Optical transmission through silver film with compound periodic array of annular apertures

ZHANG Yue (张玥), **YAO Wen-jie** (姚文杰), **and YU Hong** (于虹)*
Key Laboratory of MEMS of Ministry of Education, Southeast University, Nanjing 210096, China

(Received 12 September 2014; Revised 8 October 2014)

Recently, some kinds of structures have been found to show the property of extraordinary optical transmission (EOT). In this paper, we present a novel composite structure based on array of annular apertures (AAA) with compound lattice. The lattice includes two kinds of annular apertures with the same outer radius and different inner radii. The transmission spectrum of this compound periodic AAA can be achieved by adding up the spectra of two corresponding simple periodic AAAs, and the transmission shows EOT property. The transmission peaks of this kind of structure can be adjusted to desire wavelengths by changing the inner radius of aperture or the index of the dielectric material in the aperture. This structure can be used as a filter with dual pass bands when the difference between inner radii or indices of dielectric inside is large enough for two kinds of apertures.
Document code: A **Article ID:** 1673-1905(2015)02-0116-5
DOI 10.1007/s11801-015-4226-8

According to the principle of light diffraction, when wavelength is less than the size of hole, light transmittance is very small. In 1944, Bethe[1] analyzed the transmittance of holes in ideal metal thin film. Transmittance of metal holes is proportional to $(d/\lambda)^4$ (d is diameter of metal hole and λ is wavelength of incident light). Therefore transmittance is almost 0 when the wavelength of incident light is much less than the diameter of metal hole. And transmittance decreases rapidly with diameter of hole decreasing. However, Ebbesen[2] analyzed transmittance of subwavelength metal holes array, and found that if the subwavelength metal holes are arranged periodically, the normalized transmittance of single hole is a few orders of magnitude larger than Bethe's calculation at certain wavelength. Extraordinary optical transmission (EOT) is proposed. Then much effort is put into uncovering the underlying mechanism, and it is acknowledged now that the waveguides of aperture play an important role on EOT[3-5]. As the waveguide is mainly related to the shape of aperture, many kinds of apertures with special shapes are proposed, like the annular and the rectangle apertures[6-8]. Compared with the circle and the rectangle apertures, the transmission peaks of the metal film perforated with a periodic array of annular apertures are stronger and located at longer wavelength. Thus, after the array of annular apertures (AAA) was proposed firstly by Baida et al[9], many kinds of derived structures were presented soon. However, for most of them, the arrays of annular apertures are based on simple lattice.

In this paper, we present a novel composite structure based on compound lattice and AAA, which can be achieved by perforating a compound periodic AAA in silver film. The free-stand silver films perforated with the simple and the compound array of annular apertures are both shown in Fig.1. The simulated structures are illuminated by a plane wave in normal incidence, whose spectrum is from 400 nm to 1 100 nm, and the polar direction of source is along the x-axis. In Fig.1(b), the compound periodic AAA is designed by setting a annular aperture at the center of rectangular cell. As shown in the figure, there are two kinds of annular apertures labeled as A1 and A2, and they have different inner radii and dielectrics filled in the apertures.

The optical properties of the compound periodic structure are simulated using 3D-FDTD[13-15] algorithm. The spatial mesh steps are set as $\Delta x=\Delta y=\Delta z=1$ nm. In the simulation, the periodic boundary condition is set at the end in directions of x and y, and the perfect match condition is set at the end in direction of z. The optical transmissions of three compound periodic structures (R_{i2}=20 nm, 50 nm and 75 nm, R_{i2} is the inner radius of A2) have been simulated. As shown in Fig.2(a), the transmissions of simple periodic structure with R_i =20 nm, 50 nm, 75 nm, R_o=100 nm are depicted as blue, green and red curves. When we increase the inner radius of annular aperture for simple periodic AAA, the peak of transmission shifts towards long wavelength.

* E-mail:h_yu@seu.edu.cn

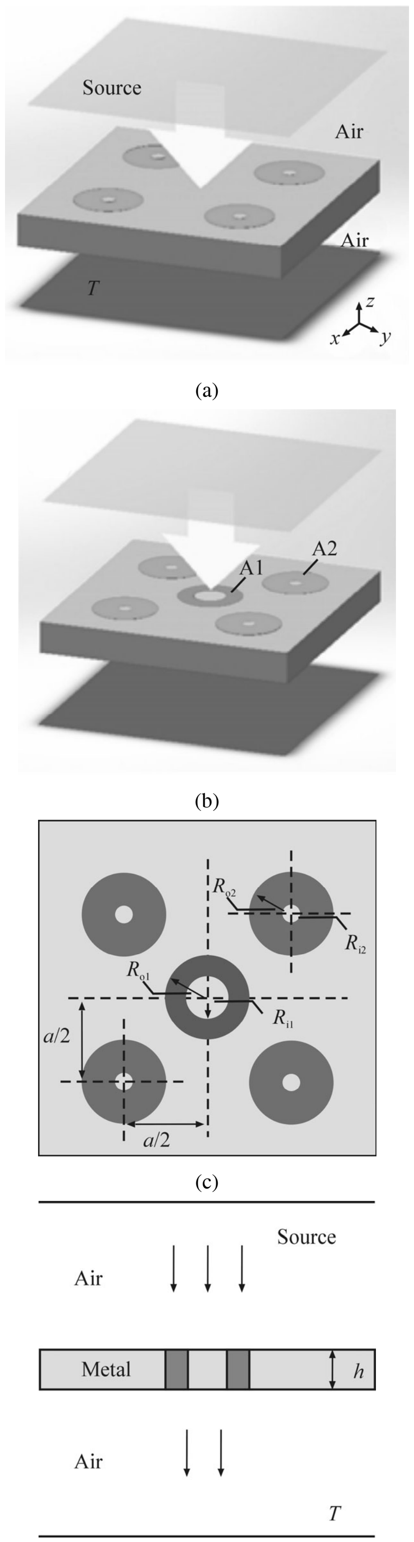


Fig.1 Schematic diagram of the structure (The thickness of the film is 100 nm, and lattice constant of array is 400 nm.): (a) Primitive cell of simple periodic AAA; (b) Primitive cell of compound periodic AAA, which is designed by setting an annular aperture at the center of rectangular cell; (c) The silver film perforated with compound periodic AAA in the *xy* cross section; (d) The *yz* cross section with *x* = 0

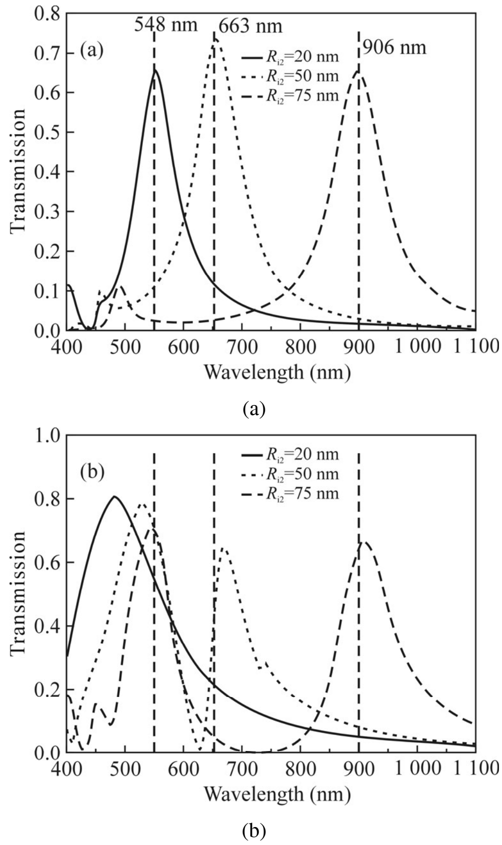


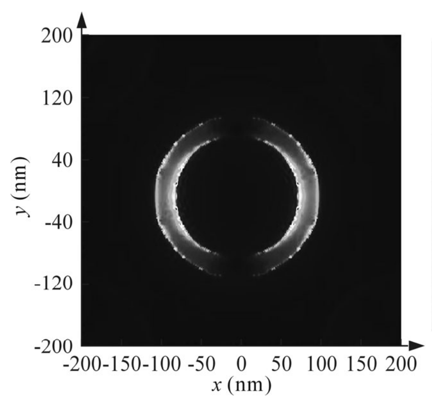
Fig.2 Transmissions of simulated structures with different inner radii for annular apertures (R_o = 100 nm, dielectric material filled in apertures is air): (a) Simple periodic lattice; (b) Compound periodic lattice

The transmissions of the compound periodic structures with R_{i2}=20 nm, 50 nm, 75 nm, R_{i1}=20 nm, R_{o1}=R_{o2}=100 nm are depicted in Fig.2(b), respectively. As shown with the line corresponding to R_{i2}=75 nm, the transmission of compound periodic AAA can be achieved by adding up the spectra of the corresponding simple periodic AAA (R_i=20 nm and R_i=75 nm), and the transmission peaks are almost at the same wavelength with the corresponding simple lattice. Fig.2 shows that the transmission spectrum of compound periodic structure with R_{i2}=75 nm contains four transmission peaks, λ_{peak}=910 nm, 543 nm, 456 nm and 456 nm. However, as the other two lines show, when the inner radii of two kinds of annular apertures are close to each other (R_{i1}=20 nm and R_{i2}=20 nm or 50 nm), the peak at short wavelength has a blue shift, and the peak at long wavelength has a red shift. We consider that it results from the interaction between waveguides in two kinds of annular apertures.

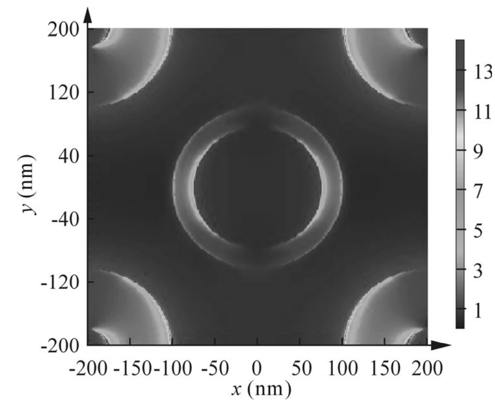
Fig.3 shows the distributions of electric field in *xy* plane at four transmission peaks. For λ_{peak}=910 nm and λ_{peak}=456 nm, the strongest electric field is located at A1 (R_{i1}=75 nm) as shown in Fig.3(a) and Fig.3(c), respectively. It can be seen that the distribution pattern is two-disc type, thus the mode of transmission peak is transmission plasma waveguide TE_{11} mode[10] for A1.

However, for λ_{peak}=543 nm and λ_{peak}=413 nm, the strongest electric field distributes at A2 (R_{i2}=20 nm) shown in Fig.3(b) and Fig.3(d), thus the transmission mode is TE_{11} mode for A2. The wavelength shifts of four transmission peaks are $\Delta\lambda_1$=910-906=4 nm, $\Delta\lambda_2$=543-548=-5 nm, $\Delta\lambda_3$=456-489=-33 nm， $\Delta\lambda_4$=413-412=1 nm. The transmission peak positions are in keeping with the corresponding transmission peaks of simple lattice structure except λ_{peak}=456 nm. Therefore the transmission spectrum can be achieved by adding up the spectra of the corresponding simple periodic AAAs. The superposition of compound periodic AAA provides a new technology for the design of comb filter and frequency selective surface (FSS).

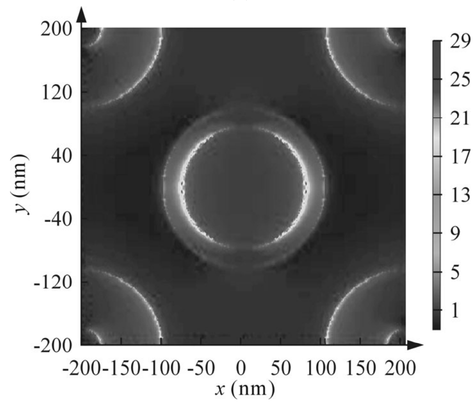
On the other hand, the transmission peak of compound periodic AAA with R_{i2}=50 nm and R_{i2}=20 nm has red shift or blue shift. Babinet principle[11] indicates that the optical property of metal hole and the corresponding same size of the metal particles are consistent. If a metal subwavelength hole has a transmission peak at wavelength A, the corresponding metal particles with the same size will also have corresponding absorption peaks at A, C and P. This theory can be used to explain red shift or blue shift in transmission spectrum of compound periodic AAA[11,12]. We consider each hole in metal subwavelength hole array structure as electric dipole. Therefore compound periodic AAA contains two couples of electric dipoles as the original cell containing two kinds of holes. For compound periodic AAA with R_{i2}=50 nm, two groups of annular's internal electric fields are in opposite directions. It means two groups of electric dipoles are in opposite polarization directions. The enhancement between two dipoles results in the coupling energy between annular waveguides of compound periodic AAA and incident light decreasing, and the coupling wavelength is red shift. On the contrary, for compound periodic AAA with R_{i2}=20 nm, two groups of annular's internal electric fields are in the same direction. It means two groups of electric dipoles are in the same polarization direction. The mutual exclusion between two dipoles results in the coupling energy increasing, and the coupling wavelength is blue shift.



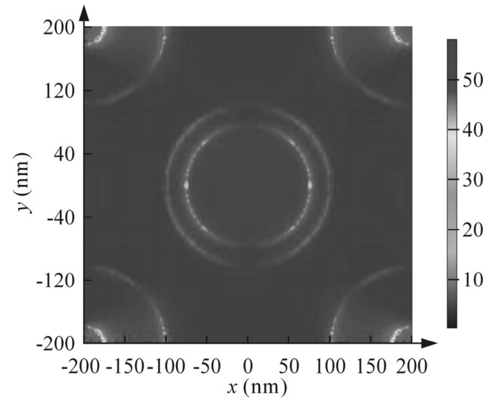
(a)



(b)



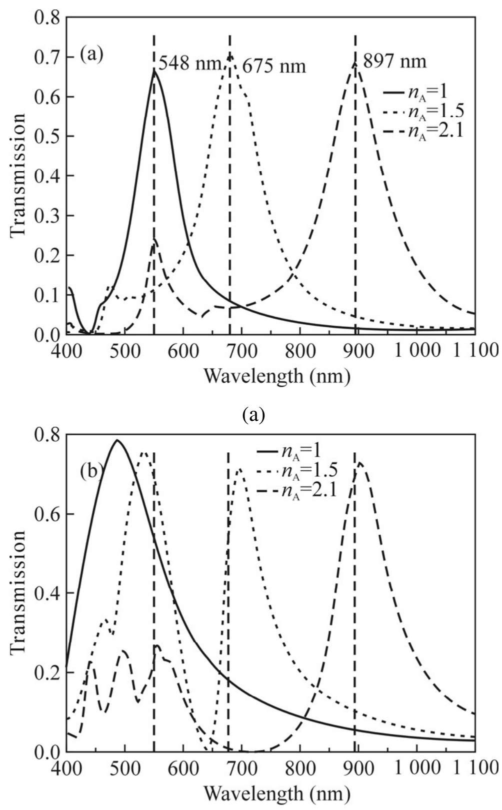
(c)



(d)

Fig.3 Distributions of electric field in *xy* plane (*z*=0, R_{i2}=75 nm) at (a) λ_{peak}=910 nm, (b) λ_{peak}=543 nm, (c) λ_{peak}=456 nm, (d) λ_{peak}=413 nm

What's more, there is another way to change the center wavelengths of the peaks, which is to alter the dielectric in the annular apertures. We research the compound periodic structures, whose primitive cell includes two annular apertures named as A1 and A2, which are filled with different dielectric materials. The optical transmissions of three compound periodic structures (ε_{d2}=1, 2.25 and 4, ε_{d2} is the dielectric constant of dielectric material filled in A2) have been studied. As shown in Fig.4(a), for the transmission of simple periodic structure (R_o=100 nm, R_i=20 nm), with the index of the dielectric increasing (n_A=1, 1.5, 2.1, $\varepsilon_A=n_A^2$), the center wavelength of the peak shifts towards long wavelength. As shown in Fig.4(b), when n_{d2}=1.5 in compound periodic AAA, there is a red shift at λ_{peak}=675 nm, and a bule shift at λ_{peak}=548 nm when n_{d2}=1. Transmission of compound periodic AAA can be achieved by adding up the spectra of the corresponding simple periodic AAAs (n_{d2}=2.1, n_{d1}=1), but at λ_{peak}=548 nm, no obvious corresponding relation is presented. It shows that the transmission spectra of above compound periodic structures are also superimposition of transmission spectra of the corresponding simple periodic structures, and the light at different peaks also would pass through the structure by different channels.

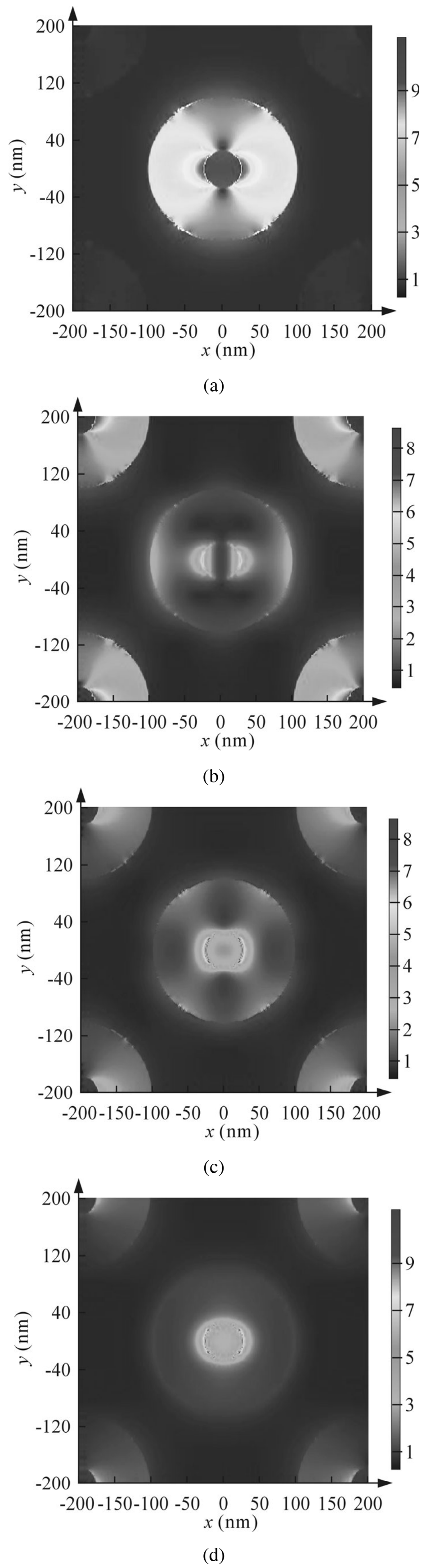


(b)

Fig.4 Transmissions of simulated structures with different dielectrics in the aperture (R_o=100 nm, R_i=20 nm): (a) Simple periodic lattice; (b) Compound periodic lattice

Fig.5 shows the electric field distributions in *xy* plane at four transmission peaks. At λ_{peak}=897 nm, the stronger electric field distributes in A1, corresponding to TE_{11} mode for A1 (Fig.5(a)). At λ_{peak}=573 nm, the stronger electric field distributes in A2, corresponding to TE_{11} mode for A2 (Fig.5(b)). Nevertheless, at λ_{peak}=500 nm and λ_{peak}=439 nm, the strong electric field exists in A1 and A2. We consider the waveguide coupling between two kinds of annular holes may cause the transmission peak.

We can explain the red shift or blue shift with aforementioned electric dipole theory when n_{d2}=1.5 and n_{d2}=1.



(d)

Fig.5 Distributions of electric field in *xy* plane (*z*=0, n_{d2}=2.1) at (a) λ_{peak}=897 nm, (b) λ_{peak}=553 nm, (c) λ_{peak}=500 nm, (d) λ_{peak}=439 nm

A large difference between the dielectric constants of two annular holes results in an excellent superposition. When the dielectric constants of two annular holes are close to each other, the strong coupling effect between electric dipoles results in red shift or blue shift of compound periodic AAA transmission spectrum, corresponding to the superposition of two simple periodic AAAs. In addition, with dielectric constant increasing, there are obvious shifts at main transmission peak and vice transmission peak. It may cause overlap of two transmission peaks. Thus waveguide mode coupling would lead to a new transmission peak. This peak is obviously changed in position and intensity, but no content with superposition.

In this paper, we show that when the difference of inner radius or dielectric constant between two apertures is large, the transmission peaks of compound periodic structure are almost at the same wavelengths with corresponding simple periodic structures. However, when the difference is small, the transmission peaks of the compound periodic structure shift to shorter or longer wavelength, and this phenomenon results from the interaction between apertures. Moreover, for each transmission peak, the light will choose corresponding apertures to pass through, by which we can separate the light with broad spectrum into two light beams with different wavelengths and locations. The compound metal subwavelength annular array structure proposed in our paper as a new type of optical structure, with good filtering characteristics, can be used for the design of selective surface or comb filter.

References

[1] Bethe H. A., Phys. Rev. **66**, 163 (1944).

[2] T. W. Ebbesen and H. J. Lezec, Nature **391**, 667 (1998).

[3] Catrysse P. B. and Fan. S., Journal of Nanophotonics **2**, 021790 (2008).

[4] Gordon R. and Brolo A. G., Laser & Photon. Rev. **4**, 311 (2010).

[5] Klein Koerkamp K. J., Enoch S. and Segerink F. B., Phys. Rev. Lett. **92**, 183901 (2004).

[6] F. I. Baida, A. Belkhir and D. Van Labeke, Physical Review B **74**, 205419 (2006).

[7] Fan W. J. and S. Zhang, Phys. Rev. Lett. **94**, 033902 (2005).

[8] Zhang Y. and M. Han, J. Appl. Phys. **112**, 013113 (2012).

[9] Baida F. I. and Van Labeke D., Appl. Phys. B **79**, 1 (2004).

[10] García de Abajo F. J., Rev. Mod. Phys. **79**, 1267 (2007).

[11] Huang C. P. and Zhang Y., J. Phys. Chem. C **115**, 24621 (2011).

[12] Zhang Y. and Han M., Appl. Phys. Lett. **112**, 013113 (2012).

[13] Yee K. S., IEEE Trans. on Antennas Propagat. **14**, 302 (1966).

[14] Taflove A. and Hagness S. C., Computational Electrodynamics: The Finite-Difference Time-Domain Method, Norwood: Artech House Publishers, 2005.

[15] Zhen F. H., Chen Z. Z. and Zhang J. Z., Microwave Theory and Techniques **48**, 1550 (2002).