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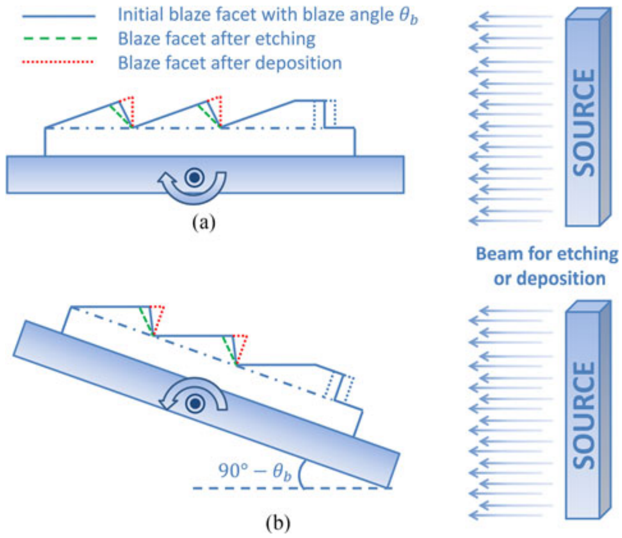
Bin Sheng
Jiaojiao Fan
Yuanshen Huang
Junjun Guo
Haoyu Lyu
Dawei Zhang
Songlin Zhuang



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Precise Blaze Angle Adjustment of Echelle Grating by Self-Shadowing Rotating Mask

**Bin Sheng, Jiaojiao Fan, Yuanshen Huang, Junjun Guo,
Haoyu Lyu, Dawei Zhang, and Songlin Zhuang**

Engineering Research Center of Optical Instruments and Systems, Ministry of Education
and Shanghai Key Laboratory of Modern Optical Systems, University of Shanghai for
Science and Technology, Shanghai 200093, China

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Abstract: Angular precision of 0.1° for the blaze angle of echelle gratings is an important technical requirement for spectral instruments with echelle gratings. This paper proposes a precise adjustment method for the blaze angle of echelle gratings that are etched or deposited by self-shadowing rotating mask. The blaze angle will decrease or increase when the grating is rotated in beams for etching or deposition, respectively. The blaze angle can be controlled by adjusting the etching or deposition conditions. For the echelle grating with nominal blaze angle of 63.0° and groove density of 52.7 g/mm, the blaze angle was decreased by 0.12° with a maximum etching depth of 19 nm on the blaze facet. Additionally, the blaze angle adjustment precision will be better than 0.02° if the maximum etch depth on the blaze facet is less than 3 nm.

Index Terms: Echelle gratings, optical fabrication, micro-nano fabrication, spectrometers.

1. Introduction

Professor Harrison at MIT first proposed the concept of echelle grating in the 1940s, and then carried out detailed research on its working principle, manufacture and performance in the following three decades [1]–[4]. Since the 1970s, spectrographs with echelle gratings have been studied and applied to spectrum detection in astronomical field [5]–[8]. With increasing manufacturing capabilities for both the gratings and the related detectors, echelle gratings began to be used widely in a variety of fields, particularly in high-resolution spectrographs. An echelle spectrograph is composed of a major dispersive element of echelle grating and a cross-dispersive element of prism or grating that is used to form a two-dimensional spectral image in the focal plane. The echelle spectrograph has many advantages, including high resolution, high measurement speeds and a compact structure. Jaffe *et al.* had fabricated and tested chemically micromachined silicon echelle gratings and grisms for infrared astronomy [9]–[12]. For wavelength division multiplexing (WDM) in telecommunications, echelle grating has been an excellent demultiplexer [13]–[18].

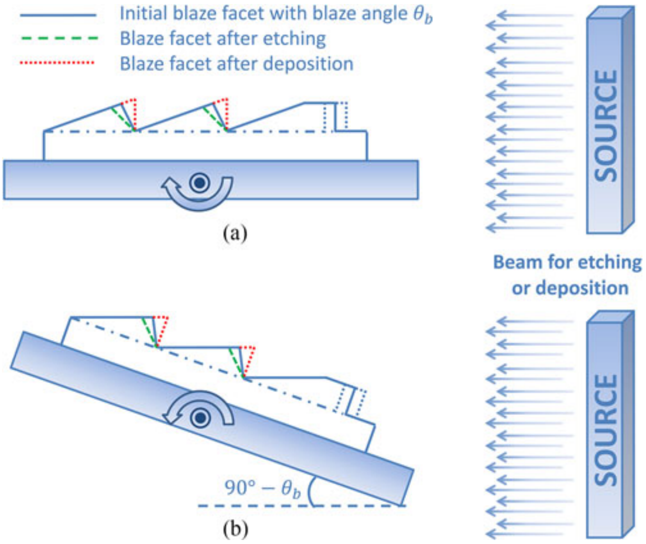


Fig. 1. Scheme for blaze angle adjustment. (a) When the included angle between the direction of the adjusting beam and the grating plane is zero, the blaze facets are shadowed completely by the neighboring grooves. (b) When the included angle between the direction of the adjusting beam and the grating plane is equal to $(90° - \theta_b)$, the echelle grating facets are totally exposed to the beam for etching or deposition. As the rotation position changes from (a) to (b), the degree of etching or deposition will vary along the blaze facet from top to bottom.

As the core element of the echelle spectrograph, a high spectral quality echelle grating requires an excellent diffraction wavefront, high diffraction efficiency over a wide wavelength range and high blazed angle precision [19]–[26]. Worldwide, Newport Corporation currently provides very high quality echelle gratings with the most complete grating parameters [27] and these gratings are widely used in various types of grating spectrograph.

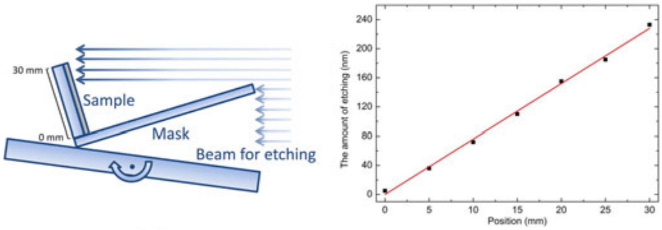
If the echelle grating's blaze angle deviates from the designed value, the actual center wavelength then also deviates from the designed center wavelength under the same usage conditions. Angular precision of 0.1° for the blaze angle is an important technical requirement for the spectral instruments using echelle gratings [28], [29]. However, difficulties in adjusting the blazed angle of echelle gratings mainly originate from elastic deformation of the metal films used during the ruling process. The corresponding angular precision available for the blaze facet is approximately 0.5°, which is much larger than the precision required for echelle-based spectral instruments [30]–[33].

This paper proposes a new high-precision adjustment method for the blaze angles of echelle gratings that are etched or deposited by self-shadowing rotating mask (SSRM).

2. Scheme of Adjustment for Blaze Angle

The shadowing effect exists when a microstructure is exposed to the beam for etching or deposition from a special direction [34]. We propose the idea that the blaze angle of an echelle grating will decrease or increase when the grating is rotated within the beam that is used for etching or deposition, respectively. The basic principle of precise adjustment of the echelle grating's blaze angle using the SSRM is shown in Fig. 1. We assume that the echelle grating has a blaze angle of θ_b and an apex angle of 90°. However, the blaze angle θ_b deviates from the desired value of θ_0 because of the limitations of the fabrication process. Therefore, the blaze facet should be etched using the SSRM at an angle of $(\theta_b - \theta_0)$ if θ_b is larger than θ_0 or should be deposited via the SSRM at an angle of $(\theta_0 - \theta_b)$ if θ_b is smaller than θ_0.

The echelle grating is placed on a rotating platform and the rotational axis is oriented parallel to the grating line. The direction of the beam that is used for etching or deposition is



(a) (b)

Fig. 2. (a) One macroscopic groove of an echelle grating with a nominal blaze angle of 63.0° comprised of two plane substrates that was used to simulate etching on the blaze facet using the SSRM. (b) Linear relationship between the amounts of etching and the position on the blaze facet, which resulted in the echelle grating's blaze angle decreasing by 0.12° with the maximum etching of 19 nm (when etched in one typical rotating cycle time) at the top of the blaze facet.

vertical to the grating line. Fig. 1(a) shows that the blaze facets are shadowed completely by the neighboring grooves if the included angle between the direction of the adjusting beam and the grating plane is zero, and thus the blaze angle θ_b will not be changed by beams for etching or deposition. In Fig. 1(b), when the echelle grating is rotated such that the included angle between the direction of the adjusting beam and the grating plane is equal to $(90^\circ - \theta_b)$, the blaze facets are now totally exposed to beams for etching or deposition. As the rotating position changes from Fig. 1(a) to (b), the amount of etching or deposition that occurs will vary along the blaze facet in the direction from top to bottom. The maximum amount of etching or deposition that occurs on the blaze facet corresponds to the amount of variation of the blaze angle.

3. Blaze Facet Etched by SSRM

The echelle grating studied in this paper was ruled on aluminum film with a density of 52.7 g/mm and a nominal blaze angle of 63.0°. Because of the limited experimental conditions available in our laboratory, in which we have no equipment that can provide a deposition beam with suitably high collimation, deposition experiments on the blaze facet have not been carried out to date.

An ion beam etching machine was used to etch the echelle grating's blaze facets using the SSRM. The radio-frequency (RF) ion beam source has a rectangular area of 220 mm $\times$ 60 mm and has inhomogeneity of less than 2%. The etching experiments all used the same parameters for ion beam etching, with beam voltage of 500 eV, beam current of 80 mA and argon gas flow rate of 10 sccm. The typical angular velocity of the rotating platform is 1.8°/s. One typical rotating cycle of etching is defined as the period in which the platform rotates from the position of Fig. 1(a) to that of Fig. 1(b) and then rotates back to the original position.

To simulate the etching on the blaze facet using the SSRM, two plane samples were used to form one macroscopic groove of an echelle grating with a nominal blaze angle of 63.0°, as shown in Fig. 2(a). A 30-mm-long plane sample with 500-nm-thick aluminum film was set as the blaze facet and another plane substrate was set as the antiblaze facet. Using the experimental condition described above, the aluminum plane sample was etched 12 times using the SSRM. The 30-mm-long plane sample was partially covered to form steps along the height direction. The steps at seven positions ranging from 0 mm to 30 mm were measured by a surface profiler (XP-1, AMBIOS). Fig. 2(b) shows the linear relationship between the depth of etching and the position on the blaze facet. The maximum aluminum etching rate that occurred at the 30 mm position at the top of the blaze facet was 38.8 nm/min. We also obtained the result where the echelle grating's blaze angle was reduced by 0.12° with maximum etching of 19 nm (when etched in one typical rotating cycle time) at the top of the blaze facet.

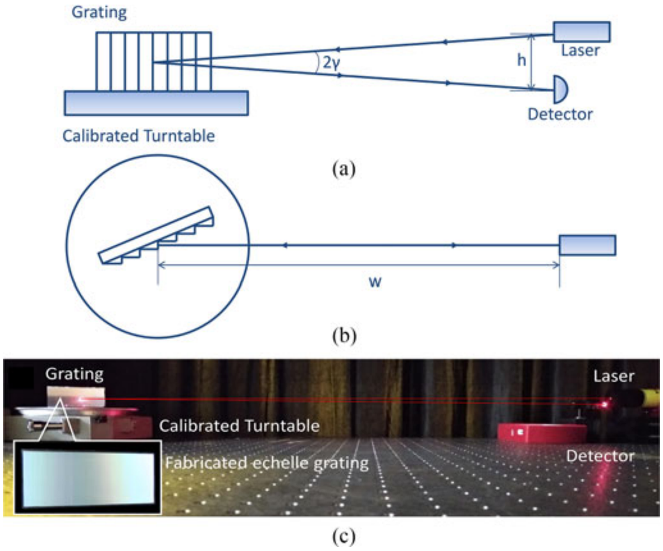


Fig. 3. Quasi-Littrow mode used to measure the intensities of the diffracted orders. (a) Lateral view, (b) top view and (c) tested echelle grating and measurement system.

4. Measurement and Discussion

The echelle grating with nominal blaze angle of 63.0° was etched by SSRM over a number of rotating cycle periods. The ion beam etching parameters were beam voltage of 500 eV, beam current of 80 mA and argon gas flow rate of 10 sccm. The typical angular velocity of the rotating platform is 1.8°/s. The echelle grating was measured after it was etched five times, nine times, 12 times, 14 times and 17 times.

Fig. 3 shows the quasi-Littrow mode used to measure the intensities of the echelle grating's diffracted orders after etching by SSRM. Different blaze angles affect the intensity distributions of the diffracted orders, and thus the variation of maximum intensity in the diffracted orders corresponds to the variation of the blaze angle. According to the grating equation

$$m\lambda = d\,(\sin\,\theta_i + \sin\,\theta_d)\cos\,\gamma \tag{1}$$

where m is the diffracted order; λ is the wavelength of the laser beam used for the measurements; d is the period of the echelle grating, which is equal to the reciprocal of echelle grating's groove density; θ_i is the angle of incidence of the laser beam; θ_d is the diffracted angle; and γ is half of the included angle of the incident light beam and the diffracted light beam in Littrow mode ($\theta_i = \theta_d$). The echelle grating was placed on a calibrated turntable such that the grating lines were perpendicular to the horizontal plane. The laser beam was then diffracted by the echelle grating and the diffracted orders were projected on the screen. The intensities of these diffracted orders were measured by a movable detector. The distance w between the echelle and the laser was approximately 1000 mm and the distance h between the detector and the laser was approximately 20 mm. Under these conditions, the angle γ was 0.57°, which is sufficiently small to allow the installation to meet the requirements of the quasi-Littrow mode.

Three lasers, comprising a He-Cd laser (325.0 nm), a semiconductor laser (405.3 nm) and a He-Ne laser (632.8 nm), were used to measure the intensity distributions of the diffracted orders. The polarization of laser we used was paralleled to the grating lines during the measurement. Echelle grating is insensitive to polarization of incident light, and the scalar theory can be applied to simulate diffraction efficiency. Diagrams in the same columns in Fig. 4 show the intensities of the diffracted orders when measured at the same laser wavelength and the three diagrams in each row are the intensities of the diffracted orders after the blaze facets were etched for the same number

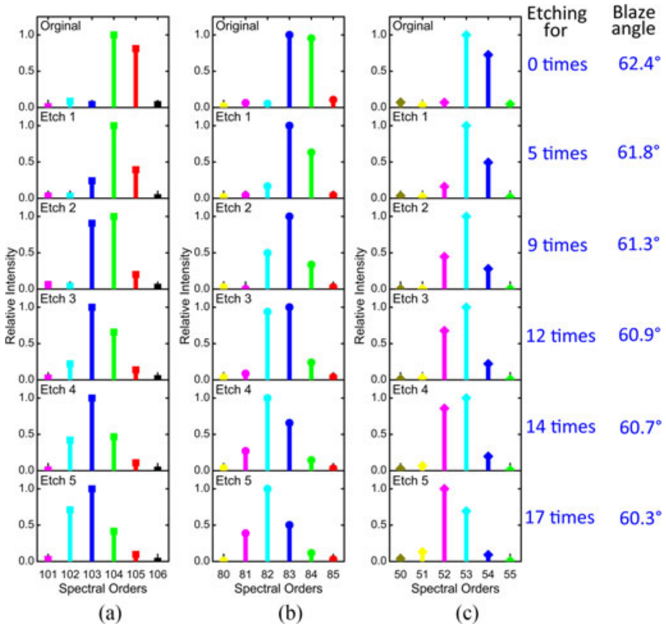


Fig. 4. Intensity distributions of the diffracted orders after the surface was etched for various numbers of cycles as measured using the three wavelengths of a He-Cd laser (325.0 nm), a semiconductor laser (405.3 nm) and a He-Ne laser (632.8 nm). Diagrams in the same column show the intensities of the diffracted orders that were measured using the same laser wavelength and the three diagrams in each row are the intensities of the diffracted orders after ion beam etching had been performed the same number of times.

of times. All the intensities of the diffracted orders were normalized with respect to the maximum intensity of the central order.

Fig. 4 shows that the central order at the wavelength of 325.0 nm changes gradually from the 104th order to the 103rd order with increasing numbers of rotating cycle times. At the wavelength of 405.3 nm, the central order changed from the 83rd order to the 82nd order. Meanwhile, the diffracted order of 53 changed to the order of 52 at the wavelength of 632.8 nm. In addition, the changes in the orders occur more quickly at shorter wavelengths than at longer wavelengths. Comparing the first and the sixth diagrams in Fig. 4(c), the intensity distributions of the diffracted orders at the wavelength of 632.8 nm were almost the same, so it was concluded that the central order changes to a lower order by one order after 17 etching times. If the central order changes from the 53rd order to the 52nd order and the blaze angle will decrease by 2.1° for a change of one order.

Engman and Lindblom [23] presented a model for the blaze function of echelle gratings for in-plane mountings. It has also been shown that by measuring the angles of incidence and diffraction for the power minima of diffracted orders, the blaze angle can be determined. Using the above method, the blaze angle of echelle grating with nominal blaze angle of 63.0° before etching was measured and fitted as 62.4°. After 17 etching times, the blaze angle was varied to 60.3° and the angular variation amount was coincident with the value mentioned above. There was a measurement error of ±0.08° of incident angle detecting the power minima of diffracted orders, so the error of fitted blaze angle could be ±0.04°.

Therefore, the blaze angle decreased by 0.12° with a maximum etching depth of 19 nm on the blaze facet after one rotating cycle period. Similarly, the change in the blaze angle after etching for one cycle time is also approximately 0.12° at the wavelengths of 325.0 nm and 405.3 nm. Furthermore, if the maximum etching amount on the blaze facet is less than 3 nm by controlling etching time and beam current during ion beam etching, the precision for adjustment of the blaze angle will be less than 0.02°. For example, we can increase rotating angular velocity from 1.8°/s to

10.8°/s, so the etching time can be decreased to one-sixth of one typical etching cycle. As a result, the etching depth will be about 3nm and the change of blaze angle will be about 0.02°.

The proposed adjustment methods include the two cases of etching and deposition, so we intend to set up a precision instrument with a highly-collimated deposition beam to explore the evolution law of the echelle's blaze angle during deposition using the SSRM in the future. Using a combination of the methods of etching and deposition with the SSRM on the blaze facet or the anti-blaze facet, the apex angle of the echelle grating can be fixed at a constant value. The proposed technique can be used to ensure the consistency of the blaze angle of echelle gratings and further enhance the reliability of echelle spectrometers.

5. Conclusion

We have proposed a precise adjustment method for the blaze angle of echelle gratings that have been etched or deposited by self-shadowing rotating mask. The blaze angle of echelle grating will decrease or increase when the grating is rotated in the beam for etching or deposition, respectively. The resulting ability to adjust the echelle grating's blaze angle can be controlled by adjusting the etching or deposition conditions. For the echelle grating with nominal blaze angle of 63.0° and groove density of 52.7 g/mm, the blaze angle was decreased by 0.12° with a maximum etching depth of 19 nm on the blaze facet. Additionally, the precision for adjustment of the blaze angle will be better than 0.02° if the maximum etching depth on the blaze facet is less than 3 nm.

References

[1] G. R. Harrison, "The production of diffraction gratings: I. Development of the ruling art," *J. Opt. Soc. Amer.*, vol. 39, no. 6, pp. 413–426, Jun. 1949.
[2] G. R. Harrison, "The production of diffraction gratings: II. The design of echelle gratings and spectrographs," *J. Opt. Soc. Amer.*, vol. 39, no. 7, pp. 522–528, Jul. 1949.
[3] G. R. Harrison, "The diffraction grating—An opinionated appraisal," *Appl. Opt.*, vol. 12, no. 9, pp. 2039–2049, Sep. 1973.
[4] G. R. Harrison, E. G. Loewen, and R. S. Wiley, "Echelle gratings: Their testing and improvement," *Appl. Opt.*, vol. 15, no. 4, pp. 971–976, Apr. 1976.
[5] D. J. Schroeder, "Design considerations for astronomical echelle spectrographs," *Publ. Astron. Soc. Pacific*, vol. 82, no. 490, pp. 1253–1275, 1970.
[6] D. J. Schroeder and C. M. Anderson, "An echelle sprectrograph for astronomical use," *Publ. Astron. Soc. Pacific*, vol. 83, no. 494, pp. 438–446, 1971.
[7] D. M. Hunten, W. K. Wells, R. A. Brown, N. M. Schneider, and R. L. Hillard, "A Cassegrain echelle spectrograph," *Publ. Astron. Soc. Pacific*, vol. 103, no. 669, pp. 1187–1192, 1991.
[8] R. I. Thompson, H. W. Epps, G. Winters, W. Womack, and E. Mentzell, "GRIS: The grating infrared spectrometer," *Publ. Astron. Soc. Pacific*, vol. 106, no. 695, pp. 94–100, 1994.
[9] U. U. Graf, "Fabrication and evaluation of an etched infrared diffraction grating," *Appl. Opt.*, vol. 33, no. 1, pp. 96–102, Jan. 1994.
[10] L. D. Keller, D. T. Jaffe, O. A. Ershov, T. Benedict, and U. U. Graf, "Fabrication and testing of chemically micromachined silicon echelle gratings," *Appl. Opt.*, vol. 39, no. 7, pp. 1094–1105, Mar. 2000.
[11] J. P. Marsh, D. J. Mar, and D. T. Jaffe, "Production and evaluation of silicon immersion gratings for infrared astronomy," *Appl. Opt.*, vol. 46, no. 17, pp. 3400–3416, Jun. 2007.
[12] D. J. Mar, J. P. Marsh, C. P. Deen, H. Ling, H. Choo, and D. T. Jaffe, "Micromachined silicon grisms for infrared optics," *Appl. Opt.*, vol. 48, no. 6, pp. 1016–1029, Feb. 2009.
[13] J. Song, N. Zhu, J.-J. He, and S. He, "Echelle grating demultiplexers with reduced return loss by using chirped diffraction order design," *IEEE Photon. Technol. Lett.*, vol. 18, no. 14, pp. 1506–1508, Apr. 2006.
[14] F. Horst, W. M. J. Green, B. J. Offrein, and Y. A. Vlasov, "Silicon-on-insulator echelle grating WDM demultiplexers with two stigmatic points," *IEEE Photon. Technol. Lett.*, vol. 21, no. 23, pp. 1743–1745, Dec. 2009.
[15] D. Feng *et al.*, "Fabrication insensitive echelle grating in silicon-on-insulator platform," *IEEE Photon. Technol. Lett.*, vol. 23, no. 5, pp. 284–286, Mar. 2011.
[16] R. J. Lycett, D. F. G. Gallagher, and V. J. Brulis, "Perfect chirped echelle grating wavelength multiplexor: Design and optimization," *IEEE Photon. J.*, vol. 5, no. 2, Apr. 2013, Art. no. 2400123.
[17] X. Ma, M. Li, and J. He, "CMOS-compatible integrated spectrometer based on echelle diffraction grating and MSM photodetector array," *IEEE Photon. J.*, vol. 5, no. 2, Apr. 2013, Art. no. 6600807.
[18] S. Pathak, P. Dumon, D. Van Thourhout, and W. Bogaerts, "Comparison of AWGs and echelle gratings for wavelength division multiplexing on silicon-on-insulator," *IEEE Photon. J.*, vol. 6, no. 5, Oct. 2014, Art. no. 4900109.
[19] D. J. Schroeder and R. L. Hilliard, "Echelle efficiencies: Theory and experiment," *Appl. Opt.*, vol. 19, no. 16, pp. 2833–2841, Aug. 1980.
[20] M. Bottema, "Echelle efficiencies: Theory and experiment; comment," *Appl. Opt.*, vol. 20, no. 4, pp. 528–530, Feb. 1981.

[21] D. J. Schroeder, "Echelle efficiencies: Theory and experiment; author's reply to comment," *Appl. Opt.*, vol. 20, no. 4, pp. 530–531, Feb. 1981.

[22] R. A. Brown, R. L. Hilliard, and A. L. Phillips, "Actual blaze angle of the Bausch & Lomb R4 echelle grating," *Appl. Opt.*, vol. 21, no. 2, pp. 167–168, Jan. 1982.

[23] S. Engman and P. Lindblom, "Blaze characteristics of echelle gratings," *Appl. Opt.*, vol. 21, no. 3, pp. 4356–4362, Dec. 1982.

[24] S. Engman and P. Lindblom, "Blaze angle of the Bausch & Lomb R4 echelle grating," *Appl. Opt.*, vol. 22, no. 17, pp. 2512–2513, Sep. 1983.

[25] S. Engman, P. Lindblom, and B. J. Olsson, "Testing echelle gratings: A simple method," *Appl. Opt.*, vol. 26, no. 1, pp. 26–28, Jan. 1987.

[26] F. Diego, "Blaze angle measurements of 31.6-g/mm and 79.01-g/mm R2 echelle gratings from Bausch & Lomb," *Appl. Opt.*, vol. 26, no. 22, pp. 4714–4716, Nov. 1987.

[27] [Online]. Available: http://www.newport.com

[28] E. Loewen, D. Maystre, E. Popov, and L. Tsonev, "Echelles: Scalar, electromagnetic, and real-groove properties," *Appl. Opt.*, vol. 34, no. 10, pp. 1707–1727, Apr. 1995.

[29] E. Loewen, D. Maystre, E. Popov, and L. Tsonev, "Diffraction efficiency of echelles working in extremely high orders," *Appl. Opt.*, vol. 35, no. 10, pp. 1700–1704, Apr. 1996.

[30] F. Zhao, "A diffraction model for echelle gratings," *J. Mod. Opt.*, vol. 38, no. 11, pp. 2241–2246, Oct. 1991.

[31] 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*, vol. 117, no. 1, pp. 279–286, Apr. 2014.

[32] Z. Z. Li, J. X. Gao, H. G. Yang, T. T. Wang, and X. Y. Wang, "Roughness reduction of large-area high-quality thick Al films for echelle gratings by multi-step deposition method," *Opt. Exp.*, vol. 23, no. 18, pp. 23738–23747, Sep. 2015.

[33] S. W. Zhang *et al.*, "Groove shape characteristics of echelle gratings with high diffraction efficiency," *Opt. Commun.*, vol. 387, pp. 401–404, Oct. 2016.

[34] E. Klein and W. Ramirez, "Consideration of local shadowing and ion beam voltage effects in the prediction of a surface evolving under ion milling," *J. Vac. Sci. Technol. A*, vol. 18, no. 1, pp. 166–175, Jan./Feb. 2000.