

Tunable phase resonances in a compound metallic grating with perpendicular bumps and cuts

Zhimin Liu,^{1,3} Hongjian Li,^{1,2*} Suxia Xie,² Haiqing Xu,¹
Shaoli Fu,¹ Xin Zhou,² and Caini Wu¹

¹ College of Physics Science and Technology, Central South University, Changsha 410083, China
² College of Materials Science and Engineering, Central South University, Changsha 410083, China
³ College of Basic Sciences, East China Jiaotong University, Nangchang 330013, China
*lihj398@yahoo.com.cn

Abstract: We propose a compound metallic grating with perpendicular bumps in each slit and investigate its transmission property theoretically. As the bumps are set symmetrically in the slits, the waveguide resonant peaks for the even (odd) modes exhibit a red-shift (blue-shift) compared with the resonant peaks of grating composed of bare slit. As the bumps are set asymmetrically, we show that the dips in transmission spectrum can be tuned by shifting the position and changing the size of bumps in the slit. The corresponding physical mechanisms for above phenomenon are discussed, followed by some qualitative explanations in terms of field distribution. We also investigate the optical transmission through a compound metallic grating with perpendicular bumps in one slit and cuts in another slit, and find that the dips in transmission spectrum are more sensitive to the simultaneous change of the bumps and cuts.

©2011 Optical Society of America

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

References and links

1. W. L. Barnes, A. Dereux, and T. W. Ebbesen, "Surface plasmon subwavelength optics," *Nature* **424**(6950), 824–830 (2003).
2. C. Genet, and T. W. Ebbesen, "Light in tiny holes," *Nature* **445**(7123), 39–46 (2007).
3. 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).
4. F. Medina, J. A. Ruiz-Cruz, F. Mesa, J. M. Rebollar, J. R. Montejo-Garai, and R. Marqués, "Experimental verification of extraordinary transmission without surface plasmons," *Appl. Phys. Lett.* **95**(7), 071102 (2009).
5. Z. C. 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).
6. H. T. Liu, and P. Lalanne, "Microscopic theory of the extraordinary optical transmission," *Nature* **452**(7188), 728–731 (2008).
7. W. Dai, and C. M. Soukoulis, "Theoretical analysis of the surface wave along a metal-dielectric interface," *Phys. Rev. B* **80**(15), 155407 (2009).
8. D. C. Skigin, and R. A. Depine, "Transmission resonances of metallic compound gratings with subwavelength slits," *Phys. Rev. Lett.* **95**(21), 217402 (2005).
9. M. Navarro-Cia, 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).
10. H. J. Rance, O. K. Hamilton, J. R. Sambles, and A. P. Hibbins, "Phase resonances on metal gratings of identical, equally spaced alternately tapered slits," *Appl. Phys. Lett.* **95**(4), 041905 (2009).
11. J.-Q. Liu, M.-D. He, X. Zhai, L.-L. Wang, S. 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).
12. J. Q. Liu, X. B. Chao, J. N. Wei, M. D. He, L. L. Wang, Q. Wan, and Y. Wang, "Multiple enhanced transmission bands through compound periodic array of rectangular holes," *J. Appl. Phys.* **106**(9), 093108 (2009).
13. Z. Liu, and G. Jin, "Phase effects in the enhanced transmission through compound subwavelength rectangular hole arrays," *J. Appl. Phys.* **106**(6), 063122 (2009).
14. Y. Wang, Y. Wang, Y. Zhang, and S. Liu, "Transmission through metallic array slits with perpendicular cuts," *Opt. Express* **17**(7), 5014–5022 (2009).

15. M.-D. He, Z.-Q. Gong, S. Li, Y.-F. Luo, J.-Q. Liu, and X. Chen, "Light transmission through metallic slit with a bar," *Solid State Commun.* **150**(29-30), 1283–1286 (2010).
16. X. Zhai, J. Q. Liu, M. D. He, L. L. Wang, S. C. Wen, and D. Y. Fan, "Adjustable phase resonances in a compound metallic grating with perpendicular cuts," *Opt. Express* **18**(7), 6871–6876 (2010).
17. A. Taflov, and S. C. Hagness, *Computational Electrodynamics: The Finite-Difference-Time-Domain Method*, 2nd ed. (Artech House, 2000).
18. K. S. Yee, "Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media," *IEEE Trans. Antenn. Propag.* **14**, 302 (1966).
19. E. D. Palik, *Handbook of Optical Constants in Solids* (Academic, 1982).
20. Y. Takakura, "Optical Resonance in a Narrow Slit in a Thick Metallic Screen," *Phys. Rev. Lett.* **86**(24), 5601–5603 (2001).
21. A. P. Hibbins, M. J. Lockyear, and J. R. Sambles, "The resonant electromagnetic fields of an array of metallic slits acting as Fabry-Perot cavities," *J. Appl. Phys.* **99**(12), 124903 (2006).
22. Z. Liu, and G. Jin, "Resonant acoustic transmission through compound subwavelength hole arrays: the role of phase resonances," *J. Phys. Condens. Matter* **21**(44), 445401 (2009).

1. Introduction

Enhanced transmission through subwavelength metallic openings has aroused great interest [1,2] since the work of extraordinary optical transmission (EOT) through a subwavelength hole array [3], not only for the rich physical mechanisms, but for their potential applications in optics and optoelectronics [2]. Though to date the physical mechanism behind the phenomenon of EOT remains controversial [3–5], it has been widely accepted that the enhanced transmission is mainly attributed to surface plasmon excitation and waveguide modes of the slit. It also has been understood as a resulting from a subtle surface wave dynamical scattering process on the film interfaces [6] or residual waves [7] and surface plasmon is not the solely factor contributing to the EOT.

In recent years, the phase resonances have received much attention. It is established that the phase resonances appear in compound metallic gratings [8]. Experimentally, Skigin et al. provided evidence of phase resonances in metallic periodic structures in the millimeter wave regime [9]. In the microwave range, Rance et al. also demonstrated the electromagnetic response of metal transmission gratings comprised of identical but alternately orientated tapered slits [10]. Theoretically, phase resonances are extended to transmission through the subwavelength compound periodic hole arrays, such as square and rectangular holes [11,12]. The dips in the transmission peak are predicted by recent calculation based on modal expansion theory [13].

Recently, Wang et al. explored the transmission of light through an array of subwavelength metallic slits modified by perpendicular cuts [14], and He et al. discussed the light transmission through metallic slit with a bar [15]. They found the influence of cuts or bars in the slit on odd and even modes of slit are different. Zhai et al. introduced perpendicular cuts into the compound metallic grating [16], and found the phase resonances can be alternately realized by shifting the cuts along the vertical slits or changing the size of one cut in the cell. Whether transmission spectrum shows transmission dips in an asymmetry compound metallic grating with perpendicular bumps or cut-bumps? In this paper, we propose a compound metallic grating with perpendicular bumps in each slit or with perpendicular bumps in one slit and cuts in another slit. It is shown that the dips of transmission spectrum for this compound periodic grating can be adjusted by shifting the position and changing the size of bumps in the slit, and the transmission dips are more sensitive to the simultaneous change of the bumps and cuts.

2. Model and method

A unit cell of a compound metallic grating with two slits engraved perpendicular bumps in each slit is shown in Fig. 1(a). The period, thickness and slit width of the grating are $p = 700\text{nm}$, $h = 1500\text{nm}$, and $w = 100\text{nm}$, respectively, which are fixed in the whole paper. The position of bump can be changed by adjusting the parameters h_1 and h_2 . The lengths and widths of the bumps are denoted with w_1 , w_2 and w_{31} , w_{32} , w_{41} , w_{42} , respectively. Two-dimensional FDTD method is used to simulate the results [17,18], the frequency dependent permittivities of the gold are approximated by the Drude model, which defines as: $\epsilon(\omega) = 1 -$

$\omega_p^2/(\omega^2 + i\omega\gamma_p)$, where $\omega_p = 1.37 \times 10^{16} \text{s}^{-1}$ is the bulk plasmon frequency and $1/\gamma_p = 245f$ represents the electron relaxation time. These values are obtained by fitting the experimental results [19]. And the calculated region is truncated by using perfectly matched layer(PML) absorbing boundary conditions on the top and bottom surfaces of the computational space along the y direction. The left and right boundaries along x direction are treated by periodic boundary conditions. The incident light is along the y direction with TM polarization.

3. Results and discussion

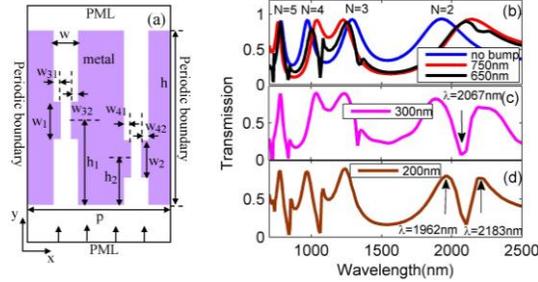


Fig. 1. (a) Scheme of a unit cell of the compound metallic grating. (b-d) Transmission spectra as a function of wavelength for different positions of bumps. The blue solid curve denotes the transmission spectra of grating without bumps. The lengths and widths of bumps are $w_1 = w_2 = 200 \text{nm}$, $w_{31} = w_{32} = w_{41} = w_{42} = 25 \text{nm}$, the value of insets shows the position (h_2) of one bump and another bump is located at the center of slit ($h_1 = 750 \text{nm}$).

Figures 1(b-d) show the transmission spectrum by adjusting the positions of perpendicular bumps, where only one of the bumps in the unit cell is shifted. In order to understand the transmission spectrum well, we give the transmission spectrum of metallic gratings consisting of bare slit without perpendicular bumps (blue solid curve, denoted by “no bump” in the inset of Fig. 1(b)), in which other geometry parameters are the same as the compound metallic grating with perpendicular bumps in the slits. The transmission spectrum shows transmission peaks at wavelength 1929nm , 1287nm , 974nm and 778nm , which correspond to the waveguide modes resonances according to previously reported results [14,16], labeled as $N = 2$, $N = 3$, $N = 4$ and $N = 5$, respectively. They are associated with different standing wave modes of the slit, and the detailed discussion can be found in the following.

Then we simulate the transmission spectrum of symmetric cases, namely all the perpendicular bumps lie in the center of slit $h_1 = h_2 = h/2 = 750 \text{nm}$. The transmission peaks for the Fabry-Perot cavity odd modes ($N = 3$ and $N = 5$) exhibit a blue-shift, while for even modes ($N = 2$ and $N = 4$) shift to region of longer wavelength compared with the transmission peak of metallic grating composed of bare slit arrays due to the introduction of bumps in the slits.

The above phenomenon can be explained by the theory in Ref [14,15], as follows. The resonant wavelength of F-P mode in a bare slit array can be obtained by $2kL_{FP} + \theta = 2N\pi$, where $k = 2n\pi/\lambda$ is the wave vector (where λ is the wavelength of the N th order mode [20,21], n is the effective refractive index of the fundamental Bloch mode propagating in the slit, it strongly depends on the slit width), L_{FP} is the length of the cavity, and θ is the total phase reflected at the ends of the slits and a N dependent value. The length of the F-P cavity varies with the distribution of surface current flow and surface charge due to the introduction of bump or cut in the slit. We definite this length of the slit with bumps or cuts as the effective length of the F-P cavity. For the bare slit, current density standing waves are established with opposite signs on both metal walls of each slit by incident oscillating light [21]. The existence of the bump is equivalent to shortening the length of current flow. The decrement in the effective F-P cavity can be expressed as Δ_j . Besides surface current flow standing waves, surface charge standing waves are also established on the walls of the slit. The slit can be considered as a parallel-plate capacitor, the capacitance is the ability of accumulating charges. Introducing bump causes an increase in the ability to accumulate charge. Increasing the length

of the slit can also increase the ability to accumulate charge. Thus the appearance of bump is equivalent to increasing the length of the slit. The increment is denoted by Δ_Q . The total effects of the bump on the effective length of the F-P cavity are determined by $L_{eff} = L_{FP} + \Delta_Q - \Delta_J$. If $\Delta_Q > \Delta_J$, the effective length is larger than the actual length, the resonant wavelength gets larger. If $\Delta_Q < \Delta_J$, the resonant wavelength becomes smaller. In addition, According to Maxwell's equations, the surface currents and charge densities on the slit walls can be obtained from $\mathbf{n} \times \mathbf{H} = \mathbf{J}$ and $\mathbf{n} \cdot \mathbf{D} = \sigma$, respectively, where \mathbf{n} is a unit normal vector directed from metal into air in slit, \mathbf{H} and \mathbf{D} are the magnetic field and electric displacement, \mathbf{J} and σ are surface current density and charge density, respectively. If the bump locates at the center of the antinodes (nodes) of the electric (magnetic) field, the bump has the most influence on the charge densities, while the current density is least influenced by the bump reaches its minimum, which means $\Delta_Q > \Delta_J$, the effective length of the F-P cavity increases. Therefore the resonance wavelength is greater than the corresponding wavelength of the bare slit. The resonances of this kind corresponds to the transmission peaks $N = 2$ and $N = 4$ (even modes) in Fig. 1(b) (red solid curve, denoted by "750nm" in the inset). When the bump locates at the center of the node (antinode) of the electric (magnetic) field, Δ_Q reaches its minimum and Δ_J reaches the maximum ($\Delta_Q < \Delta_J$), the effective length gets smaller. Hence the resonance wavelength of becomes smaller. The transmission peaks $N = 3$ and $N = 5$ (odd modes) correspond to this kind of case. Now, let us make a comparison between our results and Ref [16]. Both the bump and cut influence the surface charge and surface current flow on the slit, but it should be noted that the existence of the bump results in an increase in the ability to accumulate surface charge and a decrease in the length of surface current flow, while the introduction of a cut leads to an increase in the length of current flow and a decrease in the ability to accumulate charge.

In addition, we can find that almost all the waveguide resonance peaks exhibit dips in the transmission spectrum when one of the bump shifts to the position $h_2 = 650nm$, shown in Fig. 1(b) (black solid curve), and the transmission spectra show obvious dip at the peak for mode $N = 4$, while the dips for waveguide modes $N = 2$, $N = 3$, $N = 5$ are smaller. As h_2 deviates from the center position 750nm, the dips are further deepened. However, no dips appear for the peak corresponding to the waveguide mode for $N = 4$ as $h_2 = 300nm$ shown in Fig. 1(c) and $N = 3$ as $h_2 = 200nm$ shown in Fig. 1(d). The results in Figs. 1(b-d) show that the dips for phase resonances can be tuned by shifting the positions of perpendicular bump in the proposed compound metallic gratings. And it is easy to imagine that the dips also can be adjusted by the width and length of perpendicular bumps in the proposed compound metallic grating. Similar phase resonance dips occur in the spectrum for waveguide mode (not shown here).

The physical origin of the transmission dips can be explained in terms of phase resonances as follows. On one hand, for a single periodic slit array, the translation invariance can reduce the field degrees of freedom to just a unit cell. Therefore, the fields in all slits are equal when a light is normally incident. As for compound periodic grating arrays, it can also reduce the degrees of freedom to a unit cell, but it cannot ensure that the fields of different slits in a unit cell are identical. On the other hand, the F-P resonances arise from individual cavities, so the addition of extra cavities to each unit cell can introduce new F-P modes. These modes induced by different slits in a unit cell are degenerate if the slits have identical size, and nondegenerate if these sizes are different. For the nondegenerate case, it is understandable that the field phases in different slits are unequal [13,16,22]. As for our structure, if all the bumps lie at the center of the slit, namely, symmetric case, it is equivalent to a single periodic slit array, the field phases in the two slits are equal due to the symmetry. If the bumps lie at the different positions, they affect the current density and charge density in a different way due to the asymmetry. Therefore, the effective lengths for two slits with bumps are different, which provide new degrees of freedom for the field phase distribution. When the phase difference between adjacent slits approaches π , an obvious dip resulting from destructive interference between adjacent slits presents in the transmission spectrum.

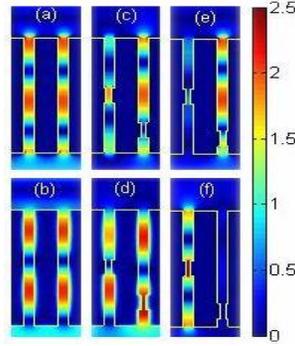


Fig. 2. (a-b) The magnitudes of electric (magnetic) field $|E_x|$ ($|H_z|$) of gratings composed of bare slit without bumps for waveguide mode $N = 2$. (c-d) The magnitudes of electric (magnetic) field $|E_x|$ ($|H_z|$) for $\lambda = 2067nm$ in Fig. 1(c). (e-f) The magnitude of electric field $|E_x|$ at $\lambda = 2183nm$ and $\lambda = 1962nm$ in Fig. 1(d).

In order to understand the dependence of phase resonance on the position of bumps well, we also draw the electronic and magnetic field distributions in Fig. 2. The distributions of electric field (Fig. 2(a)) and magnetic field (Fig. 2(b)) for the resonance mode peak $N = 2$ with $\lambda = 1929nm$ of gratings composed of bare slit without bumps are also shown for comparison. In Fig. 2(c), it shows one bump ($h_1 = 750nm$) exists at the antinode of electric field (the center of grating at y direction), while another bump ($h_2 = 300nm$) locates at the node of electric field. Correspondingly, in Fig. 2(d), the effects of bumps on the magnetic field are contrary to the case of Fig. 2(c). For bumps lie at the center of antinode of electric field in slits ($h_1 = 750nm$), the charge density affected by the bumps reaches its maximum, but its influence on the current density reaches the minimum [15,16]. If the bumps located at the antinode(node) of magnetic(electric) field, they affect the current density and charge density in a contrary way. Therefore, the effective lengths of two slits with bumps are different. Additionally, in Figs. 2(e) and (f), we draw the electric field distributions for two peaks at wavelength 2183nm and 1962nm in Fig. 1(d). We can find that the electric field is mainly concentrated on the right slit with bump ($h_2 = 200nm$) for resonant wavelength 2183nm and the resonant peak at 1962nm is determined by another slit with bump $h_1 = 750nm$. It is because the resonant wavelength for each slit relies on the effective length, which is affected by the position of bumps in the slit. The results confirm that the interference behavior of phase resonances between adjacent slits is modulated by the arrangement of compound grating, which may lead to many new applications. For example, the proposed method to adjust transmission spectra and field is proposed as a new method of selecting output channel, new types of actively-controlled nano-optic devices, frequency selector or filter, and optical switching, etc.

In Ref [16], Zhai et al. demonstrated the transmission dips for the compound grating with perpendicular cuts in the slit. We introduce perpendicular bumps into the compound grating, and find the transmission dips can be tuned by shifting the position and changing the size of bumps. Whether compound grating with perpendicular cuts and bumps shows transmission dips? Then we propose a compound metallic grating with perpendicular bumps in one slit and with cuts in another slit. The width w_{31} and w_{32} of two bumps in one slit equal the depth w_{41} and w_{42} of two cuts in another slit, all the bumps and cuts lie in the same position $h_1 = h_2 = h/2 = 750nm$ in slits, and other parameters are the same as in Fig. 1, a scheme of a unit cell of this compound grating is displayed in Fig. 3(a). Figures 3(b) and (c) show that the dips are sensitive to the change of the width of bumps and the depth of cuts. All the resonance peaks exhibit dips in the transmission spectra when $w_{31} = w_{32} = w_{41} = w_{42} = 10nm$, compared with the transmission peak of metallic grating consisting of bare slit. When the width of bumps and the depth of cuts change to $w_{31} = w_{32} = w_{41} = w_{42} = 30nm$, the dips are further deepened, and almost all the values of the dips are near to zero. Compared with the spectra in Fig. 1, it seems that phase resonance is more sensitive to the simultaneous change of bumps and cuts.

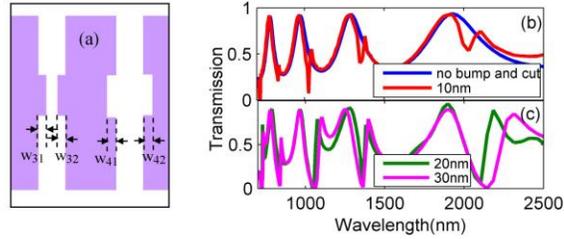


Fig. 3. (a) Scheme of a unit cell of the compound metallic grating with bump in one slit and with cut in another slit. (b-c) Transmission spectra as a function of wavelength for different widths of bumps and cuts. The lengths and positions of bumps and cuts are $w_1 = w_2 = 200nm$, $h_1 = h_2 = 750nm$, the value of insets shows the widths of bumps and cuts.

4. Conclusion

To summarize, we propose a compound metallic grating with perpendicular bumps in each slit and a compound grating with perpendicular bumps in one slit and cuts in another slit. The introduced bumps or cuts in metallic grating act as a structure defect. We find that the dips of transmission spectrum for this compound periodic structure can be realized by shifting the position, adjusting the size of bumps and changing the bumps and cuts simultaneously in the slit. The underlying physical mechanisms are discussed. We expect that our findings are useful for the design of optical devices, and contribute to more applications in the future.

Acknowledgments

This work was funded by the Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20100162110068), the Scientific Project of Jiangxi Education Department of China (Grant No. GJJ11110 and GJJ11107).