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Groove shape characteristics of echelle gratings with high diffraction efficiency

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ABSTRACT

The groove shape characteristics of echelle gratings with high diffraction efficiency are investigated. Using the coordinate transformation method (C method), an r-2 aluminum echelle with 79 grooves/mm is optimized through rigorous numerical simulations and shows high diffraction efficiency of 76–81% in the high Littrow orders. A grating is found to be essentially an echelle if it contains a series of reflective facets with a specific tilt angle that are located far from the nonworking facet of the grating and have a deep groove depth; any groove shape that meets these conditions can be called an echelle grating. The underlying mechanism is analyzed phenomenologically using electromagnetic theory. The universal model proposed here, which represents a new cognitive understanding of the concept of the echelle, is ready for use in manufacturing applications and offers a new perspective for the fabrication of these gratings.

1. Introduction

Measurement resolution is one of the most important performance parameters of spectrometers, particularly for those used in astronomical instruments. Gratings, as the most important dispersion devices in spectrometers, largely decide their resolution power. Normally, the spectrometer's resolution power can be improved directly by increasing the groove density of the grating. However, gratings with high groove densities are not only subject to the limitations of the fabrication technology but are also limited to the specified spectral band because of the diffraction limit. Echelle gratings (which are often simply called echelles) [1,2], with their stair-like step structures, have features that include a large grating constant and ideally an apex angle of 90°, and are only used at high diffraction angles in the high spectral orders; they also tend to be large in size to increase the resolution power greatly across the spectrum from the ultraviolet to the infrared [3–6]. It is therefore essential to concentrate the peak diffracted energy in specific blaze orders. The diffraction efficiency is mainly related to the material from which the echelle is made and the groove profile shape, which determines the distribution of the diffraction energy. Depending on whether scalar theory or electromagnetic diffraction theory is used, a triangular groove shape profile, which consists of the blaze angle α (see ∠ECF in Fig. 1(a)), the apex angle ϕ (see ∠CEF in Fig. 1(a)), and a grating constant (see CF in Fig. 1(a)), is the most commonly used model for echelles because they are capable of diffracting light more efficiently. The blaze angle determines the direction in which the blaze diffraction energy is directed; the traditional viewpoint is that the groove apex angle should be 90° or less [7–10]. However, the diffraction efficiency of an echelle with an apex angle of 90° is not high enough to meet the requirements of astronomical observation applications, especially in ultra-band spectra that feature strong absorption. A perfect blazing for the TE and TM polarizations of echelles with perfect triangular groove shapes can only be achieved in certain special cases where the required wavelengths, diffraction orders, angles of incidence and grating constants occur simultaneously [11,12]. These are not common cases, and it is expensive to fabricate perfectly triangular groove shapes because of their diffraction efficiency sensitivity.

In this paper, we present a universal model for echelles, which demonstrate high diffraction efficiency and consist of a set of periodic reflection facets or working facets (see the facet labeled DE in Fig. 1(a)) and nonworking facets (see the facet labeled EFG in Fig. 1(a)) with many different shapes (see Fig. 1).

Each groove in an echelle is essentially a plain reflective micromirror with a specified tilt angle (the optimized blaze angle) that has no shadow effect on the next mirror and a deep groove depth. In particular, two important points about these structures can be determined:

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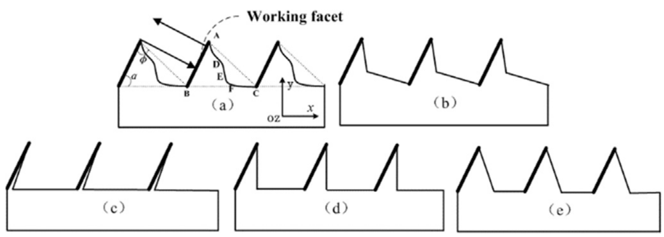

Fig. 1. Various groove shape profiles used for echelles..

(A) The higher efficiencies have little dependence on the nonworking facet, and are primarily dependent on an optimized blaze angle and a very deep groove depth.
(B) The diffraction efficiencies and the widths of the working facets of echelles show similar trends in that they vary with the groove depth.

2. Theoretical analysis

To understand the conclusions drawn above, a typical r-2 echelle grating with 79 grooves/mm is numerically simulated; the grating design is re-optimized using coordinate transformation method (C method)-based software (DELTA version 1.3 [13]) and fabricated using ruling engines that are controlled by a laser interferometer at CIOMP, China [14–17]. The echelle, which is coated with a 12-μm-thick aluminum film and shows 1% uniformity in reflection mode, is considered to be in a Littrow mounting [18,19]. Littrow mounting is considered to be important when using gratings because it corresponds to the maximum diffraction efficiency. For selection of the angle of incidence θ, the grating period d, the wavelength λ, and the diffraction order m, the relationship among these parameters can easily be derived from the grating equation:

$$\sin\theta = m\lambda/(2d) \tag{1}$$

As a classical example, Eq. (1) gives m=−36 when the echelle is illuminated at the He-Ne laser wavelength (632.8 nm). First, an echelle with a perfect triangular groove shape is simulated and re-optimized, with results as shown in Fig. 2, which illustrates the variation of the diffraction efficiency contour with blaze angle and groove depth.

The traditional model of the r-2 echelle, which has a blaze angle of 63.4° and an apex angle of 90° that correspond to a groove depth of

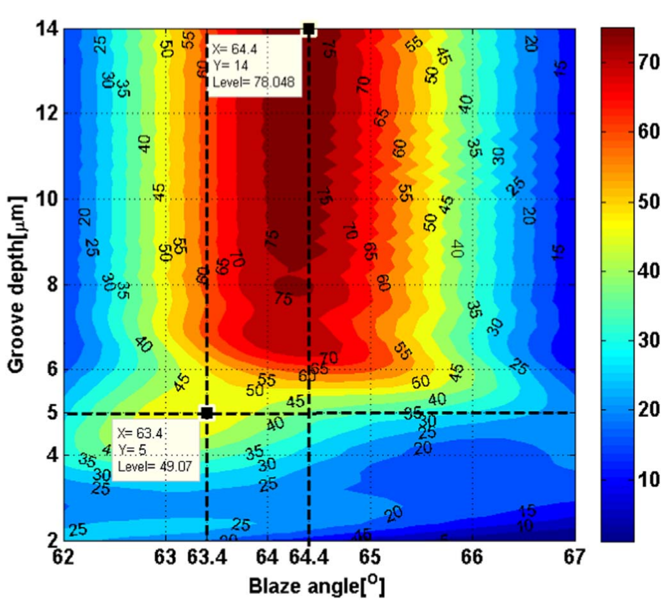

Fig. 2. Diffraction efficiency contour variation with blaze angle and groove depth; here, λ=632.8 nm, m=−36th, d=12.6582 μm, and the refractive index is 1.3730+i 7.6179..

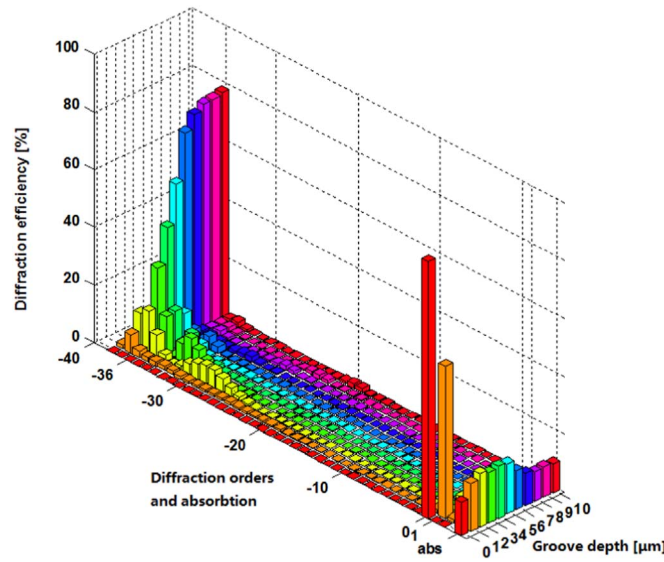

Fig. 3. Energy distributions of all diffraction orders and variation of absorption with groove depth for echelles with α=64.4°..

5 μm, has a diffraction efficiency of only 49%. However, the contours indicate that high diffraction efficiencies can be obtained using deep groove depths. When the blaze angle is fixed at 64.4°, a diffraction efficiency of 78% can be achieved using a groove depth of 14 μm. This diffraction efficiency for the echelle with deeper grooves and an optimized blaze angle is nearly 30% points higher than that of the traditional echelle. To determine the origin of this increase, it is necessary to analyze the energy distributions in all diffraction orders and the absorptions of echelles with different groove depths. Fig. 3 shows the energy distribution as the groove depth varies from 0 to 10 μm while an optimized blaze angle of 64.4° is maintained. The majority of the energy is successively concentrated in the 0, +1st, and −36th orders. The energy is ultimately increased to a high steady-state level with increasing groove depth while the absorption varies between 10% and 18%. Deepening of the groove depth presents an increase in the ratio of the working facet width to the nonworking facet width. For shallow grooves, the nonworking facets play a major role in reflecting the light beams, so the main part of the energy is concentrated on the +1st order, in a similar manner to normal blaze gratings. However, for the deep grooves, the working facets or steep facets play the leading role in diffracting most of the diffraction energy in the −36th order.

Additionally, the energy of the blaze order is analyzed in detail. The relationships between the diffraction efficiencies or widths of the working facets of the echelles and the groove depths in the different Littrow mountings are discussed, with results as shown in Fig. 4. Based on Eq. (1), the relationship between different Littrow orders can be expressed as:

$$m\lambda = m'\lambda' \tag{2}$$

Clearly, the cases at wavelengths of 632.8 nm, 474.6 nm and 258.9 nm correspond to m values of −36, −48 and −88, respectively.

The width of the working facet increases linearly with increasing groove depth before saturating at a high level when the groove depth reaches 5 μm because of shadow effects. Similarly, the diffraction efficiency shows two quasi-linear increasing regions (the first and second regions) before it reaches the third region, in which the efficiency is at a high level of 76–81%, with increasing groove depth, as shown in Fig. 4. The diffraction efficiency and working facet width show similar trends in changing with the groove depth, and look like a section of a sea-bed. In contrast, the cut-off points, which are indicated by red circles on the curves, are different because of differences in the wavelengths and the complex refractive indexes.

From a geometrical optics viewpoint, the diffraction efficiency

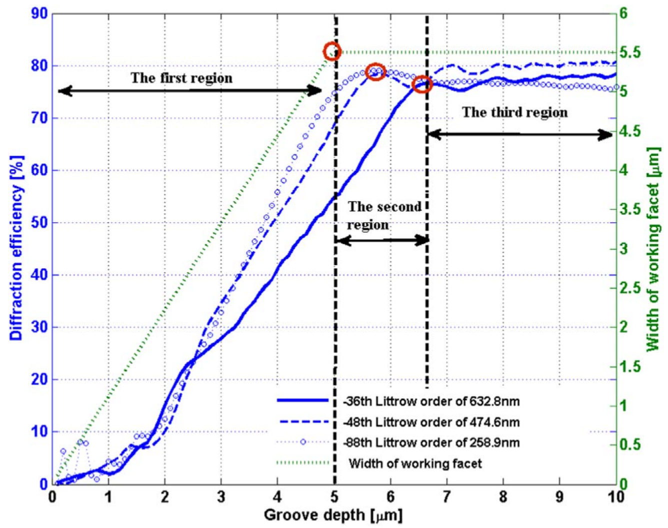

Fig. 4. Variation trends of working facet width and diffraction efficiency with groove depth.

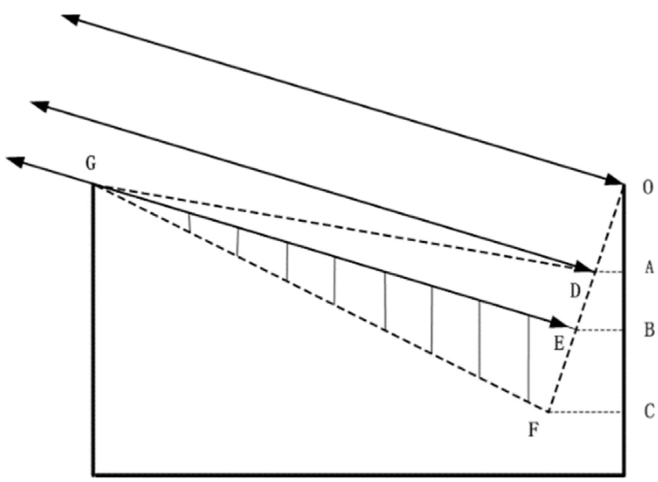

Fig. 5. Schematic diagram of echelle groove shapes with different apex angles in Littrow mounting.

distribution in the first region can be explained based on the widths of the working facets of the echelles. Fig. 5 shows a schematic diagram of three triangular groove shapes (△ODG, △OEG and △OFG) with their groove depths gradually deepening from OA to OC, which correspond to an obtuse angle, a right angle and an obtuse apex angle, respectively. Consequently, the working facet widens as it changes from OD to OE in the Littrow mounting. The wider working facet weakens the effect of the nonworking facet GD, and results in a higher diffraction efficiency in the given blaze order.

However, the diffraction efficiency in the blaze order for the echelle with the obtuse apex angle is obviously higher than that with the right angle, despite the fact that △OEG and △OFG have the same width for working facet OE because of the shadow region △EFG. This phenomenon, which corresponds to the second and third regions shown in Fig. 4, contradicts the ideas of geometrical optics. From the perspective of the electromagnetic theory of gratings, the light field or electric field is distributed within the groove space, from the incident light beam to the edges of the nonworking facets. As the incident light field approaches more closely to the edges, the interaction between them will become stronger, and thus more energy will be lost in the blaze order. It can be concluded from this that a greater groove depth produces more room, meaning that the light field is further away from the edges of the nonworking facets; this gradually weakens the

Table 1
Efficiencies of echelles for several groove shapes shown in Fig. 1 in different Littrow mountings.

	Diffraction efficiency			
Order	b	c	d	e
−36	76.3%	77.9%	78.2%	78.0%
−48	80.4%	83.3%	82.2%	81.4%
−88	78.3%	81.7%	80.7%	80.7%

interaction between them, and to some extent, sufficient space will ensure that the interaction ceases. Therefore, the diffraction efficiency will continue to increase in the second region before finally reaching a high level in the third region.

Additional simulations were performed to look for more evidence to reinforce this conclusion. In the cases of the groove profiles shown in Fig. 1, (a) expresses an universal profile with a tilted working facet, a grating constant and an arbitrary plane, curved or folding surface for the nonworking facet that is distributed in △CEF. By taking several limit conditions as examples, the diffraction efficiencies of groove shapes (b), (c), (d) and (e) are computed with a blaze angle of 64.4° and a groove depth of 7 μm, with results as shown in Table 1. For the −36th, −48th and −88th orders, the differences between their maximum and minimum diffraction efficiencies are only 1.9%, 2.9% and 3.4%, respectively. These results show that the shape of the nonworking facet has almost no relationship to the diffraction efficiency as long as the incident light has not been shadowed, and thus these groove profiles have equivalence.

3. Experimental results

The efficiencies determined above are almost the same as those of perfect triangular echelles with an obtuse apex angle. This indicates that these groove shapes are thus equivalent for the echelles. The results above indicate that it is appropriate to fabricate an echelle with a high grating constant when using a ruling engine because the interaction between the diamond and the metal film can easily produce grooves with optimized blaze angles and sufficient groove depth. Fig. 6 shows an atomic force microscope (AFM) image of a fabricated sample with a quasi-triangular profile containing 79 grooves/mm.

The measured structural parameters of the sample are: groove depth h=6.8 μm, blaze angle α=64.5°, and grating constant d=12.55 μm. The measured efficiencies for unpolarized light at 632.8 and 473 nm are 65.4% and 64.6%, respectively. The deviations of these efficiencies from the simulated results are mainly due to the 8° deviation between the incident and diffracted light beams, some shadow effects on the top of the groove shape, and shifts in the wavelength.

4. Conclusions

We have proposed and investigated a universal model for echelles with high diffraction efficiency. The diffraction efficiency of an echelle has little dependence on the shape of the nonworking facet, and is primarily dependent on the working facet in terms of an optimized blaze angle and a very deep groove depth, which produces sufficient space to ensure that the light is incident on the working facet with no shadow effects, while also weakening the interaction of the incident light field with the edges of the nonworking facets. Any groove shape (see Fig. 1(a)) with these characteristics can be called an echelle. The universal model represents a new cognitive understanding of the concept of the echelle, which will ease the manufacture of echelles by changing the perspective on fabrication.

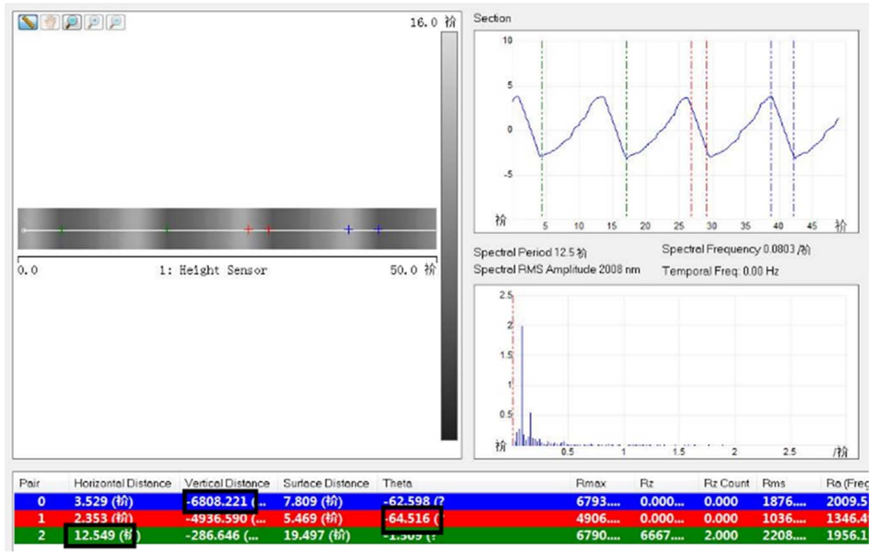

Fig. 6. Cross-section of AFM image of echelle groove shape obtained containing 79 grooves/mm.

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