Vol 18 No 12, December 2009
1674-1056/2009/18(12)/5326-05

Chinese Physics B

© 2009 Chin. Phys. Soc.
and IOP Publishing Ltd

Optimal design of sub-wavelength metal rectangular gratings for polarizing beam splitter based on effective medium theory*

Zhao Hua-Jun(赵华君)†, Peng Yong-Jun(彭拥军), Tan Ju(谭 菊)
Liao Chang-Rong(廖长荣), Li Peng(李 鹏), and Ren Xiao-Xia(任晓霞)
Department of Electronic and Electrical Engineering, Chongqing University of Arts and Sciences, Chongqing 402160, *China*

(Received 15 January 2009; revised manuscript received 22 June 2009)

A novel optimal design of sub-wavelength metal rectangular gratings for the polarizing beam splitter (PBS) is proposed. The method is based on effective medium theory and the method of designing single layer antireflection coating. The polarization performance of PBS is discussed by rigorous couple-wave analysis (RCWA) method at a wavelength of 1550 nm. The result shows that sub-wavelength metal rectangular grating is characterized by a high reflectivity, like metal films for TE polarization, and high transmissivity, like dielectric films for TM polarization. The optimal design accords well with the results simulated by RCWA method.

Keywords: polarizing beam splitter, sub-wavelength metal rectangular gratings, effective medium theory, antireflection
PACC: 4225F, 4280F, 7865

1. Introduction

Polarizing beam splitters (PBS) are essential components in optical information processing systems, such as optical fibre communication, magneto-optic data storage, polarization detection and analysis, polarization-based wave modulators, and polarization-based imaging systems, all of which require the PBS to provide a high extinction ratio over a wide angular bandwidth with maintaining high efficiency and compactness in size. Conventional PBS with using either natural crystal birefringence or polarization-sensitive multilayer structure, is usually cumbersome or sensitive to angular change, and therefore it does not fully meet those requirements. In recent years, PBS with using sub-wavelength metal rectangular gratings has been proposed.[1−7] Zhang *et al* demonstrated and fabricated a metal wire sub-wavelength grating PBS at a wavelength of 1550 nm.[2,7] In addition, they applied the effective medium theory (EMT)[2,8] to initial design and rigorous couple-wave analysis (RCWA)[9,10] in order to optimize the PBS, and the designed PBS has a uniform performance in a wide angle range of $\pm 25^{\circ}$.[2] The development of sub-wavelength metal rectangular grating PBS is an important step towards the miniaturization and the integration of bulky optical systems, which are still mostly based on the assembly of discrete optical devices.

Sub-wavelength metal rectangular gratings usually behave as slabs of artificial uniaxial material with optical axes parallel to the direction of periodicity, and the indices of refraction depend on the geometry of the grating.[3] It has been shown that when the period Λ of a periodic layered structure is sufficiently small compared with the wavelength λ ($\Lambda \ll \lambda$), the whole grating layered structure behaves as if it were a homogeneous and uniaxial birefringent medium, which can be described by a set of effective indices of refraction.[10] The effective refractive indices of the grating depend on the polarization and the relative filling factor of materials that constitute the periodic layered medium.[11] Scalar diffraction theory is not applicable to the cases of sub-wavelength structures, and thus either rigorous electromagnetic grating analysis tools, or EMT should be used, the later is more efficient (by orders of magnitude) in computation than rigorous electromagnetic grating analysis approaches.[12,13] As the sub-wavelength gratings can be treat as uniform uniaxial crystal films, EMT along with single layer antireflection coating[14] can be used to make an optimal design of sub-wavelength metal rectangular gratings PBS. In the present paper, we use the method of EMT and the single layer antireflection coating to design a sub-

*Project supported by Science Foundation of the Chongqing Committee of Education, China (Grant No KJ071205).
†Corresponding author. E-mail: zhaohjcu@163.com

wavelength metal rectangular grating PBS optimized for a wavelength of 1550 nm. The polarization performance of sub-wavelength metal rectangular gratings is discussed by RCWA method.

2. Modal analysis of sub-wavelength metal rectangular gratings

The problem of general sub-wavelength metal rectangular grating diffraction is depicted in Fig.1. A plane wave with free-space wavelength λ is incident on the grating surface at incident angle θ. The main objective of diffraction grating analysis is to determine the complex amplitudes of the plane wave spectrum diffracted by a grating under plane wave irradiation. The method to determine the complex amplitudes of the diffracted orders depends on the ratio of free space wavelength to grating period, λ/Λ. In the sub-wavelength domain, where $\Lambda \ll \lambda$, it is possible to use the EMT approach to represent sub-wavelength grating for both analysis and design. The sub-wavelength periodic structure behaves as a uniaxial crystal with the optical axes parallel and perpendicular to the grooves. When the grating period is $\Lambda_{\rm th} = \lambda/n_2$, the Rayleigh–Wood anomalies will occur.[13] When the incident wavelength $\lambda = 1550$ nm, $n_2 = 1.45$ (fused-silica), we obtain Rayleigh–Wood anomaly period $\Lambda_{\rm th} = 1069$ nm. If the grating period Λ is less than 1069 nm, i.e. $\Lambda < 1069$ nm, for the diffraction grating, only zero-order diffraction is propagating order; if the grating period is $\Lambda > 1069$ nm, the ± 1 order and above will also be gradually carried into the propagating orders.

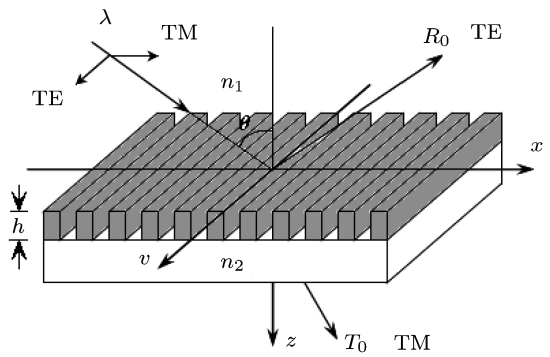


Fig.1. Geometry of the sub-wavelength metal rectangular grating PBS, which cuts off all diffracted orders, leaving only the zero orders with complex amplitudes R_0 (TE polarization) and T_0 (TM polarization) to propagate.

3. Optimal design of sub-wavelength metal rectangular grating PBS

When an electromagnetic wave is incident on metal surface, free electrons on the metal will be excited by the electric field and the excited electrons will provide electromagnetic field oscillating at certain frequency. Different polarization directions of electromagnetic wave make electrons oscillate in different directions, resulting in different transmissivity. In reality, sub-wavelength metal grating is only discontinuous with respect to the perpendicular electric field (TM polarization); therefore currents can still freely move vertically along the strips when induced by the parallel field (TE polarization). A plane wave polarized in the direction parallel to the metal wires will exhibit high reflection because the electric field continues along the grating wires, and most of the light polarized in the direction perpendicular to the wires is transmitted.[15,16] For sub-wavelength gratings, the grating periods are much smaller than the wavelength of incident light, birefringence will occur, because the effective indices exhibited in these structures are different from the TE polarization and TM polarization incidences. The values of the effective indices $n_{||}$ and $n_\perp$ for TE and TM polarization incidences can be calculated by EMT. According to EMT, TE polarization vector parallel to the grating lines can be treated as ordinary waves, and TM polarization vector perpendicular to the grating groove can be treated as extraordinary waves. The effective refractive indices for the parallel and the perpendicular polarizations are given by[2,8]

$$n_{||} = \sqrt{f n_{\rm r}^2 + (1-f) n_{\rm g}^2}, \tag{1}$$

$$n_\perp = \frac{1}{\sqrt{f n_{\rm r}^{-2} + (1-f) n_{\rm g}^{-2}}}, \tag{2}$$

where f is the filling factor (defined as the ratio of ridge width to period Λ), $n_{\rm r}$ is the refractive index of grating ridge, and $n_{\rm g}$ is the refractive index of the grating groove. From expressions (1) and (2) we can see that by adjusting the filling factor any effective refractive index on grating layer can be obtained.

For sub-wavelength metal rectangular gratings, the grating ridges are metal layers which have a complex index of refraction $n_{\rm r}$ with a real part $n'_{\rm r}$ and an imaginary part $k'_{\rm r}$. Inserting metal complex index into expressions (1) and (2), we can obtain the effective

refractive indices of TE polarization and TM polarization. Optical properties of the device depicted in Fig.1 are revealed by calculating the effective refractive indices of the grating layer (Al) with an incident wavelength of 1550 nm. Figure 2 shows the calculated effective indices $n_{\parallel}$ and $n_{\perp}$, each as a function of filling factor. For the TE polarization, the effective index $n_{\parallel}$ has a large imaginary part $k'_{||}$, so the grating layer can be equivalent to a metal film with high reflectivity. For the TM polarization, the imaginary part $k'_{\perp}$ of $n_{\perp}$ is kept mostly near zero as shown in Fig.2. In this case, the gratings act as a dielectric film with a small transmission loss. Any desired effective refractive index of sub-wavelength metal rectangular gratings can be produced by changing the filling factor, which makes possible the design of an artificial layer of anisotropic material with effective refractive index over a wide range of values between those of the grating groove and grating ridge materials.

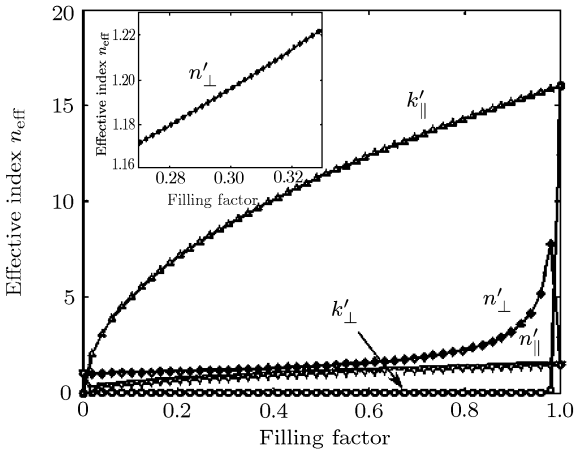


Fig.2. Calculated real and imaginary parts of the effective indices of refraction versus filling factor for $n_{\rm r} = 1.44+16{\rm i}$ (Al at $\lambda = 1550$ nm): $n_{||} = n'_{||} + k'_{\perp}$ i electric field parallel to the grating lines; $n_{\perp} = n'_{\perp} + k'_{\perp}$ i electric field perpendicular to the grating lines.

The goal of designing a polarization selective device is to maximize the reflected efficiency for TE polarization while at the same time to minimize the reflected efficiency for TM polarization. According to the method of designing single layer antireflection coating,[14] the films have the maximium transmission efficiencies at of normal incidence angle, when the coating refractive index is equivalent to the effective refractive index of grating layer for TM polarization, namely $n = \sqrt{n_1 n_2}$, where n_1 and n_2 are the refractive index of cover and substrate regions, respectively, and at the same time satisfies the optical grating layer thickness as given by

$$nh = \lambda/4, \tag{3}$$

where h is the thickness of coating, which is equivalent to the grating groove depth. For $\lambda = 1550$ nm, $n_1 = 1.0$ and $n_2 = 1.45$, from $n = \sqrt{n_1 n_2}$, the required coating refractive index n can be calculated to be 1.2, i.e. $n = 1.2$. According to expression 3), the thickness of grating groove depth h can be obtained to be 322 nm, i.e. $h = 322$ nm. When $n'_{\perp} = n = 1.2$, the filling factor is $f \approx 0.3$ as shown in Fig.3, where the maximium TM polarization transmission efficiencies can be obtained. In addition, in order to obtain stable diffraction efficiencies, the grating period must be consistent with the conditions of sub-wavelength ($\Lambda \ll \lambda$). The grating period is taken to be $\Lambda = 150$ nm for the incident wavelength 1550 nm. The optimal design parameters of aluminum metal sub-wavelength metal rectangular gratings PBS are $\Lambda = 150$ nm, $h = 322$ nm, and $f = 0.3$.

4. Numerical analysis

Polarizing beam splitter usually requires large acceptable angle wide spectrum, high extinction ratio, and low insertion loss for both reflection and transmission waves.[13] The polarization properties of PBS based on sub-wavelength metal rectangular gratings are analysed by the RCWA method at a wavelength of 1550 nm. By calculating the grating transmission efficiencies ($T_{\rm te}$, $T_{\rm tm}$) and reflectivity efficiencies ($R_{\rm te}$, $R_{\rm tm}$) of TE polarized and TM polarized fields, we can calculate the following parameters: transmission extinction ratio $T_{\rm ext} = 10\lg(T_{\rm tm}/T_{\rm te})$, reflection extinction ratio $R_{\rm ext} = 10\lg(R_{\rm te}/R_{\rm tm})$, transmission insertion loss $T_{\rm loss} = 10\lg(1/T_{\rm tm})$ and reflecting insertion loss $R_{\rm loss} = 10\lg(1/R_{\rm te})$.

For optimal grating parameters, the curves for diffraction properties of order 0 versus incident angle for the orthogonal directions of polarization (TE and TM) are shown in Fig.3. When the incident angle θ is less than 28°, zero-order diffraction efficiencies for TE reflection and TM transmission can be greater than 96.3% and 97.5% respectively, as shown in Fig.3(a), while at the same time the TE transmission and TM reflection are both close to zero. Extinction ratios are better than 64 dB and 25 dB for transmission and reflection waves, and insertion losses are less than 0.13 dB and 0.16 dB as shown in Figs.3(b) and 3(c) respectively. It is shown that PBS can keep high diffraction efficiencies at incident angles in a wide range.

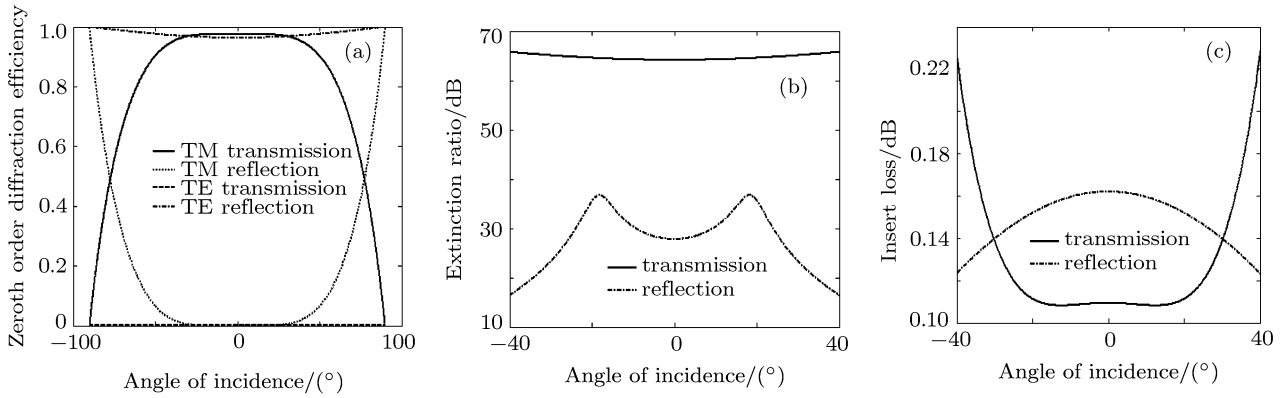


Fig.3. Dependences of diffraction properties of sub-wavelength metal rectangular gratings on incidence angle for both orthogonal polarizations (TE and TM). The grating filling factor is $f = 0.3$, the grating period is 150 nm, the grating depth is 322 nm, the incident wavelength is $\lambda = 1550$ nm. Panel (a) shows 0-th order diffraction efficiencies, panel (b) displays extinction ratio, and panel (c) exhibits insert loss.

The curves for zero-order diffraction efficiency versus grating period for both orthogonal polarizations are shown in Fig.4. The diffraction efficiencies keep relatively stable in the area of sub-wavelength regions ($\Lambda < 200$ nm). With the increase of grating period, the diffraction grating enters into relatively unstable resonance domain, and the zero-order diffraction efficiencies shows drastic fluctuations as shown in Fig.4. When the period Λ is 1069 nm, i.e. $\Lambda = 1069$ nm, the diffraction efficiencies can suddenly change, which is the Rayleigh anomaly. The result of Rayeigh anomaly period simulated by RCWA method is just the same as the previous result.

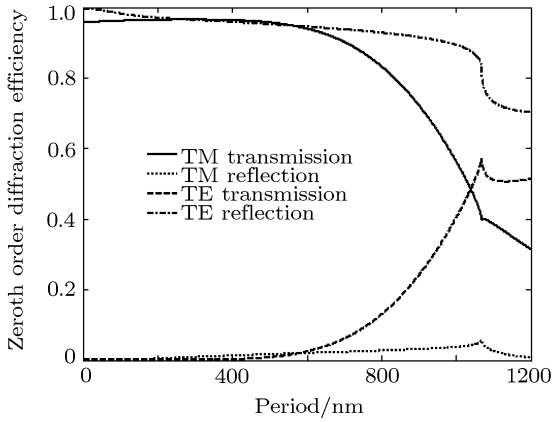


Fig.4. Curves for zero-order diffraction efficiency versus grating period for both orthogonal polarizations. The grating filling factor is $f = 0.3$, the grating depth is $h = 322$ nm, and the incident wavelength is $\lambda = 1550$ nm.

Figure 5 shows the effects of grating depth h on polarization-dependent transmittance for both orthogonal polarizations. As can be seen, for TE polarization, reflection for radiation polarized in the direction parallel to the grating lines increases exponentially with film thickness h. However, for the TM polarization, the effective refractive index of the grating layer has very small imaginary part $k'_{\perp}$, and the film is only slightly metallic, the transmission for radiation polarized in the direction perpendicular to the grating lines is kept at high diffraction efficiency with the film thickness h. If the film is non-absorbing ($k'_{\perp} = 0$) to the TM polarization, the zero-order diffraction efficiency of TM transmission will be a periodic function of grating height h. The presence of small $k'_{\perp}$ in $n_{\perp}$ reduces the amplitude of the successive maxima and gives rise to a displacement of the maxima toward smaller film thickness. When the groove depth is $h = 322$ nm, grating layer behaves like a dielectric film

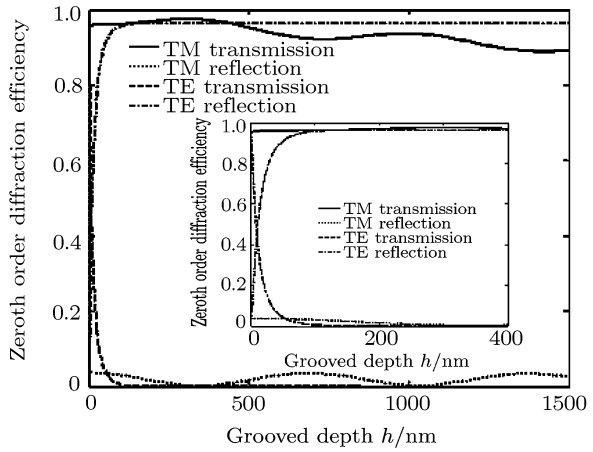


Fig.5. Dependences of zero-order diffraction efficiency on grating depth for both orthogonal polarizations. The grating filling factor is $f = 0.3$, the grating period is 150 nm, and the incident wavelength is $\lambda = 1550$ nm.

for TM-polarization and meets the optimal conditions for transmission because of single layer antireflection

coating. The TM polarization has a perfect zero-order transmission efficiency (greater than 97.5%).

Figure 6 shows the curves for zero-order diffraction characteristic of the grating versus incident wavelength, in which we have neglected the changes of refractive index. The incident wavelength in a range from 1200 to 1800 nm, i.e. 1200 nm$< \lambda <$ 1800 nm, zero-order diffraction efficiencies for both TE reflection and TM transmission are greater than 96% as shown in Fig.6(a). Extinction ratios are better than 61 dB and 23 dB for transmission and reflection waves and insertion loss are both less than 0.16 dB as shown in Figs.6(b) and 6(c), respectively. It is shown that the sub-wavelength metal rectangular gratings have a high polarization splitting capacity in a wide range of the incident angle and incident wavelength.

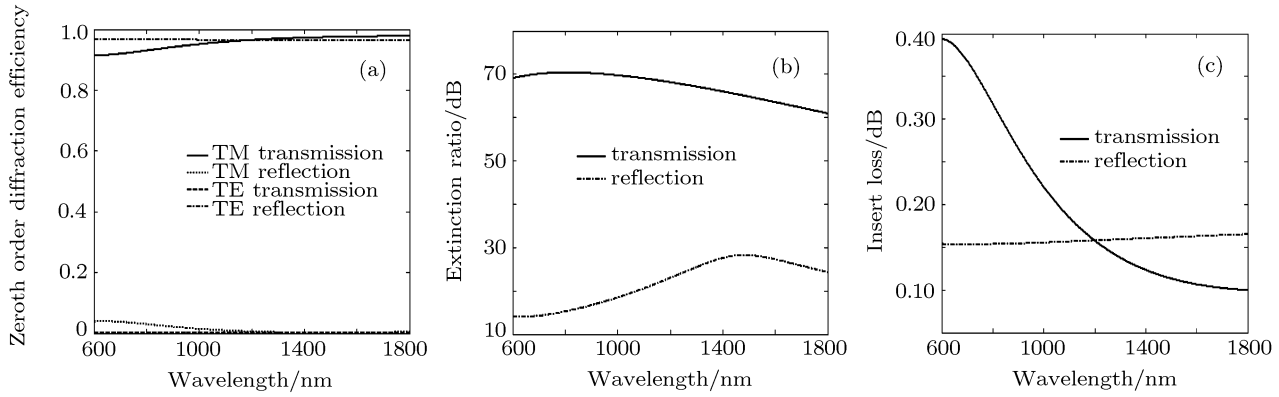


Fig.6. Dependences of diffraction characteristics of sub-wavelength metal rectangular gratings on incidence wavelength for both orthogonal polarizations (TE and TM). The grating filling factor is $f = 0.3$, the grating period is 150 nm, the grating depth is 322 nm, the incident wavelength is $\lambda = 1550$ nm. Panel (a) is for 0-th order diffraction efficiencies, panel (b) for extinction ratio, and panel (c) for insert loss.

5. Conclusions

In the present paper we show a unique method for designing a PBS composed of sub-wavelength metal rectangular gratings, which is based on EMT and the method of designing single layer antireflection coating. The polarization properties of gratings are analysed by the RCWA method at a wavelength of 1550 nm. The results show that optimal design and the method of RCWA for PBS are in good agreement with each other. Furthermore, it is shown that the PBS exhibits a high polarization extinction ratio and low insertion loss over a wide incident angle range ($-28° < \theta < 28°$) for both the reflected and the transmitted beams.

Acknowledgement

The authors are grateful to Dr. Lu Dan (Key Laboratory of Information Photonics and Optical Communications, Ministry of Education, Beijing University of Posts and Telecommunications) for their valuable discussions.

References

[1] Bomzon Z, Kleiner V and Hasman E 2001 *Opt. Commun.* **192** 169
[2] Zhang L, Li J, Li C F and Zhang F 2006 *Chin. Phys. Lett.* **23** 1820
[3] Davis J A and Jingo A 2001 *Opt. Lett.* **26** 587
[4] Liu M M, Zhang G P and Zou M 2006 *Acta Phys. Sin.* **55** 4608 (in Chinese)
[5] Wang D, Liu W, Xiao Q and Shi J 2008 *Appl. Opt.* **47** 312
[6] Zhou L and Liu W 2005 *Opt. Lett.* **30** 1434
[7] Zhang L, Li C F, Liu W, Zhou L B, Wen G Y and Wang D L 2006 *Acta Opt. Sin.* **26** 1048 (in Chinese)
[8] Paul K, Zhu E C, Love J C and Whitesides G M 2001 *Appl. Opt.* **40** 4557
[9] Moharam M G, Pommet D A, Grann E B and Gaylord T K 1995 *J. Opt. Soc. Am.* A **12** 1077
[10] Li L 1996 *J. Opt. Soc. Am.* A **13** 1870
[11] Yeh P, Yariv A and Hong C S 1977 *J. Opt. Soc. Am.* **67** 423
[12] Lou J, Fu S J, Xu X D and He S P 2006 *Acta Phys. Sin.* **55** 6405 (in Chinese)
[13] Honkanen M, Kettunen V and Kuittinen M 1999 *Appl. Phys.* B **68** 81
[14] Hantehzadeh M R, Ghoranneviss M, Sari A H, Shokuhi A and Shariati M 2006 *Thin Solid Films* **515** 547
[15] Ebbesen T W, Lezec H J Ghaemi H F Thio T and Wolff P A 1998 *Nature* **391** 667
[16] Ma J Y, Xu C, Liu S J, Zhang D W, Jin Y X, Fan Z X and Shao J D 2009 *Chin. Phys.* B **18** 1029