Effects on extraordinary transmission of TE wave through varying structure of sub-wavelength metallic gratings without host media*

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A model of sub-wavelength metallic grating without host media is proposed. Under the excitation of TE polarized light, the extraordinary transmission is also found, and their transmission energy distributions corresponding to different structural parameters of this model are calculated systematically by using finite difference time domain (FDTD) method. The influence of slit width, grating thickness and grating period on the location of transmission peak is obtained. By studying these relations, it is found that Fabry-Perot-like (FPL) effect of the slit is the main physical reason of this extraordinary transmission. Varying the slit width can cause the change of reflection phase transition at both ends, and then the characteristics of FPL resonance of slit cavity are affected. The surface mode of metallic gratings has less effect on the location of transmission peak.

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The important potential applications of sub-wavelength gratings are increasingly realized[1-3]. Consequently, the phenomenon of extraordinary transmission through sub-wavelength metallic gratings has been studied and discussed at home and abroad in recent years[4-9]. There are two theoretical models on analyzing the physical nature of extraordinary transmission: the surface plasma (SP) model and the Fabry-Perot (F-P) resonance model[10]. The SP model is only applied to the situation that incident wave is transverse magnetic (TM) wave. Ebbesen[11] found in 1998 that when a bunch of parallel light vertically illuminates the metal film with periodic sub-wavelength hole arrays, the transmission intensity would increase to dozens of times of theoretical value in some specific wavelengths[11].

In recent years, the extraordinary transmission of transverse electric (TE) wave has been achieved by adding dielectric coating on the metallic gratings[12-16]. In order to take a further study on the physical mechanism of extraordinary transmission for TE wave, this paper builds a metallic grating model with the same thickness, different slit widths and periods to investigate the influence of the structure of metallic gratings on extraordinary transmission, and calculates the TE field transmission distributions by finite difference time domain (FDTD) method.

A grating model is built as shown in Fig.1. The slit width is w=60 nm, period is p=400 nm, silver skin thickness is t=100 nm, and refractive index of dielectric layer filled in slit is n_d=2.5. The incident wave is TE-polarized plane wave, which

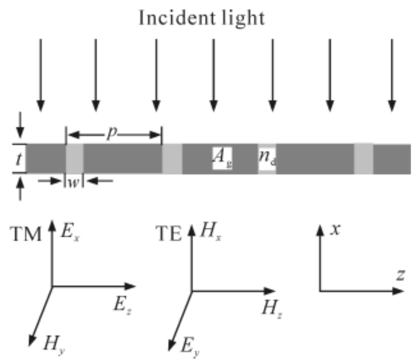

Fig.1 Grating model without host media but adding medium in slit

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vertically irradiates the metallic gratings, and the wavelength ranges from 300 nm to 900 nm.

When the TE wave goes through the slit of the one-dimensional sub-wavelength metallic film, FDTD method is used, all the boundaries to perfectly matched layer truncation electromagnetic field are set, and the periodic boundary conditions are set for the light source in y direction to plane wave source. The relation of the relative permittivity of metal ε_r and frequency ω can be described by the Lorenz-Drude model[16]:

$$\varepsilon_r(\omega)=\varepsilon_{r,\infty}+\sum_{m=0}^{M}\frac{G_m\Omega_m^2}{\omega_m^2-\omega^2+\mathrm{j}\omega\Gamma_m}\ ,\qquad(1)$$

where $\varepsilon_{r,\infty}$ is the relative permittivity at infinite frequency, Ω_m is the plasma frequency, ω_m is the resonance frequency, and Γ_m and G_m are the damping coefficient and the oscillator strength, respectively. The Ag under the excitation of visible and near-infrared light is represented by 6 Lorenz dipole models. In calculation, the frequency-domain function of permittivity is transformed into the time-domain function by using auxiliary differential equation (ADE) method[17,18], and the distance between the right surface of the film and observation surface is set to 1000 nm. The TE mode consists of H_x, E_y and H_z (E_y along the direction of slit length). In Maxwell equations, the derivative is replaced by the numerical difference quotient, so the iterative equations are obtained as

$$E_y^n(i,k)=E_y^{n-1}(i,k)+$$
$$\frac{\Delta t}{\varepsilon\Delta z}[H_x^{n-1/2}(i,k+1/2)-H_x^{n-1/2}(i,k-1/2)]-$$
$$\frac{\Delta t}{\varepsilon\Delta x}[H_z^{n-1/2}(i+1/2,k)-H_z^{n-1/2}(i-1/2,k)]\ ,\qquad(2)$$

$$H_x^{n+1/2}(i,k+1/2)=H_x^{n-1/2}(i,k+1/2)+$$
$$\frac{\Delta t}{\mu_0\Delta z}[E_y^n(i,k+1)-E_y^n(i,k)]\ ,\qquad(3)$$

$$H_z^{n+1/2}(i+1/2,k)=H_x^{n-1/2}(i+1/2,k)-$$
$$\frac{\Delta t}{\mu_0\Delta x}[E_y^n(i+1,k)-E_y^n(i,k)]\ .\qquad(4)$$

In two directions of the x-z surface, the mesh size and the time step are set to 5 nm and 10^{-17} s, respectively. The transmission efficiency is defined as the ratio of the energy through the observation surface to the energy vertically irradiating the slit per unit time, which can be described by $\eta=U_{2z}S_2/(U_{1z}S_1)$, where U_{1z} and U_{2z} are the z-components of the Poynting vectors (U=Re($E\times H$*)/2) of the irradiated surface and the observation surface, respectively, and S_1 and S_2 are the areas of the slit and the observation surface, respectively.

Assuming that the slit width is w = 60 nm, period is p = 400 nm, silver skin thickness is t = 100 nm, and the thickness of dielectric layer filled in slit ranges from 100 nm to 600 nm, the relationship of the far-field transmission wavelength and transmittance is obtained by calculation, as shown in Fig.2.

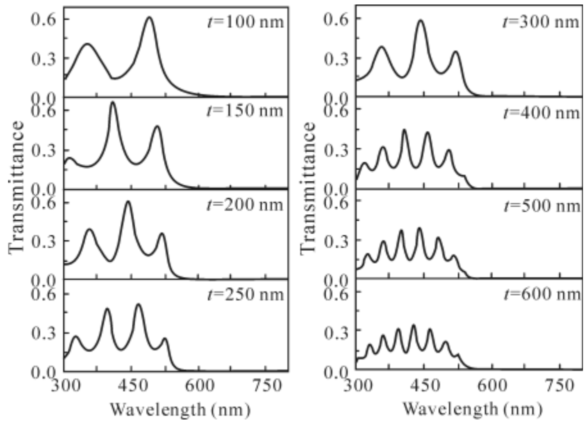

Fig.2 Relation between the transmittance and incident wavelength for different grating thicknesses

For t=100 nm, it can be clearly seen from Fig.2 that there are two transmission peaks at λ=351 nm and 489 nm. When t increases, the peak has a red shift, and new transmission peaks appear in the high frequency area. The transmittance of the peak decreases substantially with the increase of grating thickness. Although the peak has a red shift, the extraordinary transmission does not appear at λ>550 nm. When the peak shifts to 550 nm, the intensity of the peak decreases rapidly, until to zero. In addition, we also find that the differences between adjacent transmission peak wavelengths under the same structural parameters are equal. All above suggest that under the excitation of the TE wave, the extraordinary transmission exists in the gratings with dielectric filled in the slit, and the regularity of the phenomenon is obvious, which is consistent with the previous experimental results[11].

When t=200 nm, there are three transmission peaks. When λ=356 nm, 442 nm and 519 nm, the resonance is excited, and the transmission maximum appears. When λ=402 nm and 487 nm, the resonance is not excited, and the transmission trough appears. When λ>550 nm, the transmittance of the grating is almost zero, and λ=600 nm is selected to represent this frequency domain.

According to Figs.3 and 4, they show the distributions of the electromagnetic field amplitudes under above three conditions respectively. For λ = 356 nm, 442 nm and 519 nm, the distribution of optical field in the slit is symmetrical, and the standing wave is formed. On the contrary, for λ = 402 nm and 487 nm, the distribution of optical field in the slit is asymmetric, and there is no formation of standing wave. According to Fig.4(c), it illustrates that the optical field energy does not enter the slit, which is probably due to the cut-off wavelength existing in grating waveguide for TE polarization.

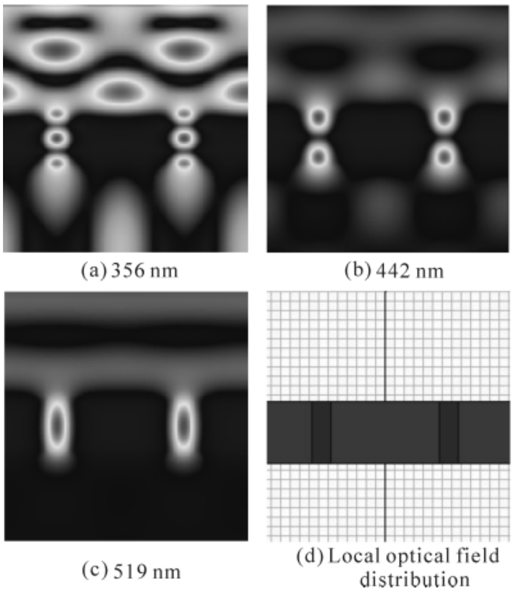

Fig.3 Optical field distributions of the grating for λ=356 nm, 442 nm and 519 nm

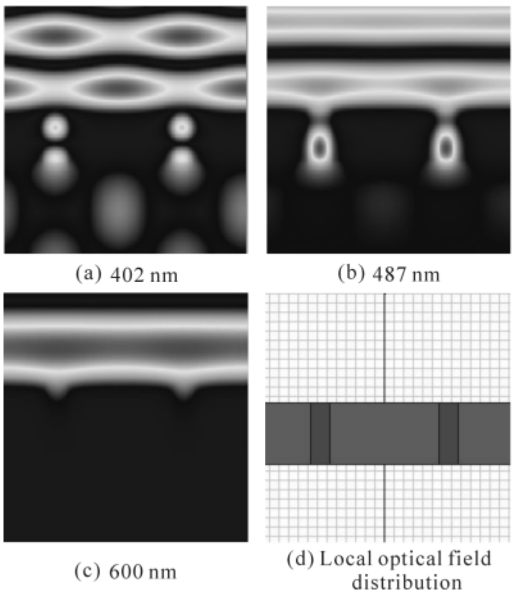

Fig.4 Optical field distributions of the grating for λ=402 nm, 487 nm and 600 nm

The results mentioned above strongly suggest that the optical field within the slit is mainly forward or backward by a sole transmission mode, and the slit can be seen as an F-P cavity at this moment. When the standing wave is formed, the transmission can be enhanced. Consequently, it can explain the law of spectral distribution along with the change of grating thickness as shown in Fig.2: the increase of the grating thickness is equivalent to the increase of the length of the F-P cavity, the wavelength of the standing wave formed in the slit can also be increased, and then transmission spectrum has a red shift. In addition, varying the grating thickness can cause the formation of standing wave in the high frequency field. Subsequently, new transmission peaks are formed.

Fig.5 shows the influence of slit width on the transmission spectra when t = 100 nm and 200 nm.

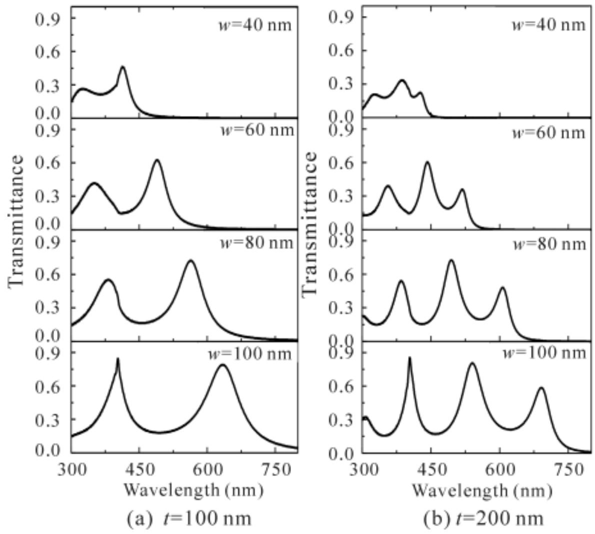

Fig.5 Influence of slit width on the transmission spectra

According to Fig.5, it indicates that when the value of slit width increases, all the transmission peaks shift to the right, and there is no new peak appearing in the high frequency area, which is consistent with the experimental results[15,18]. The results mentioned above suggest that when the length of the slit cavity keeps constant, the change of the slit width leads to the change of the wavelength of resonance transmission, which is caused by the reflection phase transition of both ends of the slit. The condition of F-P resonance transmission can be described by[19]:

$$\lambda_{FP} = \frac{2t}{n - \phi/\pi} , \quad (5)$$

where λ_{FP} is the resonance wavelength when the standing wave is formed in the F-P cavity, n is an integer, and ϕ is the reflection phase transition at both ends of the slit cavity. When the slit width increases, the reflection phase transition ϕ also increases subsequently, which contributes to the increases of λ_{FP} and the interval between transmission peaks as well as the half-wave width of transmission peaks. So Fabry-Perot-like (FPL) effect of slit plays an important role in extraordinary transmission.

When the grating period p ranges from 400 nm to 600 nm, and the other structural parameters keep constant, the relations between transmittance and wavelength obtained by calculation are shown in Fig.6.

From Fig.6, we can clearly see that when the grating period changes, the location of the transmission peak is nearly

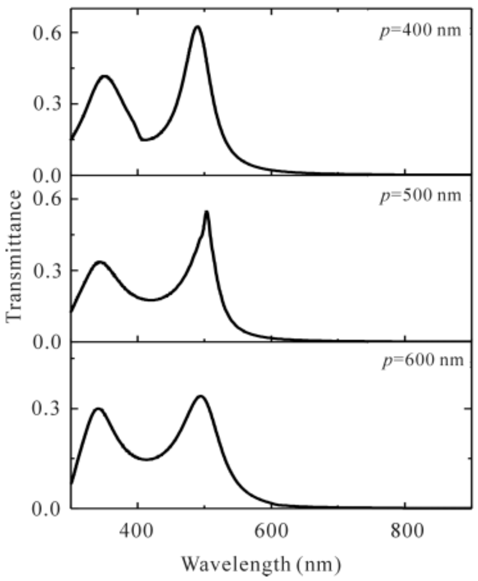

Fig.6 Relation between the transmittance and incident wavelength for different grating periods

unchanged, which indicates that the period is not the main factor to determine the position of the transmission peak. The transmittance in the peak decreases according to the increase of the period, which illustrates that the transmittance is inversely proportional to the duty ratio of the metallic gratings. It is similar to the conclusions obtained by previous experiments[15]. All mentioned above illustrate that the location of transmission peak is only related to the size of the grating slit (grating thickness and slit width), but not to the surface mode of the metallic gratings; the period is only related to the transmission intensity, and in extraordinary transmission, the surface metal of the gratings only plays a role in collecting energy and converging the energy on the slit. It is generally believed that the surface current of the polarized metal and the SP radiation can make the energy spread on the metal surface. There is no SP produced under the TE-polarization. Therefore, on the metallic gratings surface, the surface current excited by the TE wave plays a role in converging the incident optical energy. Finally, the light energy is transmitted to the other side of the gratings by the resonance transmission of the slit cavity, which is consistent with the previous research results on the optical energy transfer along the metallic gratings surface[20].

Under the excitation of the TE wave, the extraordinary transmission obviously exists in sub-wavelength metallic gratings without host media. The depth and the width of the slit cavity of metallic gratings both play a decisive role in the location of transmission peak, and the FPL effect of the slit is the physical essence of the extraordinary transmission through sub-wavelength metallic gratings. The change of the grating period almost has no influence on the location of the transmission peak, but has influence on the transmission intensity. The transmittance is inversely proportional to the duty ratio.

References

[1] Yang Yisu, Huang Yongqing, Huang Hui, Wang Qi and Ren Xiaomin, Chinese Journal of Lasers **36**, 2352 (2009). (in Chinese)

[2] Wang Fang, Su Jingqin, Wang Fang, Liu Lanqin, Wang Wenyi and Mo Lei, Acta Optica Sinica **30**, 508 (2010). (in Chinese)

[3] Zhou Yun, Shen Su, Ye Yan, Pu Donglin and Chen Linsen, Acta Optica Sinica **30**, 1158 (2010). (in Chinese)

[4] V. I. Belotelov, L. L. Doskolovich, V. A. Kotov, E. A. Bezus, D. A. Bykov and A. K. Zvezdin, Opt. Commun. **278**, 104 (2007).

[5] A. S. Vengurlekar, Indian Acad Sciences **98**, 1020 (2010).

[6] V. Delgado, R. Marqués and L. Jelinek, Opt. Express **19**, 13612 (2011).

[7] R. Marqués, F. Mesa and L. Jelinek, Opt. Express **17**, 5571 (2009).

[8] KONG Wei-jin, WANG Shu-hao, YUN Mao-jin, SUN Xin, WEI Shi-jie, ZHANG Wen-fei, ZHENG Bing-bing and JIANG Li-na, Journal of Optoelectronics • Laser **22**, 1769 (2011). (in Chinese)

[9] SHI Jun-xiu, QIN Li, YE Shu-juan, ZHANG Nan, LIU Yun, NING Yong-qiang, TONG Cun-zhu, ZENG Yu-gang and WANG Li-jun, Journal of Optoelectronics • Laser **22**, 1488 (2011). (in Chinese)

[10] HAO Zhi-qiang, CHEN Jing, CHEN Zong-qiang, LU Wen-qiang, XU Jing-jun and SUN Qian, Journal of Optoelectronics • Laser **23**, 1211 (2012). (in Chinese)

[11] T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio and P. A. Wolff, Nature **391**, 667 (1998).

[12] E. Moreno, L. Martín-Moreno and F. J. García-Vidal, J. Opt. A: Pure Appl. Opt. **8**, S94 (2006).

[13] Wang Ya-Wei, Liu Ming-Li, Liu Ren-Jie, Lei Hai-Na and Deng Xiao-Bin, Acta Phys. Sin. **59**, 4030 (2010). (in Chinese)

[14] S. A. Kuznetsov, M. Navarro-Cía, V. V. Kubarev, A. V. Gelfand, M. Beruete, I. Campillo and M. Sorolla, Opt. Express **17**, 11730 (2009).

[15] M. Guillaumée, A. Y. Nikitin, M. J. K. Klein, L. A. Dunbar, V. Spassov, R. Eckert, L. Martín-Moreno, F. J. García-Vidal and R. P. Stanley, Opt. Express **18**, 9722 (2010).

[16] Wang Ya-Wei, Liu Ming-Li, Liu Ren-Jie, Lei Hai-Na and Tian Xiang-Long, Acta Phys. Sin. **60**, 1 (2011). (in Chinese)

[17] Tan Chunlei, Yi Yongxiang and Wang Guoping, Acta Phys. Sin. **51**, 1063 (2002). (in Chinese)

[18] Y. Pang, C. Genet and T. W. Ebbesen, Opt. Commun. **280**, 10 (2007).

[19] F. J. Garcia-Vidal and L. Martin-Moreno, Phys. Rev. B **66**, 155412 (2002).

[20] Wang Yawei, Meng Zenghui, Feng Wei and Tian Xianglong, Acta Optica Sinica **32**, 0231002 (2012). (in Chinese)