doi:10.3788/gzxb20144301.0105002

# 高效全偏振矩形闪耀光栅的设计

赵华君[a],吴强[b],任晓霞[b]

(重庆文理学院 a. 机电工程学院;b. 电子电气工程学院,重庆 402160)

**摘 要**:入射光在光栅内传输时将激发产生离散模. 本文采用模态法调节光栅内离散模的传输特性,使TE和TM偏振光所激发的0、1模为传输模,其余高阶模为消逝模. 通过调控0模和1模间的累积相位差,对衍射光进行调控,实现了−1级近100%的高效衍射. 采用模态法分三部设计了共振域的矩形全偏振闪耀光栅:1)根据光栅的共振条件给出光栅周期,光栅周期越大槽深越小;2)根据特征模方程计算出光栅占空比;3)根据耦合模条件计算机光栅槽深. 实验结果表明,该光栅的TE和TM偏振光同时具备近100%的−1级衍射效率. 给出了633 nm波长−1级矩形石英全偏振闪耀光栅的典型设计实例,计算结果表明:所设计的全偏振闪耀光栅对TE和TM偏振入射光的−1级衍射效率分别高达96.7%和98.1%,且具有较宽的入射角及入射波长的变化适应范围,较大的制作容差.

**关键词**:闪耀光栅;全偏振;矩形槽;模态法;−1级

**中图分类号**:O436 **文献标识码**:A **文章编号**:1004-4213(2014)01-0105002-6

# Design of High-efficiency Full Polarization Blazed Gratings with Rectangular Groove

ZHAO Hua-jun[a], WU Qiang[b], REN Xiao-xia[b]

(a. *College of Mechanical and Electronic Engineering*; b. *College of Electronic and Electrical Engineering*, *Chongqing University of Arts and Sciences*, *Chongqing*, 402160 *China*)

**Abstract**: A plan wave incident upon the grating will excite discrete modes. The modes with $n_{\mathrm{eff}}^2>0$ can propagate through the gratings, while those with $n_{\mathrm{eff}}^2<0$ are evanescent modes. The basic idea behind the simplified modal investigation is the excitation and coupling of the propagating modes in gratings. If an odd number multiple phase difference is accumulated for the first two propagating modes, the incident light will be diffracted into the $-1^{\mathrm{st}}$ order with nearly 100 % diffraction efficiency. A highly efficient full polarization blazed grating with rectangular groove was designed theoretically by modal method in the resonance domain. The design procedure of the full polarization rectangular blazed grating could be divided into three steps. Step 1: present the grating period in the resonance domain. Step 2: present fill factor by the eigenvalue functions of the grating. Step 3: present groove depth based on the phase difference of the propagating modes. As an example, the design of the fused silica full polarization rectangular blazed grating was demonstrated for the wavelength of 633 nm, which has about 96.7% and 98.1% negative first-order diffraction efficiency for TE and TM polarizations, respectively. The full polarization blazed grating with fused silica has a wide-band incident angles and incident wavelengths, which especially has high fabrication tolerances.

**Key words**: Blazed gratings; Full polarization; Rectangular groove; Modal method; $-1^{\mathrm{st}}$ order

**OCIS Codes**: 050.2770; 050.1950; 260.5430; 310.5448;

**Foundation item**: The Natural Science Foundation Project of CQ China (CSTC, 2010BB2352) and Chongqing Committee of Education Foundation of China (No. KJ121224)

**First author**: ZHAO Hua-jun (1974−), male, professor, M. S. degree, mainly focuses on diffraction optics. Email: Zhaohjcu@163.com

**Responsible author (Corresponding author)**: WU Qiang (1965−), male, professor, M. S. degree, mainly focuses on film optics and diffraction optics. Email: wuqiang2072@163.com

**Received**: May. 16, 2013; **Accepted**: Jul. 2, 2013

## 0 Introduction

Blazed gratings can highly efficient redirected the incoming light into one diffraction order, which play a significant role in modern optics for their using at the foundation of fields such as spectroscopy and diffractive optics. Usually, the profile of the classical blazed grating is the typical triangular sawtooth shape (i. e. mechanically ruled gratings). With the progress of the grating fabrication technologies, the conventional ruled gratings were gradually replaced by multilevel diffraction gratings[1]. In recent years, researches have shown that rectangular dielectric gratings in the resonance domain exhibit excellent polarizing property[2,3]. The fabrication of the rectangular-groove dielectric surface-relief gratings is easier than multilevel gratings with similar periods. Most importantly, the dielectric gratings have a high laser damage threshold, which make them have many applications in high-power lasers setup[4].

Since the rectangular grating in the resonance domain is a diffraction device, they can redirect highly efficient diffraction into the dispersive $-1^{st}$ order[3]. However, the groove depths of the rectangular blazed grating for TE- and TM-polarizations (*i. e.* full polarization) usually reach up to about several microns[5]. Although the fabrication deeps seem to be fairly large, it is still difficult to fabricate a grating with such deep grooves in dielectric, such as fused silica. For many applications the incident light is not linearly polarized so the $-1^{st}$ order diffraction has to be done for both polarization states. The aim of this paper is to design theoretically a rectangular full polarization blazed gratings with shallow groove by the modal method[2,3,6-8] in the resonance domain. For validation, numerical calculations using the rigorous coupled wave analysis (RCWA) method[9-10] will be given additionally.

## 1 Modal analyses and design of the full polarization blazed grating

Assuming the geometry of the rectangular full polarization gratings is shown in Fig. 1, where $n_1$ and $n_2$ is the refractive index of the air and the substrate dielectric material, respectively. A plane wave with both polarization states incidents on the grating at Littrow mounting $\theta = \arcsin(\lambda / 2\Lambda)$, where $\Lambda$ is the grating period, $\lambda$ is the wavelength of incident plane wave in air.

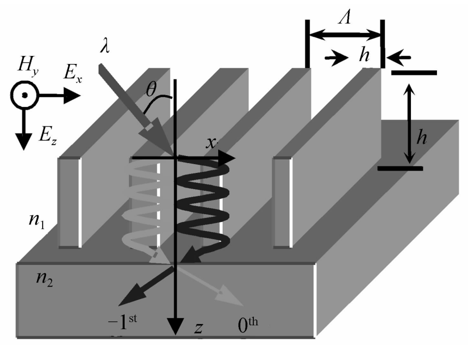



Fig. 1 Geometry of the full polarization blazed grating with rectangular groove

In the resonance domain, the grating period $\Lambda$ is decided by

$$\frac{\lambda}{2} < \Lambda < \frac{3\lambda}{2n_2} \tag{1}$$

Thus, the grating diffraction orders only include the $-1^{st}$ and $0^{th}$ order with Littrow mounting[3]. In this condition, there have two propagating modes (i. e. modes 1 and 0) for each polarization in the grating. The basic idea behind the simplified modal method is the excitation and transmission of the propagating modes. From the field continuity conditions of the boundaries between the ridges and grooves of the grating, the eigenvalue equation can be derived by $\cos(\alpha\Lambda) = F(n_{\mathrm{eff}}^2)$[8], where $F(n_{\mathrm{eff}}^2)$ is the eigenvalue function propagating in the grating. For TE and TM polarization, the eigenvalue functions are respectively defined by

$$F(n_{\mathrm{eff}}^2) = \cos(\beta b)\cos(\gamma g) - \frac{\beta^2+\gamma^2}{2\beta\gamma}\sin(\beta b)\cdot \sin(\gamma g) \tag{2a}$$

$$F(n_{\mathrm{eff}}^2) = \cos(\beta b)\cos(\gamma g) - \frac{n_1\beta^2+n_2\gamma^2}{2n_1 n_2\beta\gamma}\cdot \sin(\beta b)\sin(\gamma g) \tag{2b}$$

where $\alpha = k_0 \sin\theta$, $\beta = k_0\sqrt{1-n_{\mathrm{eff}}^2}$, $\gamma = k_0\sqrt{1-n_{\mathrm{eff}}^2}$ and $k_0 = 2\pi/\lambda$, $n_{\mathrm{eff}}$ is the effective indices for the discrete modes, $b$ and $g$ are the ridge and groove widths, respectively.

A plan wave incident upon the grating will excite discrete modes comparable to the simple case of a slab waveguide[11]. The modes with $n_{\mathrm{eff}}^2 > 0$ can propagate through the gratings, while those with $n_{\mathrm{eff}}^2 < 0$ are evanescent modes, since their effective refractive index $n_{\mathrm{eff}}$ is imaginary. The left part of the eigenvalue equation represents the incidence conditions, where $\cos(\alpha\Lambda) = -1$ is under Littrow mounting incidence. The eigenvalue function $F(n_{\mathrm{eff}}^2)$ depends on grating period, fill factor $f$ and the refractive index of the dielectric material. Since the grating is illuminated under Littrow mounting, the intersection of the illustrated functions $F(n_{\mathrm{eff}}^2)$ with $\cos(\alpha\Lambda) = -1$ gives the effective indices of all modes that might be excited by the incident wave. In the resonance domain, there are only modes 0 and 1 with real effective indices propagating along the grating grooves and ridges in the $z$ direction.

In the resonance domain, the rectangular gratings exhibit much interesting effects such as high diffraction efficiency[12], high laser damage threshold[4], and high extinction ratio[13]. The modal method offers a simple physical understanding of the interference phenomena taking place in the grating, which is a very effective method for grating design[14-15]. The design procedure of the full polarization rectangular blazed grating can be divided into three steps by modal method. Step 1: Present the grating period. Step 2: Present fill factor. Step 3: Present groove depth.

For the grating period fulfils Eq. (1), the incident wave will be excited only two propagating modes with Littrow mounting, as shown in Fig. 2.

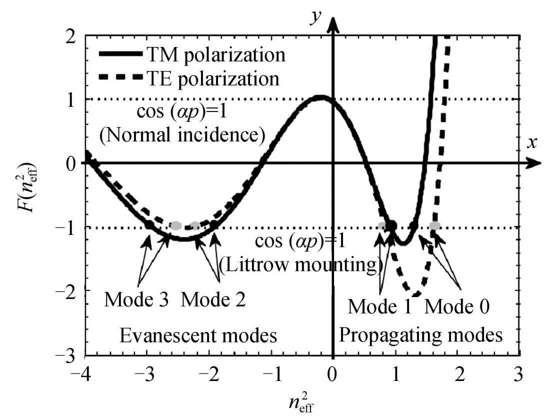



Fig. 2 Eigenvalue $F(n^2_{eff})$ of the modes as a function of $n^2_{eff}$ with $f=0.5$, $n_1=1$, $n_2=1.5$, $p=800$ nm, $\lambda=1.064$ $\mu$m by modal method for both polarizations

This diffraction process is very similar to Mach-Zehnder interferometer. In this condition, the modes 0 and 1 forward and backward traveling propagating constructively and destructively interfere with one another for different grating depths, thus leading to variety diffraction efficiency of the $-1^{st}$ and $0^{th}$ orders for both polarizations at a proper grating thickness. In fact, the output intensity of the diffraction orders from the grating is determined by the phase difference accumulated by the two propagating modes while transmitting along the grating ridges and grooves in the $z$ direction. If the phase difference is zero or even multiple of $\pi$, the incident wave is almost 100% transmitted to the $0^{th}$ order. Conversely, the diffraction of the $-1^{st}$ order is about 100 %, if the phase difference is an odd multiple of $\pi$. That is

$$\Delta\varphi=\frac{2\pi}{\lambda}\Delta n_{eff}h=(2m-1)\pi,\ m=1,\ 2,\ 3\ \cdots \qquad (3)$$

where $h$ is the grating groove depth, $\Delta n_{eff}$ is the effective indices difference of the modes 0 and 1, defined by $\Delta n_{eff}=|n^0_{eff}-n^1_{eff}|$. The phase difference of the first two propagating modes is determined by the effective indices difference and the groove depth. The modes 0 and 1 have different effective indices for TE/TM polarization, which will accumulate a phase difference transmitting through the grating. The phase difference of an odd multiple $\pi$ transmitting through the grating must be accumulated for full polarization blazed grating. Under some special conditions, the effective indices difference is almost the same for both polarizations. There the phase difference is nearly equal for TE- or TM-polarization transmitting through the grating. It can be used to design a full polarization blazed grating. In this condition, the fill factor and the effective indices difference of the blazed grating can be obtained.

According to Eq. (3), the groove depth of the full polarization blazed grating for both polarizations can be obtained by

$$h=\frac{\lambda}{2*\Delta n_{eff}}(2m-1),\ m=1,\ 2,\ 3\ \cdots \qquad (4)$$

However, the effective indices difference is usually small. This means a large grating groove depth for design of the full polarization blazed grating. It is noteworthy that with the periods increasing the groove depth of the full polarization blazed grating can be reduced. However, the grating periods must be in the range defined by the Eq. (1). The maximal period is $p_{max}=3\lambda/2n_2$. Therefore, we should choose a large grating period in above condition for design of the full polarization blazed grating.

Fig. 3 shows the grating depths as a function of the periods with a phase difference of $\pi$ for both polarizations using modal method . The depth and

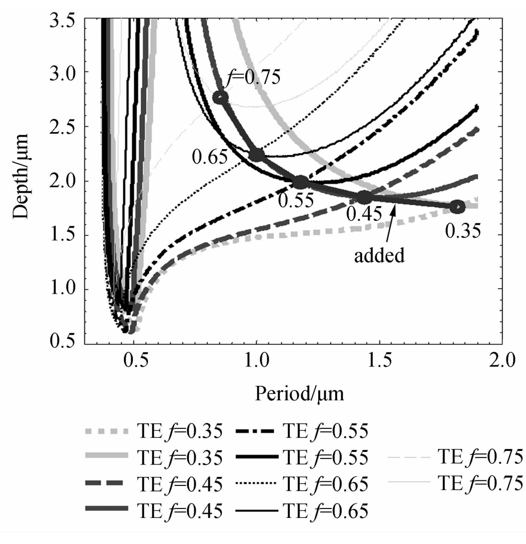



Fig. 3 Grating depths as a function of the periods for phase difference $\pi$ (i. e. the $-1^{st}$ order transmitted diffraction blazed grating for both polarizations) with $n_2=1.5$ and $\lambda=1.064$ $\mu$m for both polarizations, where the fill factor of the grating is varied between 0.35, 0.45, 0.55, 0.65, and 0.75. Inset added curve: Intersections of the curves for both polarizations with vary fill factor

period of the −1st order transmitted diffraction blazed grating can be determined by the intersections of the curves for both polarizations. The intersections of these curves represent the grating profile parameters, which can achieve nearly 100% diffraction efficiency for −1st transmitted order with a phase difference of π for TE- and TM-polarization, respectively. As grating fill factors reducing, the periods are increased (see inset added curve in Fig. 3). Specially, the increase of the grating period will reduce the grating depth as shown in Fig. 3. And the incident angle will reduce with the period from Eq. (1), which means the Fresnel-reflection decreasing at the grating interface.

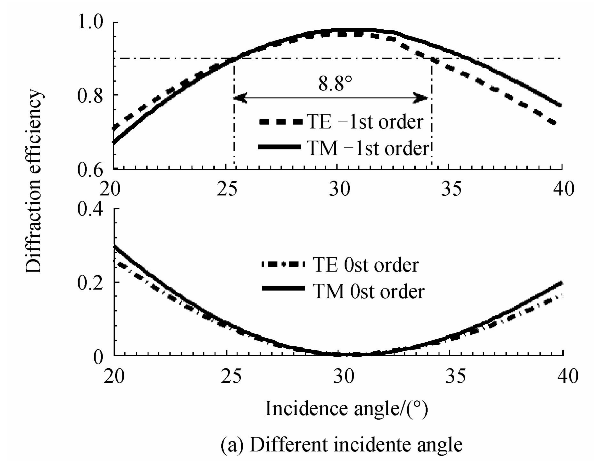
## 2 Example for design of the full polarization blazed grating

In the previous section, we discussed the design of the full polarization blazed grating by modal method. It is shown that the $-1^{st}$ transmitted order has highly diffraction efficiency for both polarizations with a phase difference of π accumulated transmitting through the grating. As an example, the full polarization blazed grating is designed using modal method with the incident wavelengths of 633 nm. The geometry parameters of the grating are listed in Table 1. Assuming the substrate dielectric is the fused-silica ($n_2=1.5$). The diffraction efficiency and polarization extinction ratio of the full polarization blazed gratings are calculated by RCWA method.

**Table 1 The grating parameters of the full polarization blazed grating by modal method**

| Wavelength/nm | Depth/μm | Period/nm | Filling | θ/(°) |
|---|---|---|---|---|
| 633 | 1.277 | 620 | 0.622 3 | 30.696 1 |

In practice, the angle and the wavelength of incidence are not always fixed for full polarization blazed grating. So the diffraction efficiencies with the varying incident angles and wavelengths should be considered. Fig. 4 shows the diffraction efficiencies of the $-1^{st}$ and $0^{th}$ order dependence on the incident



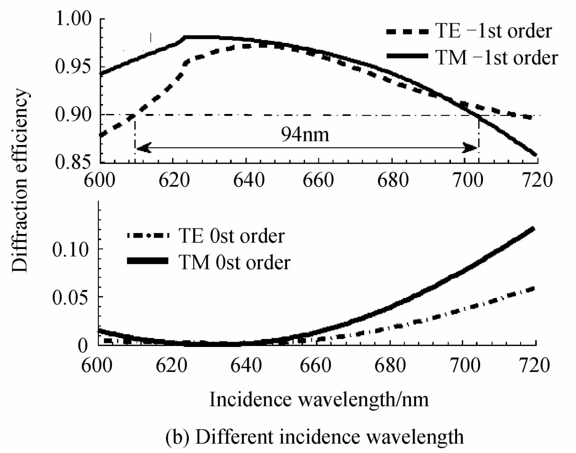




Fig. 4 Diffraction efficiencies of the full polarization blazed grating for different incidence conditions with the grating parameters of the table 1

conditions for TM and TE polarization, respectively. For grating parameters as table 1, the diffraction efficiencies of the $-1^{st}$ order are better than 90% in both polarizations for incident angle ranging from $25.4° < \theta < 34.2°$, which corresponds to a ±4.4° tolerance for both polarizations, as shown in Fig. 4(a). Meanwhile, the $0^{th}$ order diffraction efficiency of the grating is less than 7.5%, and the minimum value is less than 0.17% in this range of incident angles. Furthermore the divergence of the incident wavelength is 94 nm, where the diffraction efficiencies are better than 90% in both polarizations. Accordingly the $0^{th}$ order diffraction efficiency of the grating is less than 8.5% as shown in Fig. 4(b).

The fabrication tolerances should be as large as possible for grating. The diffraction efficiencies for over 90% are illustrated between the two level dashed red lines areas, as shown in Fig. 5. We note that the diffraction efficiency of the $-1^{st}$ and $0^{th}$ transmitted order varies nearly between 0% and 100% for coupling between the two propagating modes as a function of the groove depth. The transmitted diffraction efficiencies of the $-1^{st}$ order reach the maximum at the grating geometrical parameters listed in table 1, where a phase difference of π is accumulated for both polarizations. In contrast, the $0^{th}$ transmitted order for both polarizations is nearly zero, because the energy is mostly coupled into $-1^{st}$ order. If the depth varies between 1.12 μm and 1.52 μm with the grating profile parameters of the table 1, the efficiencies are better than 90% can be achieved, as shown in Fig. 5(a). The groove has ±0.2 μm tolerance for both polarizations. Furthermore, the periods and the filling factors have ±49 nm and 0.067 tolerances for the fabrication on both polarizations, as shown in Fig. 5(b) and (c).

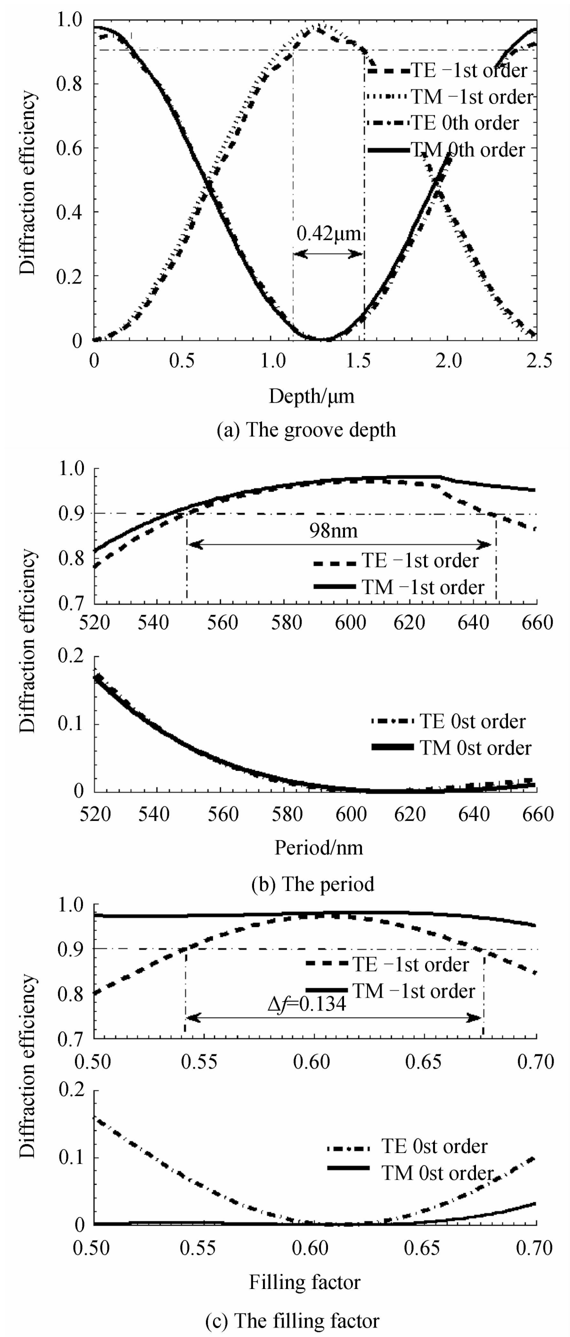



Fig. 5 The fabrication tolerances of the full polarization blazed grating with the grating parameters of the table 1

Table 2 presents the grating groove depths, diffraction efficiencies and polarization extinction ratios of the blazed grating calculated by RCWA method with the grating parameters of the table 1. The polarization extinction ratio of the TE- and TM-polarization can be defined by $EX_{\mathrm{TE}} = 10\lg\eta_{-1}^{\mathrm{TE}}/\eta_0^{\mathrm{TE}}$ and $EX_{\mathrm{TM}} = 10\lg\eta_{-1}^{\mathrm{TM}}/\eta_0^{\mathrm{TM}}$, respectively. There the $\eta_0^{\mathrm{TM}}(\eta_{-1}^{\mathrm{TM}})$ and $\eta_0^{\mathrm{TE}}(\eta_{-1}^{\mathrm{TE}})$ is the diffraction efficiency for TE and TM polarization, respectively. As shows in Table 2, the grating depths calculated by RCWA are in good agreement with the results by modal method. In particular, with wavelength of 633 nm the $-1^{\mathrm{st}}$ transmitted order

**Table 2 The groove depths, diffraction efficiencies and polarization extinction ratios of the full polarization blazed grating based on RCWA with the grating parameters excepting depths of the table 1**

| $\lambda$/nm | Depth/ $\mu$m | $\eta_{-1}^{\mathrm{TE}}$/% | $\eta_{-1}^{\mathrm{TM}}$/% | $\eta_0^{\mathrm{TE}}$/% | $\eta_0^{\mathrm{TM}}$/% | $EX_{\mathrm{TE}}$/ dB | $EX_{\mathrm{TM}}$/ dB |
|---|---|---|---|---|---|---|---|
| 633 | 1.28 | 96.66 | 98.07 | 0.174 | 0.022 | 27 | 36 |

diffraction efficiency is ~ 96.66 % and 98.07% for TE and TM polarization, respectively. In contrast, the diffraction efficiencies of the $0^{\mathrm{th}}$ transmitted order for both polarizations are ~0.174 % and 0.022%, respectively. Therefore there has a high polarization extinction ratio.

## 3 Conclusions

In this paper, a rectangular groove dielectric full polarization blazed grating is designed theoretically by modal method. It is shown that the basic idea behind the simplified modal investigation is the excitation and coupling of the propagating modes in gratings. If a phase difference of the odd number multiple $\pi$ is accumulated for the first two propagating modes in gratings, the incident light will be diffracted into the $-1^{\mathrm{st}}$ order with about 100 % diffraction efficiency for both polarizations. As an example, the optimal design of the rectangular full polarization blazed grating with the fused silica is discussed for the wavelength of 633 nm. It is shown that the blazed grating with nearly 100 % diffraction efficiency redirected into the $-1^{\mathrm{st}}$ order for TE- and TM-polarization, respectively. The full polarization blazed grating designed by modal method has a wide-band incident angles and incident wavelengths, especially have high laser intensity tolerance. To be more specific, the geometrical parameters of the full polarization blazed grating calculated by modal method agree well with the results simulated by RCWA.

**References**

[1] OLIVA M, HARZENDORF T, MICHAELIS D, *et al*. Multilevel blazed gratings in resonance domain: an alternative to the classical fabrication approach[J]. *Optics Express*, 2011, **19**(15): 14735-14745.

[2] WANG B, ZHOU C H, WANG S Q, *et al*. Polarizing beam splitter of a deep-etched fused-silica grating[J]. *Optics Letter*, 2007, **32**(10): 1299-1301.

[3] CLAUSNITZER T, KAMPFE T, KLEY E, *et al*. Highly-dispersive dielectric transmission gratings with 100% diffraction efficiency[J]. *Optics Express*, 2008, **16**(8): 5577-5584.

[4] NEAUPORT J, LAVASTRE E, RAZE G, *et al*. Effect of electric field on laser induced damage threshold of multilayer dielectric gratings[J]. *Optics Express*, 2007, **15**(19): 12508-12522.

[5] ZHAO H J, YUAN D R, Design of fused silica blazed gratings with a high power damage threshold[J]. *High Power Laser*

*and Particle Beams*, 2011, **23**(1): 725-729.

[6] CHIOU Y P, SHEN C K. Higher-order finite-difference modal method with interface conditions for the electromagnetic analysis of gratings[J]. *Journal of Lightwave Technology*, 2012, **30**(10): 1393-1398.

[7] CAMPBELL S, BOTTEN L C, MCPHEDRAN R C, *et al*. Modal method for conical diffraction by slanted lamellar gratings[J]. *Journal Optical Socieby America A*, 2009, **26**(4): 938-948.

[8] CLAUSNITZER T, KAMPFE T, KLEY E, *et al*. An intelligible explanation of highly-efficient diffraction in deep dielectric rectangular transmission gratings [J]. *Optics Express*, 2005, **13**(26): 10448-10456.

[9] MOHARAM M, POMMET D, GRANN E, *et al*. Stable implementation of the rigorous coupled-wave analysis for surface-relief gratings: enhanced transmittance matrix approach[J]. *Optical Socieby America A*, 1995, **12**(5): 1077-1086.

[10] LI L F. Use of Fourier series in the analysis of discontinuous periodic structures [J]. *Journal of the Optical Socieby America A*, 1996, **13**(9): 1870-1876.

[11] SHENG P, STEPLEMAN R, SANDA P. Exact eigenfunctions for square-wave grating-Application to diffraction and surface-plasmon calculations [J]. *Physical Review B*, 1982, **26**(6): 2907-2916.

[12] WANG S, ZHOU C, ZHANG Y, *et al*. Polarizing beam splitter of a deep-etched fused-silica grating [J]. *Applied Optics*, 2006, **45**(12): 2567-2571.

[13] ZHAO H J, YUAN D R, Design of fused-silica rectangular transmission gratings for polarizing beam splitter based on modal method[J]. *Applied Optics*, 2010, **49**(5): 759-763.

[14] FENG J J, ZHOU C H, ZHENG J J, *et al*. Dual-function beam splitter of a subwavelength fused-silica grating [J]. *Applied Optics*, 2009, **48**(14): 2697-2701.

[15] GRANET G. Fourier-matching pseudospectral modal method for diffraction gratings: comment[J]. *Journal of the Optical Socieby of America A*, 2012, **29**(9): 1843-1845.