


Fig.7. Extinction ratio of zero order for transmission in symmetric grating.

3. Conclusion

We systemically demonstrate how the original modal structure is modified to further improve the transmission at an optical communication wavelength. The transmission can be enhanced to about 96% at a central wavelength of 1053 nm, and it is apparent that such novel structure is suitable for applications in optical communications. Moreover, the structure can act as tunable filters because the wavelength of the transmission can be adjusted simply by changing the period of the gratings.

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