Transmission resonances of compound metallic gratings with two subwavelength slits in each period

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Abstract: Based on the finite-difference time-domain method, we investigate the transmission resonances of compound metallic gratings with two subwavelength slits filled with different dielectrics inside each period in the visible and near infrared regions. The results show that the transmission spectrum is almost a compound of that of two corresponding simple gratings expect for the transmission feature at a certain resonant wavelength, where the Fabry-Pérot (FP)-like phenomena have been found both inside the two slits, but the orders of the FP-like modes are different. If the order of the FP-like mode inside one slit is one bigger than inside the other, the intensity of the transmission will be significantly weakened. We attribute this phenomenon to the phase resonance because the phases at the exits of the two slits are opposite to each other.

OCIS codes: (120.7000) Transmission; (240.6680) Surface plasmons; (260.5740) Resonance.

References and links

1. T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, “Extraordinary optical transmission through sub-wavelength hole arrays,” Nature **391**(6668), 667–669 (1998).
2. J. A. Porto, F. J. García-Vidal, and J. B. Pendry, “Transmission resonance on metallic gratings with very narrow slits,” Phys. Rev. Lett. **83**(14), 2845–2848 (1999).
3. Y. Xie, A. R. Zakharian, J. V. Moloney, and M. Mansuripur, “Transmission of light through a periodic array of slits in a thick metallic film,” Opt. Express **13**(12), 4485–4491 (2005).
4. X. Jiao, P. Wang, L. Tang, Y. Lu, Q. Li, D. Zhang, P. Yao, H. Ming, and J. Xie, “Fabry–Pérot-like phenomenon in the surface plasmons resonant transmission of metallic gratings with very narrow slits,” Appl. Phys. B **80**(3), 301–305 (2005).
5. Q. Cao, and P. Lalanne, “Negative role of surface plasmons in the transmission of metallic gratings with very narrow slits,” Phys. Rev. Lett. **88**(5), 057403 (2002).
6. L. Moreno, and F. J. García-Vidal, “Optical transmission through circular hole arrays in optically thick metal films,” Opt. Express **12**(16), 3619–3628 (2004).
7. Z. Ruan, and M. Qiu, “Enhanced transmission through periodic arrays of subwavelength holes: the role of localized waveguide resonances,” Phys. Rev. Lett. **96**(23), 233901 (2006).
8. A. Mary, S. G. Rodrigo, L. Martin-Moreno, and F. J. García-Vidal, “Theory of light transmission through an array of rectangular holes,” Phys. Rev. B **76**(19), 195414 (2007).
9. D. C. Skigin, and R. A. Depine, “Transmission resonances of metallic compound gratings with subwavelength slits,” Phys. Rev. Lett. **95**(21), 217402 (2005).
10. D. C. Skigin, and R. A. Depine, “Narrow gaps for transmission through metallic structured gratings with subwavelength slits,” Phys. Rev. E Stat. Nonlin. Soft Matter Phys. **74**(4), 046606 (2006).
11. A. P. Hibbins, I. R. Hooper, M. J. Lockyear, and J. R. Sambles, “Microwave transmission of a compound metal grating,” Phys. Rev. Lett. **96**(25), 257402 (2006).
12. Y. G. Ma, X. S. Rao, G. F. Zhang, and C. K. Ong, “Microwave transmission modes in compound metallic gratings,” Phys. Rev. B **76**(8), 085413 (2007).
13. M. Navarro-Cía, D. C. Skigin, M. Beruete, and M. Sorolla, “Experimental demonstration of phase resonances in metallic compound gratings with subwavelength slits in the millimeter wave regime,” Appl. Phys. Lett. **94**(9), 091107 (2009).

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14. J. Q. Liu, M. D. He, X. Zhai, L. L. Wang, S. C. Wen, L. Chen, Z. Shao, Q. Wan, B. S. Zou, and J. Yao, "Tailoring optical transmission via the arrangement of compound subwavelength hole arrays," Opt. Express **17**(3), 1859–1864 (2009).
15. E. D. Palik, *Handbook of Optical Constants and Solids* (Academic, New York, 1985).
16. S. K. Gray, and T. Kupka, "Propagation of light in metallic nanowire arrays: Finite-difference time-domain studies of silver cylinders," Phys. Rev. B **68**(4), 045415 (2003).
17. J. A. Dionne, L. A. Sweatlock, H. A. Atwater, and A. Polman, "Plasmon slot waveguides: Towards chip-scale propagation with subwavelength-scale localization," Phys. Rev. B **73**(3), 035407 (2006).

1. Introduction

In the last few years after the first experimental report of extraordinary optical transmission (EOT) through a metallic film perforated with a two-dimensional (2D) array of subwavelength holes [1], much effort has been done to understand the EOT through metallic gratings with various subwavelength microstructures, such as one-dimensional (1D) periodic arrays of slits [2–5] and 2D periodic arrays of holes [6–8]. Previously investigations on EOT have focussed on the periodic subwavelength structures composed of only one hole or slit in each primitive unit cell. Two kinds of transmission resonances, namely the coupled surface plasmon polariton (SPP) resonant mode and the Fabry-Pérot (FP)-like resonant mode, have been involved in the explanation of EOT. Recently, the compound periodic structures composed of several slits or holes within each cell attracted much attention [9–14]. A third kind of resonance known as phase resonance was found. It is characterized by the splitting of FP-like resonant peak because of a phase reversal of the magnetic field in adjacent slits within each period.

For 1D compound metallic gratings, previous workers usually investigated the transmission modes in the microwave region [9–13]. Phase resonances are observed in the metal transmission gratings, which usually consist of a basic unit of several slits filled with identical dielectrics (air). Recent advances allow metals to be structured and characterized on the nanometer scale, which expands this issue to optical region. It is well known that the metal in the microwave region can be regarded as a perfect electric conductor. While in the visible and near infrared regions, the story is different.

In this work, we propose a compound metallic grating, in which each repeat period is comprised of just two slits with identical widths but filled with different dielectrics, and explore the transmission behavior in the visible and near infrared regions. Our results show that the transmission spectrum is almost a compound of that of two corresponding simple gratings. When suitable dielectrics are chosen, the FP-like modes with the different orders can also be found inside the two kinds of slits at a certain resonant frequency: one is the Nth-order FP-like mode and the other is the $(N+1)$th-order FP-like mode (where N is a relative integer), with greatly weakened transmission. We attribute this phenomenon to the phase resonance because the phases at the exits of the two kinds of slits are opposite to each other. An example of the possible application of our findings is in frequency selective surfaces in the visible and near infrared regions, with the length much smaller than that currently achieved.

2. Simulated model and method

In Fig. 1, we show a schematic view of one period of 1D compound metallic grating under study. Each period of the grating comprises two slits, slit 1 and slit 2, with identical widths (w = 50nm) but filled with different dielectric media with low and high relative permittivities ε_{d1} and ε_{d2}, respectively. The interspacing between the two slits (center to center) is denoted as d = 200nm. The period and thickness of the grating are p = 600nm and h = 700nm, respectively. The metal is chosen to be silver, whose frequency-dependent relative permittivity ε_m is described using the tables reported in Ref [15].

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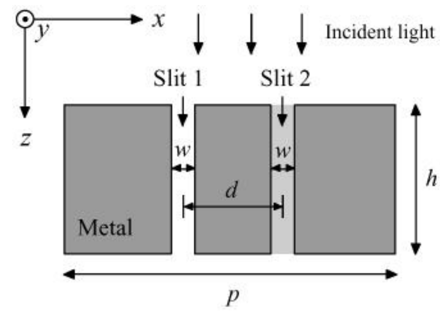

Fig. 1. Scheme of a compound metallic grating.

The two-dimensional finite-difference time-domain (FDTD) method [16] is employed to simulate and calculate the optical transmission through the compound metallic gratings. In our simulation, the spatial mesh steps are set $\Delta x = \Delta z = 5$ nm and the time step is set $\Delta t = \Delta x/2c$ (c is the velocity of light in the vacuum). The calculated region is truncated by using perfectly matched layer absorbing boundary conditions on the top and bottom boundaries, and the left and right boundaries are treated by periodic boundary conditions due to the periodicity of the structure. Only normally incident p-polarized plane waves are considered here, implying that the magnetic field is parallel to the slits (along the y direction).

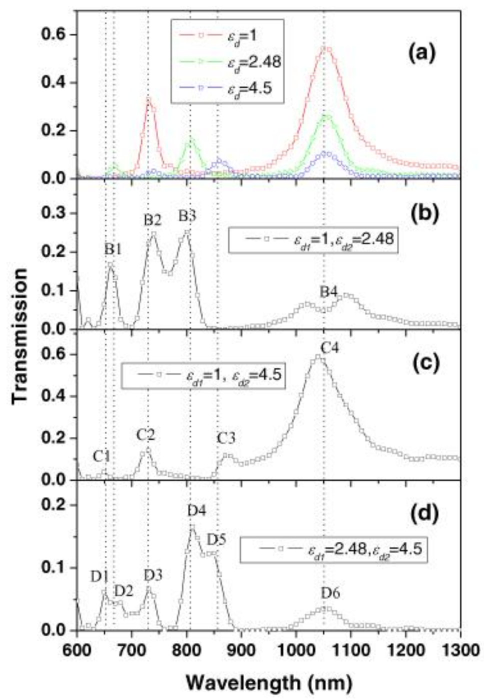

Fig. 2. (Color on line) The calculated transmission spectra of the simple metallic gratings (a) and the compound metallic gratings (b)-(d). (a) are transmission spectra of the simple metallic gratings with subwavelength slits filled with different dielectric $\varepsilon_d = 1$ (air), 2.48 and 4.5, respectively. (b)-(d) are transmission spectra of the compound metallic gratings with two kinds of subwavelength slits filled with different dielectrics $\varepsilon_{d1} = 1$ and $\varepsilon_{d2} = 2.48$, with $\varepsilon_{d1} = 1$ and $\varepsilon_{d2} = 4.5$, and with $\varepsilon_{d1} = 2.48$ and $\varepsilon_{d2} = 4.5$, respectively.

3. Results and discussion

Initially we investigate the situation of the simple metallic gratings, which have same parameters (slit width w, the grating period p and the grating thickness h) as the compound

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metallic gratings under study. Figure 2(a) displays the calculated zero-transmission spectra of the simple gratings with subwavelength slits filled with different dielectric $\varepsilon_d = 1$ (air), 2.48 and 4.5, respectively. For $\varepsilon_d = 1$, the transmission peaks at wavelengths 730nm and 1050nm are associated with the third- and second-order FP-like modes, respectively, because the FP-like resonant wavelengths are approximately determined by the following equation [4,5]:

$$2k_0 \,\mathrm{Re}(n_{eff})h + \Delta\phi = N \cdot 2\pi \tag{1}$$

where $k_0 = 2\pi/\lambda$ is the wave vector of light in vacuum, λ is the wavelength of the incident light in vacuum, n_{eff} is the effective refractive index of coupled-SPPs (waveguide mode) inside the slit, and $\Delta\varphi$ is an additional phase shift experienced by the fundamental mode when reflecting at the grating interfaces, respectively. For *p*–polarized case, n_{eff} can be approximately calculated by the following [17]:

$$\frac{\varepsilon_d\sqrt{n_{eff}^2-\varepsilon_m}}{\varepsilon_m\sqrt{n_{eff}^2-\varepsilon_d}} = \frac{1-\exp(k_0 w\sqrt{n_{eff}^2-\varepsilon_d})}{1+\exp(k_0 w\sqrt{n_{eff}^2-\varepsilon_d})} \tag{2}$$

Figures 3(a) and (b) plot the variation of the real and imaginary parts of n_{eff} for the metallic slit filled with different dielectric ε_d = 1, 2.48 and 4.5, respectively. Similarly, the transmission peaks at wavelengths 670 nm, 790nm and 1050nm for ε_d = 2.48 attribute to the fifth-, fourth- and third-order FP-like modes, respectively, and the transmission peaks at wavelengths 650nm, 740nm, 860nm and 1050nm for ε_d = 4.5 attribute to the seventh- sixth-, fifth- and fourth-order FP-like modes, respectively. In particular, in all cases (ε_d = 1, 2.48 and 4.5), these is a relatively fixed transmission peak at wavelength 1050nm. Moreover, the intensity of the transmission peak decreases as ε_d increases. From Fig. 3(b) we can find that the imaginary part of n_{eff} grows with increasing ε_d, which implies the energy loss increases, resulting in decreasing transmission with the increase of ε_d.

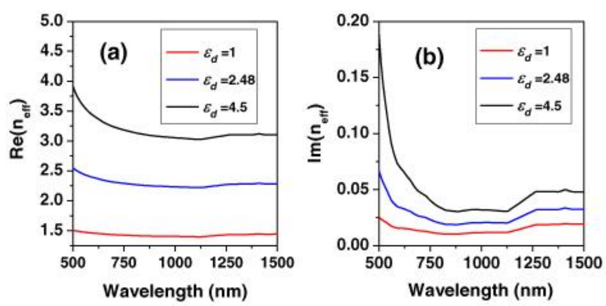

Fig. 3. (Color on line) Variation of the real (a) and imaginary (b) parts of n_{eff} with wavelength for coupld-SPPs inside the metallic slit filled with different dielectric ε_d = 1, 2.48 and 4.5, respectively.

Next, we investigate the optical transmission property of the compound metallic gratings. Figures 2(b)-(d) displays transmission spectra of the compound metallic gratings with two kinds of subwavelength slits filled with different dielectrics ε_{d1} = 1 and ε_{d2} = 2.48, with ε_{d1} = 1 and ε_{d2} = 4.5, or with ε_{d1} = 2.48 and ε_{d2} = 4.5, respectively. By comparison of Figs. 2(b)-(d), we find that the transmission spectrum of the compound metallic grating is almost a compound of that of two corresponding simple gratings (expect for the transmission feature at wavelength 1050nm). For examples, the transmission peaks at B2, B1 and B3 shown in Fig. 2(b) are corresponding to the third-order FP-like modes of the simple grating for ε_d = 1, and the fifth- and fourth-order FP-like modes of the simple grating for ε_d = 2.48, respectively; and the transmission peaks at D2, D4, D1, D3 and D5 shown in Fig. 2(d) are corresponding to the fifth- and fourth-order FP-like modes of the simple grating for ε_d = 2.48, and the seventh-sixth- and fifth-order FP-like modes of the simple grating for ε_d = 4.5, respectively. More interestingly, Some significant features are found for the compound metallic gratings at

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wavelength 1050nm. By comparison of Figs. 2(a) and (b), for the two slits filled with dielectrics $\varepsilon_{d1} = 1$ and $\varepsilon_{d2} = 2.48$, the intensity of the transmission around wavelength 1050nm for the compound metallic grating is significantly lower that for either of two corresponding simple metallic gratings, and a dip appears at wavelength 1050nm. Similarly, for the two slits filled with dielectrics $\varepsilon_{d1} = 2.48$ and $\varepsilon_{d2} = 4.5$ [as shown in Fig. 2(d)], the intensity of the transmission around 1050nm also greatly decreases. On the contrary, for the two slits filled with dielectrics $\varepsilon_{d1} = 1$ and $\varepsilon_{d2} = 4.5$ [as shown in Fig. 2(c)], the intensity of the transmission peak at wavelength 1050nm for the compound metallic grating is stronger than that for either of the corresponding simple metallic gratings.

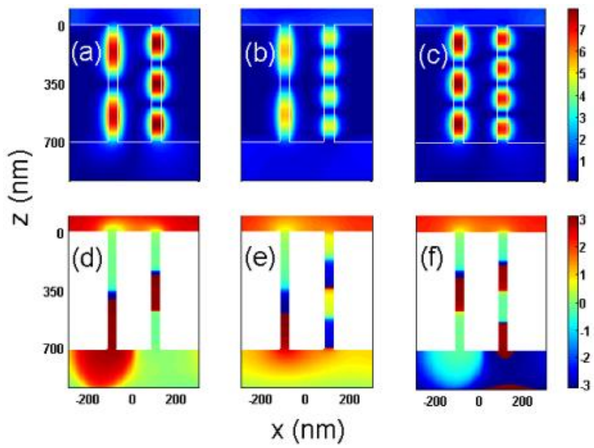

Fig. 4. (Color on line) Amplitude and phase distributions of magnetic fields of compound metallic gratings at resonant wavelength 1050nm. (a), (b) and (c) are amplitude distributions of the magnetic fields at B4, C4, and D6 which are shown in Fig. 2(b), (c), and (d), respectively. (d), (e) and (f) are the phase distributions of the magnetic fields corresponding to (a), (b) and (c), respectively.

In order to understand the physical origin of the transmission features at wavelength 1050nm, we calculate the amplitude and phase distributions of the magnetic fields of above three compound metallic gratings at resonant wavelength 1050nm, respectively. Figure 4 (a), (b), and (c) are the amplitude distributions of the magnetic fields at B4, C4, and D6 which are shown in Fig. 2(b), (c), and (d), respectively. Figures 4(d), (e) and (f) show the phase distributions of the magnetic fields corresponding to Figs. 4(a), (b) and (c), respectively. The FP-like phenomena have been found both inside the slit 1 and slit 2, but the orders of the FP-like modes inside the two slits are different. For instance, when the two slits are filled with dielectrics $\varepsilon_{d1} = 1$ and $\varepsilon_{d2} = 2.48$, one is the second-order FP-like mode and the other is the third-order FP-like mode [as shown in Fig. 4(a)]. Moreover, we find that the phases of the incident waves at the entrance of the two slits are in-phase, but at the exits they can be either in-phase or out-of-phase. It is well known that the phase retardation of the coupled-SPPs transmitted through each metallic slit is determined mainly by $k_0\mathrm{Re}(n_{eff})h$ in Eq. (1). As shown in Figs. 4(d) and (f), when the order of the FP-like mode inside the slit 2 is one bigger than that inside the slit 1, the phases at the exits of the two slits are opposite to each other, and then π resonances can be excited. This can be well understood from Eq. (1). While, as shown in Fig. 4(e), when the order of the FP-like mode inside the slit 2 is two bigger than that inside slit 1, the electromagnetic waves at the exits of the two slits are still in-phase, resulting in the enhanced transmission.

4. Summary

In conclusion, we propose a metallic compound grating, in which each repeat period is comprised of two slits with identical widths but filled with different dielectrics. We explore the transmission behavior of the light passing through the gratings in the visible and near

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infrared regions. It is found that the enhance transmission spectrum is almost a compound of that of two corresponding simple gratings expect for the transmission feature at a certain resonant wavelength, where the FP-like phenomena have been found both inside the two slits, but the orders of the FP-like modes are different. When the order of the FP-like mode inside the one slit is one bigger than inside the other, the intensity of the transmission will be significantly weakened. We attribute this phenomenon to the phase resonance. On the contrary, when the order of the FP-like mode inside the one slit is two bigger than inside the other, the intensity of the transmission will be enhanced because the light waves at the exits of the two slits are in-phase.

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