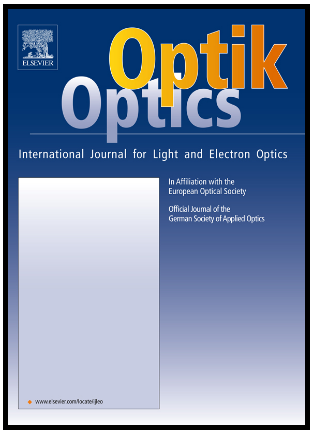

The effect of groove depth on the polarization behavior of an echelle grating

Guojun Yang, Shanwen Zhang, Xiaotao Mi, Hongzhu Yu, Xiangdong Qi

PII: S0030-4026(21)00627-6

DOI: https://doi.org/10.1016/j.ijleo.2021.166932

Reference: IJLEO166932

To appear in: *Optik*

Received date: 4 June 2020
Revised date: 7 February 2021
Accepted date: 6 April 2021

Please cite this article as: Guojun Yang, Shanwen Zhang, Xiaotao Mi, Hongzhu Yu and Xiangdong Qi, The effect of groove depth on the polarization behavior of an echelle grating, *Optik,* (2020) doi:https://doi.org/10.1016/j.ijleo.2021.166932

The effect of groove depth on the polarization behavior of an echelle grating

Guojun Yang[a,b], Shanwen Zhang[a,c], Xiaotao Mi[a], Hongzhu Yu[a,c], and Xiangdong Qi[a]

[a]*National Engineering Research Center for Diffraction Gratings Manufacturing and Application, Changchun Institute of Optics and Fine Mechanics and physics, Chinese Academy of Sciences, Changchun, Jilin, 130033, China;*

[b]*University of Chinese Academy of Sciences, Beijing 100049, China;*

Abstract: In order to provide the guidance for the design and application of echelle gratings, the reason why the diffraction efficiency of the echelle grating can be improved by increasing the groove depth or reducing the apex angle is given. The polarization behaviors of gratings with different groove depths were simulated and analyzed via integral theory. To further demonstrate the polarization behavior, gratings with right and acute apex angles for classical and conical-Littrow incidence were simulated. Experimental polarization behaviors of gratings with 5.1-μm and 6.7-μm groove depths for classical incidence were obtained. The polarization degree of the echelle grating with the 6.7-μm groove depth was 6.5% at 405 nm and 2.52% at 632.8 nm, which smaller than 7.89% at 405 nm and 35.74% at 632.8 nm for the grating with a 5.1-μm groove depth. Therefore, the diffraction efficiency of an echelle grating can be improved by increasing the groove depth or reducing the apex angle, mainly because the polarization degree is restrained.

Keywords: echelle gratings, diffraction efficiency, polarization behaviors, groove depth, polarization degree

1.Introduction

Echelle gratings, or echelles, are defined as coarse but precisely ruled gratings used only at high angles of diffraction and in high spectral orders [1-3]. Echelle gratings have been widely used in wavelength division multiplexers [4,5], commercial spectrometers [6,7], and spectrometers for astronomy [8,9] because of its high resolution, high dispersion, and wide band blaze.

In recent years, with the development of manufacturing technology of echelle gratings, a new CIOMP-6 ruling engine was developed [10-13]. The rule engine can rule grating blanks with dimensions up to 400 mm × 500 mm and rules gratings with line density up to 6000 lines/mm. However, in addition to the study of the engraving machine, the improvement of diffraction efficiency is also very important for the fabrication of echelle gratings. Diffraction efficiency is defined as the ratio of the energy of diffracted light to that of the incident light. Under the same incident light conditions, it is determined by the groove profile shape except for the material used to make the echelles [14-16]. Therefore, research on the diffraction efficiency has been mainly focused on the groove structure.

In 1983, Engman et al. [17,18] proposed that the apex angle should be less than 90 degrees to eliminate defects in the large groove edge and to improve the efficiencies of master and duplicate gratings. In 2017, Zhang et al. [19] optimized the blaze angle and increased the groove depth to avoid the shadow effects of the incident light and improve the diffraction efficiency. In 2019, Shi et al. [20,21] changed a two-faceted echelle grating into a multi-faceted grating to reduce the intensity difference between the spectral center and the edge, and to broaden the spectral distribution of the grating on the spectral plane. Based on previous analyses, it can be concluded that the diffraction efficiency of a fixed-type echelle grating can be improved by increasing the groove depth or reducing the apex angle. However, the reasons were not given. If known, this information could be used to optimize design and fabrication.

Here, it is shown that polarization effects are key to understanding why the diffraction efficiency of echelle gratings can be improved by increasing the groove depth or reducing the apex angle. In Section 2, the groove structure is presented. Section 3 simulates and analyzes the polarization behavior as a function of groove depth. The diffraction efficiency can be improved by increasing the groove depth or reducing the apex angle because the TM polarization is improved and the polarization degree (PD) is restrained. In section 4, the classical R2 (Blaze angle is 63.43^0) and R4 (Blaze angle is 75.96^0) gratings are used to simulate and analyze the polarization behavior as a function of different groove depths for classical and conical-Littrow incidences. In section 5, the experimental determination of TE and TM diffraction efficiency is discussed, and the results agree well with

---

[c]*Corresponding author: Shanwen Zhang and Hongzhu Yu*

E-mail address: zhshwen007@163.com and HongzhuYu@ciomp.ac.cn

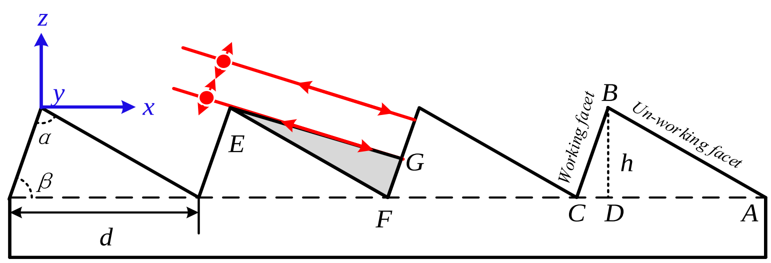

Fig.1. Groove structure of echelle grating. The x-axis is the echelle vector, the y-axis is the direction of the echelle grooves, and the z-axis is perpendicular to the echelle surface. Incident light contains TE polarization perpendicular to the xz plane and TM polarization lines in the xz plane.

the simulations.

2. Groove structure of echelle gratings

The groove structure in Fig. 1 includes the blaze angle β (BCA), the blaze facet (BC), the groove depth h (BD), the working facet (BC), the non-working facet (AB), the apex angle α (ABC), and the period d (AC in Fig.1). The gray area EFG blocks the incident light. The incident light is reflected only once by the blaze facet, which is almost perpendicular to the incident light in the Littrow mount. The surface material is aluminum [22].

The echelle coordinates in Fig. 1 are the *x*-axis (echelle vector), the *y*-axis (the groove direction), and the *z*-axis (perpendicular to the grating plane). For the incident light, the TE polarization is perpendicular to the *xz* plane and the TM polarization lines in the *xz* plane and perpendicular to the direction of incident light. When the period d and blaze angle β are fixed, different apex angles have different groove depths. The apex angle is a right angle, which indicates that the groove structure with a small groove depth. The apex angle is an acute angle, which indicates that the groove structure with a larger groove depth.

3. Polarization behavior of echelle gratings

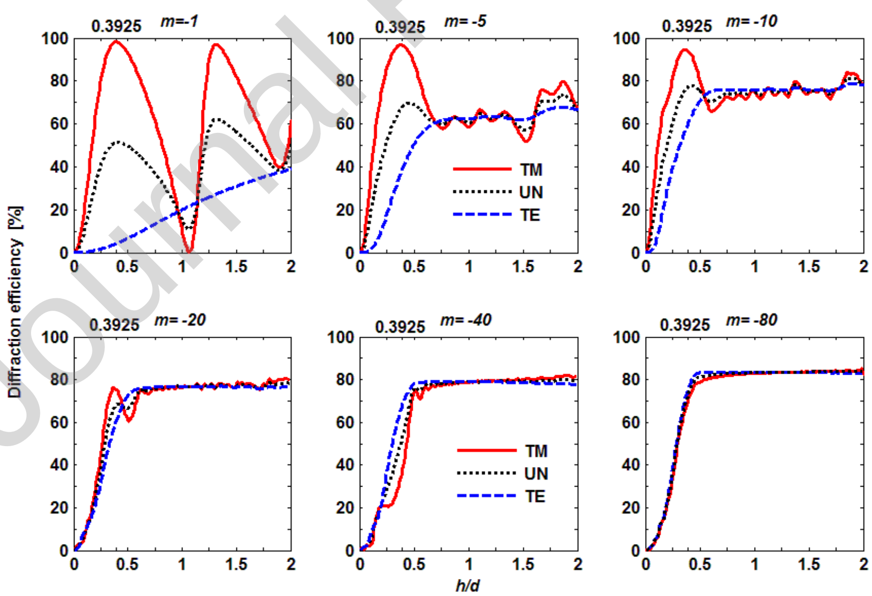

Fig.2. TE and TM polarization diffraction efficiencies as a function of groove depth for echelle gratings . The period d is 12658.2 nm, and the blaze angle α is 64.1375°. According to the grating equation, the wavelengths corresponding to the -1^{st}, -5^{th}, -10^{th}, -20^{th}, -40^{th}, and -80^{th} orders are 22780.8nm, 4556.16nm, 2278.08nm, 1139.04nm, 569.52nm, and 284.76nm respectively.

As shown in Fig. 2, the diffraction efficiency of the TE and TM polarizations vary with groove depth, as simulated with PCGrate software. PCGrate [23] is a modeling tool for analyzing and optimizing the absolute diffraction grating efficiency by using the accurate boundary integral equation method [24]. It can calculate the diffraction intensity and near-zone diffraction field for such kinds of 1-D reflection & transmission relief & phase gratings, rough mirrors, and 2-D photonic crystals as those with arbitrary shape multilayer, concave & convex, in conical mounts, irradiated by non-planar waves, in general polarization states, with various periodical & random layers' roughnesses, and in a super wide spectral from hard *x*-ray to meter wavelengths. In the far infrared (-1^{st} order), the TM polarization oscillation is very intense. At shorter wavelengths, the oscillation strength is weaker. The TM polarization curves can be divided into two sections; one where the polarization degree is high, and a more stable one where the polarization degree is low because of the deep groove depth. The polarization degree (PD) is the ratio of the difference and the sum of the peak TM and TE diffraction efficiencies, which indicates the strong polarization characteristics of the grating. The larger the PD value is, the stronger the polarization characteristic of the grating is. And PD can be seen from the locations of the TM and TE polarization diffraction efficiencies for a certain depth as shown in Fig. 2. The TE polarization curves are also divided into two sections that have no oscillations. The efficiency increased with normalized groove depth and remained at a high level for deep groove depths. The TM polarization is more sensitive to groove depth because of the shadow effect of the gray zone on the incident light. In the gray zone, the TM polarization is suppressed through the un-working facet. The effect is greater when the incident light is closer to the un-working facet, and the effect on TM polarization is greater. The echelle grating is mainly used in the ultraviolet (UV) to the near infrared (NIR) range. For the -20th to -80th orders, when h/d>1, the TM and TE diffraction efficiencies maintain the same change, and PD is zero. Hence, the diffraction efficiency of an echelle grating can be improved by adjusting the the ratio of groove depth h to period d.

Based on the above analysis, three points can be concluded: (A) The diffraction efficiency over the UV to the NIR range of an echelle grating increases until it becomes stable with respect to changes in groove depth. (B) The TM polarization is more sensitive to groove depth than TE. (C) The PD is lower for deeper groove depths. Therefore, the diffraction efficiency with a deeper groove depth is higher because the TM polarization diffraction efficiency is improved and the PD is restrained.

4. Polarization behavior of echelle gratings for classical and conical Littrow incidences

To analyze the polarization behavior of echelle gratings as a function of groove depth, a R2 echelle with a 79-line/mm groove density, a 31.6-line/mm R2 echelle, a 79-line/mm R4 echelle, and a 31.6-line/mm R4 echelle were simulated and analyzed. Curves of TE and TM polarization diffraction efficiencies for echelle gratings as a function of incident and azimuth angles were obtained with the PCGrate software, as shown in Figs. 3-6. In addition, The diffraction order and PD corresponding to the results are given in Figs. 3-6. The wavelength corresponding to each diffraction order can be calculated by the grating equation.

4.1 Diffraction efficiency of TE and TM polarizations for echelle gratings in classical incidence

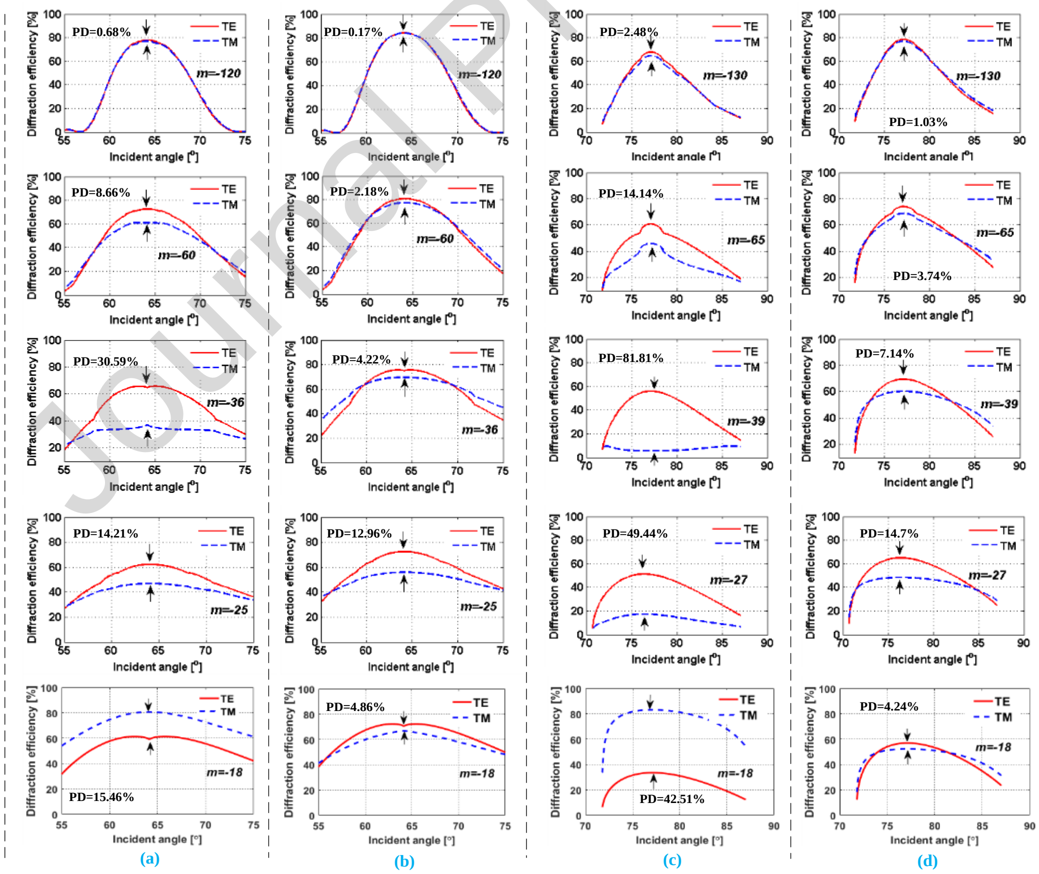

Fig.3. TE and TM polarization diffraction efficiencies on echelle gratings as a function of incident angle. (a) 79-line/mm R2 grating with a right apex angle; (b) 79-line/mm R2 grating with an acute apex angle; (c) 79-line/mm R4 grating with a right apex angle; (d) 79-line/mm R4 echelle with an acute apex angle.

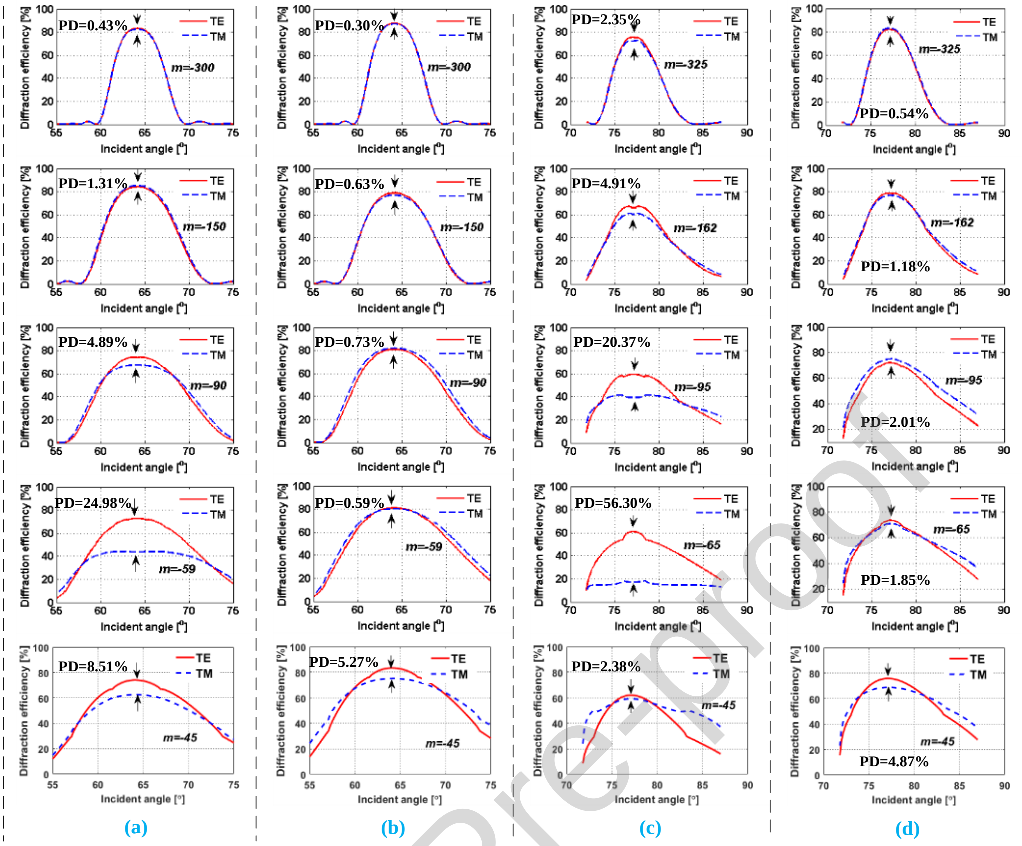

Fig.4. Diffraction efficiency of TE and TM polarization of echelle grating as a function of incident angle. (a) 31.6-line/mm R2 grating with a right apex angle; (b) 31.6-line/mm R2 grating with an acute apex angle; (c) 31.6-line/mm R4 grating with a right apex angle; (b) 31.6-line/mm R4 grating with an acute apex angle.

Classical incident means that the incident light is in the principal cross-section of the grating. In Figs. 3,4, TE and TM polarization diffraction efficiencies are in the form of peaks. From the UV to the NIR, and the TM polarization diffraction efficiency initially decreased and then increased, while that for the TE polarization decreased until it became stable. In Fig. 4(c), the unusual dips or rises in the efficiency at the center of the blaze peak are due to Wood's anomalies, or specifically the Rayleigh pass-off effect [3]. Changes in the TM diffraction efficiency were faster relative to those for the TE polarization. The TM diffraction efficiency for a grating with an acute apex angle was higher than that for a grating with a right apex angle. However, the TM diffraction efficiency for a grating with a right apex angle was higher for the NIR (-18^{th}), as shown in Fig. 3.

In Figs. 3,4, the PD increased from the UV to the visible and jumped at the NIR. The PD and the TM polarization exhibited the same variational trends. Thus, PD changes depend on the TM polarization. For the grating with an acute apex angle, the change in PD was slower and smaller relative to the grating with a right apex angle.

4.2 TE and TM polarization diffraction efficiencies for conical Littrow incidence on echelle gratings

Conical Littrow means that the incident light deviates from the principal cross-section of the grating at a certain angle, and the diffraction angle is equal to the incident angle. The TE and TM diffraction efficiency curves as a function of azimuth angle were obtained with the PCGrate software, as shown in Figs. 5,6. The TE and TM curves were in the form of peaks and valleys. When the working wavelength was closer to the NIR band, the TE and TM curves were closer to gentle peaks. The TM and TE diffraction efficiencies had the same variation trends as shown in Figs. 3,4. The change in PD were also the same as shown in Figs. 3,4. In an echelle grating spectrometer, the diffraction efficiency of the grating is highest and the astigmatism of the system is minimized when the grating works in the Littrow state. In practical, there is a deviation of the azimuth angle from the optical axis in the main section of the grating, which will affect the two-dimensional spectral distribution and the energy transfer of the system. To determine the diffraction efficiency of the grating with different azimuth angles, the error tolerance for the azimuth angle can be determined from Figs. 5,6 to improve the imaging quality of the system.

Based on the results in Figs. 3-6, it can be concluded that the diffraction efficiency was higher for an echelle grating having an acute apex angle. The TM polarization was more sensitive to groove depth, and the PD is lower for a grating having an acute apex angle. The analysis results demonstrates the effect of groove depth on the polarization behavior of echelle gratings.

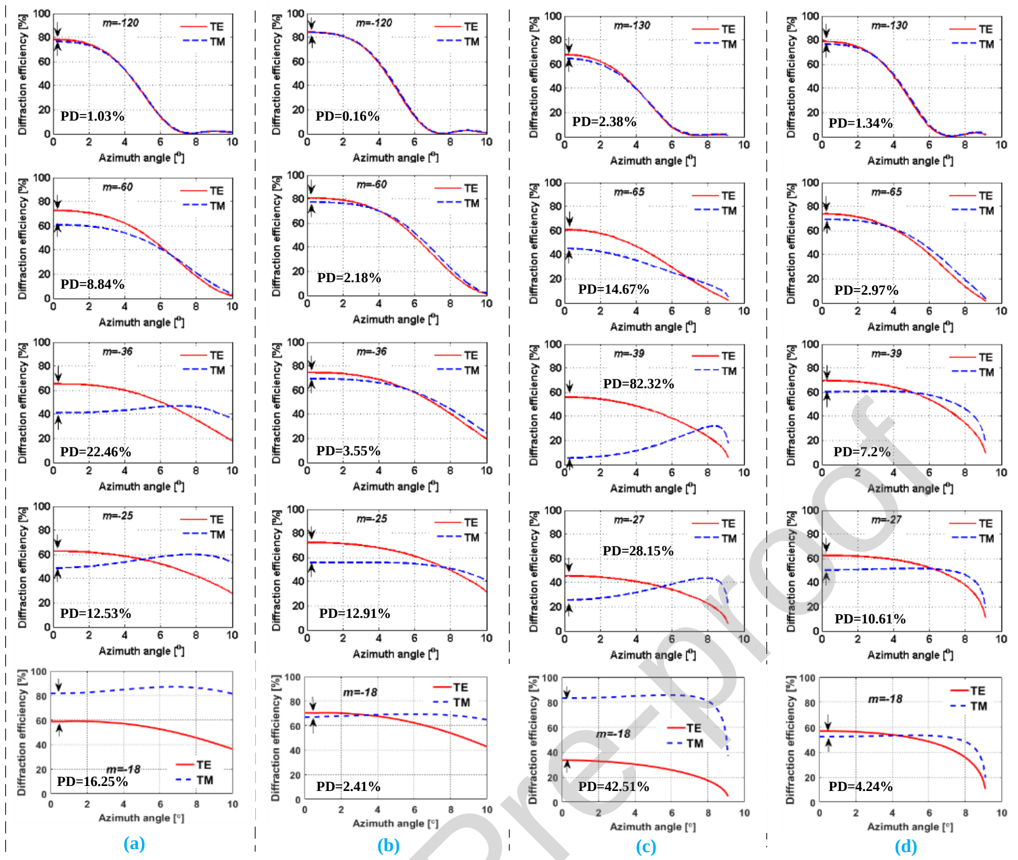

Fig. 5. TE and TM diffraction efficiencies on an echelle grating as a function of azimuthal angle. (a) 79-line/mm R2 grating with a right apex angle; (b) 79-line/mm R2 grating with an acute apex angle; (c) 79-line/mm R4 grating with a right apex angle; (d) 79-line/mm R4 echelle with an acute apex angle.

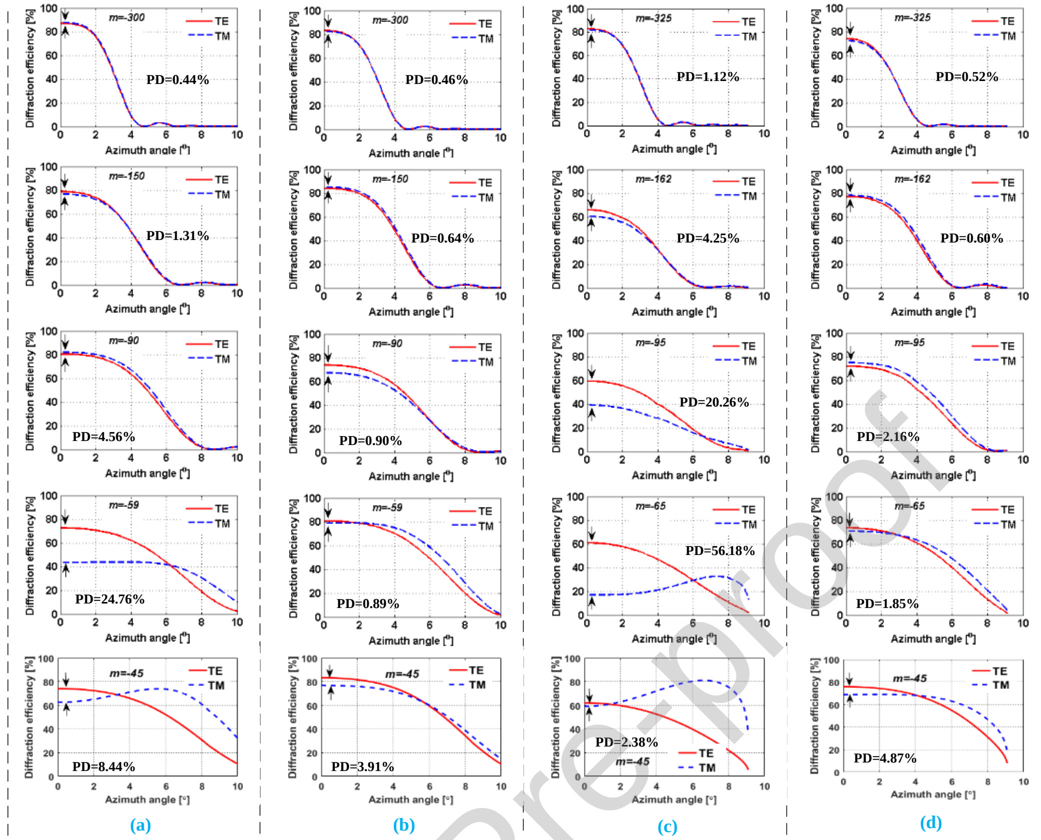

Fig.6. TE and TM diffraction efficiencies for gratings as a function of azimuthal angle. (a) 31.6-line/mm R2 grating with a right apex angle; (b) 31.6-line/mm R2 grating with an acute apex angle; (c) 31.6-line/mm R4 grating with a right apex angle; (b) 31.6-line/mm R4 grating with an acute apex angle.

5.Experiments and results

The optical layout for determining the diffraction efficiency of an echelle grating is shown in Fig. 7. The light sources were 405-nm and 632.8-nm lasers. The surface film layer on the grating was aluminum, and parameters for all the components are listed in Table 1. The angle of incidence was adjusted with a rotary table. Grating groove structures for different groove depths were imaged with an atomic force microscope (Fig. 8). Experimental diffraction efficiencies vs. groove depth are given in Fig. 9.

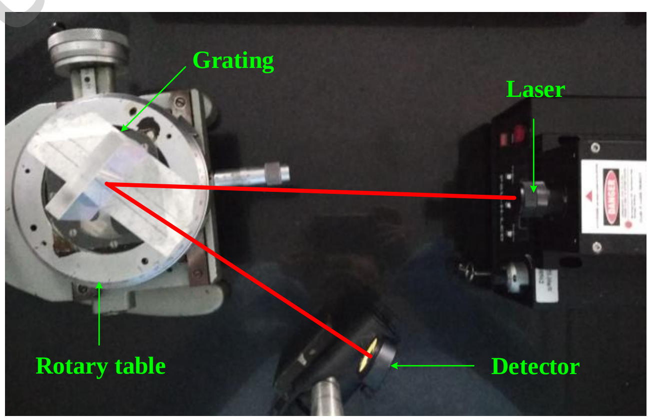

Fig.7 Optical path for determining the diffraction efficiency of an echelle grating

Table 1. Key parameters for all components

Components	Parameters	Performance Index
Light source1	Wavelength	405 nm
	Type	MDL-III-405
	Power	10mw
Light source2	Wavelength	632.8 nm
	Type	HNL150LB
	Power	15mw
Grating1	Line density	79 line/mm
	Groove depth	5.1 μm
	Blaze angle	64.2^0
Grating2	Line density	79 line/mm
	Groove depth	6.7 μm
	Blaze angle	64.2^0
Rotary table	Rotation accuracy	0.1^0
Detector	Type	THORLABS S120VC

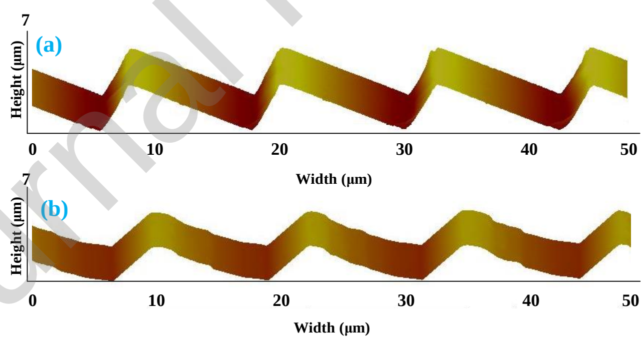

Fig.8 Groove structures of echelle gratings with different groove depths imaged with atomic force microscopy. The two gratings are made by Changchun Institute of Optics, Fine Mechanics and Physics. (a) 6.7-μm groove depth; (b) 5.1-μm groove depth.

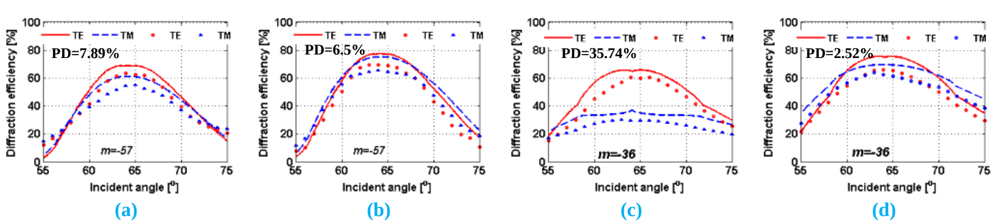

Fig.9. Diffraction efficiency of echelle grating vs. groove depth. (a) 405-nm light and 5.1-μm groove depth; (b) 405-nm light and 6.7-μm groove depth; (c) 632.8-nm light and 5.1-μm groove depth; (d) 632.8-nm light and 6.7-μm groove depth. Curves were generated by PCGrate and the scatter diagrams were experiment.

The experimental results shown in Fig. 9 includes simulation results obtained with PCGrate. The experiment results agree well the simulation results, which proves the quality of the grating. The maximum diffraction efficiency of the echelle grating with a 6.7-μm groove depth was 64.6% at 405 nm and 67.5% at 632.8 nm, while that for the grating with a 5.1-μm groove depth was 57.65% at 405 nm and 47% at 632.8 nm. The maximum diffraction efficiency of TM polarization for the grating with a 6.7-μm groove depth was 60.4% at

405 nm and 65.8% at 632.8 nm, while that for the grating with a 5.1-μm groove was 53.1% at 405 nm and 30.2% at 632.8 nm. The PD of the grating with a 6.7-μm groove depth was 6.5% at 405 nm and 2.52% at 632.8 nm, while that for the grating with the 5.1μm groove depth was 7.89% at 405 nm and 35.74% at 632.8 nm. The polarization behavior of echelle gratings obtained by the experiment is in good agreement with the polarization behavior of echelle gratings obtained by the simulation. The diffraction efficiency of echelle gratings was higher for deeper groove depths, the TM polarization was more sensitive to groove depth than TE, and the PD was lower for deeper groove depths.

6. Conclusion

The polarization behavior of echelle gratings with different groove depths was simulated and analyzed. The diffraction efficiency increased until it became stable with the change in groove depth. TM polarization changes more obviously than TE polarization with the changes of groove depth, and the PD was lower for deeper groove depths.

Polarization behaviors of echelle gratings with right and acute apex angles were simulated for classical and conical Littrow incidence. The diffraction efficiency was higher with an acute apex angle, the TM polarization was more sensitive to groove depth than TE, and the PD for acute apex angles was lower. The simulation results of the two kinds of incident conditions are applicable to all blazed gratings with different line density and different blaze angle. The experimental diffraction efficiency of TM polarization for the grating with a 6.7-μm groove depth was greater than that for the grating with a 5.1-μm groove depth, and the PD of the grating with a 6.7-μm groove depth was lower. Therefore, the diffraction efficiency with deeper groove depths was higher because that for TM polarization improved, while the PD was restrained.

In an echelle-grating spectrometer, the azimuthal angle of the optical axis deviating from the main section of the grating will affect the imaging quality of the system. Therefore, these results can be used not only to guide the design and fabrication of echelle gratings, but also to guide the design of the spectrometer.

Acknowledgements

The authors acknowledge supports from the International Cooperation Fund of Changchun Institute of Optics and Machinery (Y8E43WH) and the Cooperation Fund of Fudan Univeisity and Changchun Institute of Optics and Machinery (Y9S133H190).

Reference

[1]. G. R. Harrison, The production of diffraction gratings: II. The design of echelle gratings and spectrographs, J. Opt. Soc. Am. 39 (1949) 522-527.

[2]. G. R. Harrison, E. G. Loewen, and R. S. Wiley, Echelle gratings: their testing and improvement, Appl. Opt. 15 (1976) 971–976.

[3]. E. Loewen, E. Popov, Diffraction Gratings and Applications, Marcel Dekker (1997).

[4]. J. Qiao, F. Zhao, R. T. Chen, J. W. Horwitz and W. W. Morey, Athermalized low-loss echelle-grating-based multimode dense wavelength division demultiplexer, Appl. Opt. 41(31) (2002) 6567- 6575.

[5]. R. J. Lycett, D. F. G. Gallagher, V. J. Brulis, Perfect Chirped Echelle Grating Wavelength Multiplexor: Design and Optimization, IEEE. Photonics. J. 5(2) (2015) 2400123.

[6]. L. Yin, H. G. Bayan, J. Yang, Y. X. Lu, R. Zhang, C. Sun and J. C. Cui, High-accuracy spectral reduction algorithm for the échelle spectrometer, Appl. Opt. 55 (2016) 3574-3581.

[7]. R. Jacob, B. Aaron, P. Kevin, and P. Jannick, Freedom spectrometer enabling increased compactness, Light Sci. Appl. 6 (2017) 1-10.

[8]. A. Szentgyorgyi, D. Baldwin, S. Barnes, J. Bean, S. Ben-Ami, P. Brennan, J. Budynkiewicz, M. Y. Chun, C. Conroy, J. D. Crane, H. Epps, I. Evans, J. Evans, J. Foster, A. Frebel, T. Gauron, D. Guzmán, T. Hare, B. H. Jang, J. G. Jang, A. Jordan, J. Kim, K. M. Kim, C. M. M. Oliveira, M. Lopez-Morales, K. McCracken, S. McMuldroch, J. Miller, M. Mueller, J. S. Oh, C. Onyuksel, M. Ordway, B. G. Park, C. Park, S. J. Park, C. Paxson, D. Phillips, D. Plummer, W. Podgorski, A. Seifahrt, D. Stark, J. Steiner, A. Uomoto, R. Walsworth, and Y. S. Yu, The GMT-Consortium Large Earth Finder (G-CLEF): an optical Echelle spectrograph for the Giant Magellan Telescope (GMT), Proc. SPIE. 9908 (2016) 990822.

[9]. J. L. Lizon, H. Dekker, A. Manescau, D. Megevan, F. A. Pepe, and M. Riva, A large mosaic echelle grating for ESPRESSO spectrograph, Proc. SPIE. 10701 (2018) 107012P.

[10]. H. L. Yu, X. T. Li, J. W. Zhu, H. Z. Yu, X. D. Qi, and S. L. Feng, Reducing the line curvature error of mechanically ruled gratings by interferometric control, Appl. Phys. B: Lasers Opt. 117 (1) (2014) 279–286.

[11]. X. T. Mi, H. Z. Yu, J. X. Gao, H. L. Yu, S. W. Zhang, and X. D. Qi, Design of the controller of the micro-positioning system for large diffraction grating ruling engine. Chinese J Sci instrument. 36 (2015) 473-480.

[12]. Y. Chao, H. L. Yu, X. T. Li, H. Bayan, J. C. Cui, Xiangdong Qi, Yuguo Tang, "Real-time monitoring of ruling grating resolution by digital wavefront, Appl. Opt. 54 (3) (2015) 492–497.

[13]. X. T. Li, H. L. Yu, X. D. Qi, S. L. Feng, J. C. Cui, S. W. Zhang, L. T. Jiri, 300-mm ruling engine producing gratings and echelles under interferometric control in China, Appl. Opt. 54 (2015) 1819–1826.

[14]. Daniel J. Schroeder, R.L. Hilliard, Echelle efficiencies: theory and experiment, Appl. Opt. 19 (1980) 2833–2841.

[15]. S. Engman, P. Lindblom, Improving echelle grating efficiencies, Physica Scr. 28 (1983) 86–88.

[16]. B.H. Kleemann, Perfect blazing with echelle gratings in TE and TM polarization, Opt. Lett. 37 (2012) 1002–1004.

[17]. S. Engman, P. Lindblom, E. Leibhardt. Improving Echelle Grating Efficiencies, Phys. Scripta. 28(1) (1983) 86-88.

[18]. S. Engman, P. Lindblom, E. Leibhardt. Blaze characteristics of echelle gratings, Appl. Opt. 21(23) (1982) 4356-4362.

[19]. S. W. Zhang, X. T. Tao, Q. Zhang, G. L. T. Jiri, S. L. Feng, H. L. Yu, X. D. Qi, Groove shape characteristics of echelle gratings with high diffraction efficiency, Opt. Commun. 387 (2017) 401-404.

[20]. J. Shi, B. Sheng, Y. S. Huang, L. N. Peng, L. Y. Wang, Z. J. Ni, D. W. Zhang, Y. F. Zhao and M. He, Multifacet echelle grating for intensity broadening on spectral plane fabricated by rotating ion-beam etching, Appl. Opt. 58(18) (2019) 5040-5044.

[21]. B. Sheng, J. J. Fan, Y. S. Huang, J. J. Guo, H. Y. Lu, D. Zhang, and S. G. Zhuang, Precise Blaze Angle Adjustment of Echelle Grating by Self-Shadowing Rotating Mask, IEEE. Photonics. J. 10(1) (2018) 2400107.

[22]. E. D. Palik. Handbook of optical constants in solids, Academic Press (1995).

[23]. http://www.PCGrate.com.

[24]. B. H. Kleemann, A. Mitreiter, and F. Wyrowski, Integral equation method with parametrization of grating profile - theory and experiments, J. mod. Opt. 43(7) (1996) 1323-1349.

Declaration of interests

☑ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: