Novel diffraction gratings for next generation Spectrographs with high spectral dispersion


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ABSTRACT

As a transmission grating, a surface-relief (SR) grating with sawtooth shaped ridges and volume phase holographic (VPH) grating are widely used for instruments of astronomical observations. However the SR grating is difficult to achieve high diffraction efficiency at high angular dispersion, and the VPH grating has low diffraction efficiency in high diffraction orders. We propose novel gratings that solve these problems. We introduce the hybrid grism which combines a high refractive index prism with a replicated transmission grating, which has sawtooth shaped ridges of an acute apex angle. The birefringence VPH (B-VPH) grating which contains an anisotropic medium, such as a liquid crystal, achieves diffraction efficiency up to 100% at the first diffraction order for natural polarization and for circular polarization. The quasi-Bragg (QB) grating which consists of long rectangular mirrors aligned in parallel precisely, like a window blind, achieves diffraction efficiency of 60% or more in higher than the 4th diffraction order. The volume binary (VB) grating with narrow grooves also achieves diffraction efficiency of 60% or more in higher than the 6th diffraction order. The reflector facet transmission (RFT) grating which is a SR grating with sawtooth shaped ridges of an acute apex angle achieves diffraction efficiency up to 80% in higher than the 4th diffraction order.

Keywords: Echelle, Volume grating, Birefringence grating, Bragg grating, RCWA

1. INTRODUCTION

Diffraction grating for the 8.2m Subaru Telescope [1] and for the next generation huge telescopes of ground-based [2-4] and space-borne [5] are required large angular dispersion and high diffraction efficiency. The physical image size of a star at the focal plane of a ground-based telescope is typically determined by a seeing size. The size of a spectrograph for the ground-based telescope without adaptive optics increases as a size of the telescope increases because a slit width of the spectrograph is proportional to the seeing size, which is proportional to a diameter of the primary mirror of the telescope. Although a space-borne telescope achieves a diffraction-limited imaging, the diameter of the telescope is increased, and light-gathering power increases, astronomers desire a spectrograph with a higher and higher resolving power. Reduction in size and weight of the spectrograph by using a diffraction grating with high angular dispersion is required because restrictions of weight and volume of a scientific instrument for the space-borne telescope are very strict.

In the case of a spectrograph using a reflection grating with the Littrow mount (the configurations which the incident and diffraction angles are equal, and shapes of incident and diffracted beams are identical), since a collimator and camera (imaging optical element) of the spectrograph need to place a large distance from the diffraction grating, the diameters of the collimator and the camera optics become large. On the other hand, a spectrometer using a transmission grating, diameters of collimator and camera optics are able to be smaller than the spectrograph with the reflection grating because the optical elements can place in the close vicinity of the diffraction grating. Moreover, the spectrometer using the transmission grating achieves a long slit spectrum with a small curvature and reduces aberrations for a point image because the spectrograph is able to realize the perfect Littrow mount.

1.1 Surface relief grating

The conventional surface relief (SR) grating with sawtooth shaped ridges (Fig. 1) is commonly used as a transmission grating for a low-dispersion spectrograph and as a grism (the direct diffraction grating). However, in the case of the transmission grating, a diffraction efficiency of an SR grating at the first diffraction order decreases steeply at grating
period with 4 times of the wavelength or smaller [6]. Moreover an SR grating of the transmission type is necessary to increase a refractive index of a medium of grating ridges according as a diffraction angle (an angular dispersion) becomes large.

Equations of refractions at incident and exit surfaces of the SR transmission grating in Fig. 1 are given by
\[
\sin \theta_0 = n \sin \theta_1 \quad (1-1)
\]
and
\[
n \sin (\alpha - \theta_1) = \sin \theta_2, \quad (1-2)
\]
respectively. In the case of the Littrow mount, that is \(\theta_2 = \alpha + \theta_0\), the Eq. 1-2 is rewritten as
\[
n \sin (\alpha - \theta_1) = \sin (\alpha + \theta_0)
\]
\[
n (\sin \alpha \cos \theta_1 - \sin \theta_1 \cos \alpha) = \sin \alpha \cos \theta_0 + \sin \theta_0 \cos \alpha
\]
\[
(n \cos \theta_1 - \cos \theta_0) \sin \alpha = (\sin \theta_0 + n \sin \theta_1) \cos \alpha. \quad (1-3)
\]
Eq. 1-3 is transformed by substitution of Eq. 1-1 as
\[
(n \cos \theta_1 - \cos \theta_0) \sin \alpha = 2 \sin \theta_0 \cos \alpha.
\]
As the result, the equation for the blazed angle \(\alpha\) is given by
\[
\tan \alpha = \frac{2 \sin \theta_0}{(n \cos \theta_1 - \cos \theta_0)}. \quad (1-4)
\]
The Eqs. 1-1, 1-2 and 1-4 apply to the grating ridges with the refractive index of 1.5, the incident and the diffraction angles \(\theta_0\) must be smaller than 20° by the restriction of the critical angle for \(\theta_2\) which is smaller than 90°. As well as, in the case of \(\theta_0 = 45°\), the refractive index of the grating ridges must be larger than 2.3. Clear materials with the refractive index of 2.3 or more in the visible wavelength are limited such as ZnS, ZnSe, TiO2 and diamond. Especially, no clear material except diamond with the refractive index of 2.3 or more exists in the ultra violet wavelength.

1.2 Volume phase holographic grating

While a volume phase holographic (VPH) grating achieves very high diffraction efficiency up to 100% at the first diffraction order for \(S\) or \(P\) polarization [6, 7]. In these reasons, a lot of VPH gratings and VPH grism have been installed in numerous instruments for relatively high-dispersion spectroscopic observations [8-11]. However the VPH grating is not able to achieve high efficiency for natural polarization and circular polarization according as a diffraction angle increases because the properties of the diffraction efficiency are different between \(S\) and \(P\) polarization [12]. Moreover, a wavelength bandwidth of a VPH grating is limited by a refractive index modulation of a recoding material using for the VPH grating, which has the maximum of about 0.15 at present [7]. Furthermore, the VPH grating is not suitable for an echelle spectrograph which several to hundreds of diffraction orders are folded onto a two dimensional detector by combination of a grating of high diffraction orders with a cross disperser, such as a prism or a low-dispersion grating of the first diffraction order, because diffraction efficiency of the VPH grating decreases as the diffraction order increases [13].

![Figure 1 Propagation of incident beam in surface relief grating with saw tooth ridges in the case of the Littrow mount [14].](image1)

![Figure 2 Schematic representation of hybrid grism for MOIRCS.](image2)
We introduce novel transmission gratings for instruments of the 8.2m Subaru Telescope, the Thirty Meter Telescope (TMT) and the next generation huge telescopes about their expected performances based on simulations and about fabrication methods in this paper [14, 15]. Those are the hybrid grism, the birefringence VPH (B-VPH) grating, the quasi-Bragg (QB) grating, the volume binary (VB) grating and the reflector facet transmission (RFT) grating.

2. HYBRID GRISM

The middle dispersion grisms for the MOIRCS [16] of the Subaru Telescope are fabricated by directly ruling of saw-tooth shaped ridges onto a hypotenuse of a KRS-5 (the mixed crystal of TaCl and TaBr) prism. However many cracks like tiny mosaic are seen on the surfaces of the KRS-5 grisms. And the KRS-5 grisms seriously deteriorate efficiency and width of line spectrum. These damages of the grisms are supposed to be caused by repetition of heat cycles between a room temperature and cryogenic temperature when open and shut of the cryostat vessel of the MOIRCS. We have decided the development of hybrid grisms for replacement of the KRS-5 grisms in this reason. The hybrid grism is consisted by the combination of a ZnSe prism (n=2.46@1.65 µm) and replicated SR grating (n~1.5@1.65 µm) with ridges of an acute apex angle.

The beam propagation in the hybrid grism as shown in Fig. 2 is expressed as follows. The equations for refraction at the incident surface of the prism, the boundary between the prism and the glass substrate and the exit surface of a ridge are given by

\[
\sin \theta_0 = n_1 \sin \theta_1, \quad (2-1)
\]

\[
n_1 \sin (\alpha - \theta_1) = n_2 \sin \theta_2 \quad (2-2)
\]

and

\[
n_2 \sin (\beta - \theta_2) = \sin (\beta - \theta_3), \quad (2-3)
\]

respectively. The Eq. 2-3 is transformed by the following procedure as

\[
n_2 (\sin \beta \cos \theta_2 - \cos \beta \sin \theta_2) = \sin \beta \cos \theta_2 - \cos \beta \sin \theta_2,
\]

\[
\tan \beta = \frac{n_2 \sin \theta_2 - \sin \theta_3}{n_2 \cos \theta_2 - \cos \theta_1}. \quad (2-4)
\]

The diffraction angle \(\theta_3\) is given by equation of diffraction as

\[
m\lambda = \Lambda (n_2 \sin \theta_2 - \sin \theta_3). \quad (2-5)
\]

\[
\sin \theta_3 = n_2 \sin \theta_2 - \frac{m\lambda}{\Lambda}. \quad (2-6)
\]

When the diffraction beam is parallel to the incident beam, the blazed angle \(\beta\) is obtained by substitution of \(\theta_3 = \alpha - \theta_0\) and the Eq. 2-6 into the Eq. 2-4 as

\[
\tan \beta = \frac{m\lambda_0}{\Lambda \left[n_2 \cos \theta_2 - \cos (\alpha - \theta_0)\right]}, \quad (2-7)
\]

where \(\lambda_0\) is the direct vision wavelength. The apex angle \(\gamma\) is given by

\[
\gamma = 90^\circ - \beta + \theta_2, \quad (2-8)
\]

when \(\theta_2\) is parallel to the other facet of the exit surface of the sawtooth shaped ridge.

The hybrid grism for the MOIRCS has the grating period of about 10µm and the apex angle of the sawtooth shaped ridges of about 60°. Figure 3 shows a fabrication procedure of the transmission grating with an acute apex angle for the hybrid grism. The master grating (die) for the hybrid grism is cut onto a surface of a work piece of the nickel-phosphorus alloy, produced by the non-electrolytic plating on a metal substrate, by the shaper process with an ultra-high
3. BIREFRINGENCE VPH GRATING

The B-VPH grating consists of an optically anisotropic medium such as a liquid crystal (LC) and optically isotropic medium or consisted with two kinds of optically anisotropic media [17]. We carried out numerical calculations of the diffraction efficiency of the B-VPH gratings by using our own software of the rigorous coupled-wave analysis (RCWA) method [18, 19] that is improved for a diffraction grating with an optical anisotropic medium. We confirmed that the B-VPH grating is able to achieve high diffraction efficiency up to 100 % (neglecting the surface Fresnel’s reflection losses) at the first diffraction order with respect to natural polarization and circularly polarization because the characteristics of the diffraction efficiencies of the B-VPH grating is able to coincide S and P polarizations.

B-VPH gratings which recording materials are combined three kinds of LCs of ultra-violet curable with a normal LC were fabricated by a two beams interferometer with a He-Cd laser (315 nm) as an exposure optical system. The LC gratings have the thickness of the LC layer of 1.3µm and the grating period of 0.45µm. As a result, all of the LC-VPH gratings of combination are able to observe diffraction beams (Fig. 4). However the LC-VPH grating of the combination with LCs of the same maker that is RMC03 (UV-curable LC made by Merck) and MJ041609 (normal LC made by Merck), has week diffraction efficiency. We are going to fabricate LC-VPH gratings with thickness of the LC layer of 10~20µm and the grating period of 1.0µm.

4. QUASI-BRAGG GRATING AND VOLUME BINARY GRATING

The Wide Field Optical Spectrograph (WFOS) which is the first generation instrument of the Thirty Meter Telescope (TMT) is planed to use the reflection gratings in the current design concept [20]. The conventional SR grating of the...
reflection type has advantages that the grating achieves comparatively high diffraction efficiency and a grating with a large size is easily fabricated by a replication from a master grating. However a diameter of the camera of the WFOS becomes very large because the Littrow configuration with a reflection grating needs a long distance between the camera and the grating as mentioned in the section of the introduction.

In these reasons, we have evaluated the performance of novel transmission gratings for the WFOS. The transmission gratings have the same incident and diffraction angles of 36°–53°, the grating period of 2–5 µm, the diffraction orders of 5th–9th and 8th–13th. However a conventional SR transmission grating and VPH grating are not available for the WFOS gratings as mentioned in the subsection 1.1 and 1.2.

The QB grating [13] which has long rectangular mirrors aligned accurately in parallel like a window blind as shown in Fig. 5 achieves high diffraction efficiencies in higher than the 4th diffraction order at the incident and diffraction angles of 45° as shown in Fig. 7 (neglected surface Fresnel’s reflection losses). The dropping of diffraction efficiency of P polarization around the 8th and the 9th orders in Fig. 8 is supposed to be influence of the surface plasmon resonance. As well as the VB grating [21, 22] as shown in Fig. 6 achieves high diffraction efficiencies [23] in higher than the 5th diffraction orders at the incident and the diffraction angles of 45° by matching a line and space ratio to coincide S polarization with P polarization as shown in Fig. 8 (including the reflection loss by the incident surface). It is able to regard the VB grating as a QB grating in this case because grooves of the VB grating function as total reflection mirrors. The droppings of diffraction efficiency of S polarization below the 6th order and of P polarization below the 4th order in Fig. 9 are supposed to be influence of the evanescent wave coupling between a ridge and the next ridge beyond the groove. And the reason of P polarization achieves higher efficiency than S polarization in Fig. 9 is suppose to be that the incident angle is close to the Brewster angle.

4.1 Fabrications of quasi-Bragg grating

The first fabrication of the QB grating was done by stacking of 40 sheets of quartz mirror substrates. The mirror substrate is a thickness of 0.2 mm, and chromium as a mirror is deposited on one side. The mirror substrates were laminated by an optical adhesive mixed with glass beads of 10 µm in diameter. However, the QB grating did not function as a diffraction grating in the visible wavelength because the glass beads have large variations in diameter [14, 15].
The subsequent fabrications of the QB grating consisted of 20 sheets of quartz mirror substrates with a thickness of 0.5 mm and with a uniform gold film deposited onto both sides. These substrates were laminated by atoms fusion bonding at room temperature in air, processed by the Frontier Research Institute for Interdisciplinary Sciences, Tohoku University [24]. The QB grating has very high accuracy regarding the grating period, which is available for the visible wavelength, because a symmetrical diffraction pattern was seen [14].

The third fabrications of the QB grating consisted of 47 sheets of mirror substrates of quartz glass with a thickness of 0.5 mm, as shown in Fig. 9. The substrate has a chromium mirror deposited onto one surface, and the back surface of the mirror substrate was embossed by wet etching itself, maintaining the thickness of the substrate by the left panel of Fig. 9. The embossing was performed by the Nanotechnology Platform facilities of the Toyota Technology Institute. The mirror substrates were laminated by a UV-curable optical adhesive by the right panel of Fig. 9. Although the QB grating did not show optimal condition of adhesion as it has partial periodic errors, the lattice spacing of the grating achieves practical accuracy even in visible light [14].

4.2 Fabrications of Volume binary grating

To achieve a thick binary grating with a high aspect ratio, we are developing a fabrication method for the thick binary grating by applying MEMS (Micro Electro Mechanical Systems) technology in the Nanotechnology Platform facilities. We had fabricated volume binary gratings of a photoresist, which grating period is 5 µm, line and space ratio is 4:1, and thickness of the grating is 10 µm. However, a uniform VB grating with a large area was hard to fabricate by this process.

We are planning to develop a high-dispersion echelle grism for MOIRCS, which grating period is 5.1 µm, line and space ratio is 9:1, thickness of the grating is 16 µm, and the Bragg angle in the vacuum is 28.4°. The master grating for the grism is going to be fabricated by the Bosch process as shown in Fig. 10.

5. REFLECTOR FACET TRANSMISSION GRATING

The RFT grating is an SR grating with saw-tooth shaped ridges of an acute apex angle as shown in Fig. 11. The incident beam from one side of a ridge of the RFT grating is reflected by another surface of the ridge, and the diffraction beam is exited from the rear surface of the RFT grating. In order to increase a diffraction angle, a refractive index of the conventional SR transmission grating has to increase because the beam in the SR grating is folded by refraction at the incident
and the exit interfaces, as mentioned in the subsection 1.1. On the other hand, the RFT grating is able to use a large diffraction angle even with a small refractive index of the grating ridges because the beam is folded by reflection in the RFT grating.

5.1 Basic equations for reflector facet transmission grating

The beam propagation in the RFT grating as shown in the left panel of Fig. 11 is expressed as follows. The equations for an incident angle $\theta_1$ and refraction angle $\theta_2$ at the incident surface of the ridge are given by

$$\theta_1 = \alpha - \theta_0 \tag{5-1}$$

and

$$\sin \theta_1 = n \sin \theta_2, \tag{5-2}$$

respectively. The relations in $\theta_2$, reflection angle $\theta_3$ at the other surface of the ridge and the apex angle $\gamma$ of the ridge is obtained by the sum of the interior angles of the triangle as

$$R + \theta_2 + R - \theta_3 + \gamma = 2R,$$

$$\theta_3 = \theta_2 + \gamma. \tag{5-3}$$

As well as the relation in $\theta_3$, the reflected beam angle $\theta_4$ at the exit surface and the angle of the refraction surface $\beta$ is obtained by

$$\theta_1 + \theta_4 + 2R - \beta = 2R,$$

$$\theta_4 = \beta - \theta_3. \tag{5-4}$$

The equation for refraction at the exit surface of the RFT grating is given by

$$n \sin \theta_4 = \sin \theta_0. \tag{5-5}$$

When the reflected beam propagates parallel from an angle $\phi$ to the incident surface, the angle of the incident surface $\alpha$ is obtained by

$$\theta_4 = R - \alpha + \phi,$$

$$\alpha = R - \theta_4 + \phi \tag{5-6}.$$  

Eq. 5-3 is transformed by substitution of Eq. 5-4 and the sum of the interior angles of a triangle: $\gamma + \alpha + \beta = 2R$ as

$$\theta_2 = \alpha + 2\beta - \theta_4 - 2R. \tag{5-7}$$

The angle of reflector surface $\beta$ is obtained by transformation of Eq. 5-7 as

$$\beta = (\theta_2 + \theta_4 - \alpha)/2 + R. \tag{5-8}$$

Note that the RFT grating does not achieve its essential performance if a beam enters from back surface of the ridges because a part of the beam is folded to irregular direction by the ridges.
5.2 Example of calculation of RFT grating

The inverse ray tracing of the RFT grating is expressed as follows, when a incident and exit angle of beam for a RFT grating are 45°, the refractive index of ridges of the RFT grating is 1.54 as shown in the right panel of Fig. 11. The angle of θ₄ is obtained by substitution of θ₀ = 45° and n = 1.54 in Eq. 5-5 as

$$\theta_4 = \sin^{-1} \left( \frac{\sin 45°}{1.54} \right)$$

= 27.33°.

When the diffraction angle in the vacuum is 45°±2.5°, the angle φ is obtained by

$$\phi = \sin^{-1} \left( \frac{\sin (45° + 2.5°)}{1.54} \right) - \theta_4$$

= 1.27°.

The angle of incident surface α is obtained by substitution of the values of θ₄ and φ in Eq. 5-6 as

$$\alpha = 90° - 27.33° + 1.27°$$

= 63.94°.

The angle of reflector surface β is obtained by substitution of α, θ₀, n and θ₄ in Eq. 5-8 as

$$\beta = \frac{1}{2} \sin^{-1} \left( \frac{\sin (63.94° - 45°)}{1.54} \right) + 27.33° - 63.94° + 90°$$

= 77.78°.

The angles γ, θ₃, θ₂ and θ₁ are obtained by the sum of the interior angles of the triangle, Eqs 5-4, 5-3 and 5-2 as

$$\gamma = 2R - \alpha - \beta = 180° - 63.94° - 77.78°$$

= 38.28°.

$$\theta_3 = \beta - \theta_4 = 77.78° - 27.33°$$

= 50.45°.

$$\theta_2 = \theta_3 - \gamma = 50.45° - 38.28°$$

= 12.17°.

and

$$\theta_1 = \sin^{-1} (n \sin \theta_2) = \sin^{-1} (1.54 \times \sin 12.17°)$$

= 18.94°.
respectively. The angle $\theta_1$ is also obtained by Eq. 5-1 as

$$\theta_1 = \alpha - \theta_0 = 63.94^\circ - 45^\circ = 18.94^\circ.$$ 

We are planning to fabricate a master grating of a RFT grating by using the same method as the fabrication process of the hybrid grism (Fig. 3).

6. CONCLUSIONS

In this paper, we introduced innovative diffraction gratings. The hybrid grism is consisted by combination of a ZnSe prism and replicated surface-relief grating with ridges of an acute apex angle. The B-VPH grating is able to achieve high diffraction efficiency of up to 100% for the natural polarization and the circular polarization at the first diffraction order. The QB grating and the VB grating achieve comparative high diffraction efficiency in high diffraction orders. The RFT grating is able to use for a large diffraction angle. The RFT grating achieves high diffraction efficiency of up to 80% in high diffraction orders. These types of diffraction gratings are useful for new instruments on both the existing 8m class of telescopes, as well as the upcoming 30m class and the space-borne telescopes, due to their ability to produce high spectral dispersion from a relatively small pupil, thereby making the whole instrument smaller, more practical, and less expensive.

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REFERENCES


As a transmission grating, a surface-relief (SR) grating with sawtooth shape grooves and volume phase holographic (VPH) grating are widely used for instruments of astronomical observations. However the SR grating and the VPH grating are difficult to achieve high diffraction efficiency at high angular dispersion. We propose two novel gratings that solve this problem. One is the birefringence VPH grating, which contains anisotropic media such as liquid crystals. The other is the quasi-Bragg (QB) grating, which consists long rectangle thin metallic films or low refractive index layers aligned in parallel precisely such as a window shade. We also introduce the hybrid grism, which combines a high refractive index prism and replicated transmission grating with sawtooth shape grooves of acute angle.
このバイブリッド-グリズムは格子間隔が約10μm、格子の頂角が60°程度の鏡面になる。この表面刻線型回折格子の製作方法をFig.2に示す。まず、刃先を格子形状と同じ角度の単結晶ダイアモンドバイト超精密加工装置で取り付けて無電解銅めっきのニッケル・ヒン合金のワークピースをシェーバー加工によって金型を製作する。金型に黒塗料を塗布して紫外線硬化型等の樹脂を塗りした後に平行平板基板を設置し、基板側から紫外線光を投射し、金型を刻離することによって完成する。シェーバー加工の条件が適正な場合、この加工は加工機の温度環境に極めて敏感であることがわかり、現在は恒温ブースの温度を安定させるための改造を行っている。

3. Birefringence VPH grating

透過型のVPH gratingにおいて、ホログラム記録材料として液晶等の光学異方性媒質と等方性媒質、あるいは2種類の光学異方性媒質を組み合わせた場合、任意のブラッグ角において光学異方性媒質と等方性媒質の屈折率を調整して、偏光とP偏光の2回折光の回折効率特性を一致させることによって、自然偏光や円偏光に対しても高い回折効率を達成できるようになる。

我々が独自に作成した厳密結合波解析
VPH grating は数段が高くなると回折効率が低下してしまう一方、高屈折率のプリズムに階段形状の回折格子を可視光波長域において精度よく一体加工することは困難である。

Fig. 4 のように短査査の金属膜あるいは低屈折率層を基板にプリズムのように精度よく平行に配置された Quasi-Bragg (QB) grating は、高次回折光において高い回折効率を達成できることが RCWA 法の数値解析によって確認されている (Fig.5) 10, 17).

東北大学 学際科学フロンティア研究所において、両面に厚さが均等な金の膜を堆積させた厚さ 0.5mm の石英ミラー基板 47 枚を常温接合法 21) により積層して QB grating を試作した。また、平行平面基板自体をエッチングして厚さを維持したスペースを形成した基板を積層することによって、格子周期の精度が高い QB grating を実現する方法を考案した。Fig. 6 のようにクロムがスパッタリングされれたミラー一面の裏面にエッチングによりエンボス（スペース）を形成した 0.5mm の石英ミラー基板 47 枚を紫外線硬化型接着剤により積層して、QB grating を試作した。

これらの QB grating と以前に試作したクロムがスパッタリングされたミラー基板をガラスビーズが混入された接着剤で積層した QB grating の回折像を観察したところ、ガラスビーズが混入された接着剤で積層した QB grating は、ガラスビーズの直径のばらつきのため、Fig. 7 の上段のように可視光においては回折格子として機能しないことがわかった。一方、常温接合法により積層された QB grating は、Fig. 7 の中段のように可視光において極めて高い格子周期精度であることが分かった。また、エンボス基板を積層した QB grating は接着の条件が最適ではなかったため、Fig. 7 の下段のように部分的に周期誤差

Fig. 4 Schematic representation of quasi-Bragg grating.

Fig. 5 Diffraction efficiencies of QB gratings for the 6th to 20th diffraction orders. n₀ = 1.0, n₁ = 1.54, λ = 5 μm, t = 9 μm, t₀₉ = 45°. Upper panel: S polarization, Lower panel: P polarization. 17).

Fig. 6 Fabrication process of mirror substrate with emboss for QB grating.
Fig. 7 Diffracted beam images of QB gratings, Quasi-Bragg angle: 45°. QB grating on the top panel shows that silica glass substrates of 0.2 mm in thickness deposited with a chromium film on one side are laminated by adhesive mixed with glass beads of 10 µm in diameter. QB grating on the middle panels shows that silica glass substrates of 0.5 mm in thickness deposited with gold film on both sides are laminated by fusion of gold at room temperature21). QB grating on the bottom panels shows that silica glass substrates of 0.5 mm in thickness with emboss laminated by adhesive17).

があるものの、可視光においても実用的な精度の格子間隔を実現できることを確認した。

5. おわりに

本稿で紹介したハイブリッド・グリズムは高屈折率のプリズムに溝を直接加工したプリズム（ソリッド・グリズム）と比べて、高い回折効率を達成できる上、開発期間を短くできることを期待されている。また、Birefringence VPH grating は入射角と回折角（プラック角）が真空中において30°を超える場合であっても自然偏光や円偏光に対して1次回折光の回折効率が最大100%を達成できる。一方、QB grating は高次回折光において高い効率を達成することができる。我々はミラー基板の常温接合やエンボス付きミラー基板の種類により、高精度な QB grating が製作できることを示した。

豊田工業大学のナノテクノロジープラットフォーム技術支援員の新原 健氏と奥村 優雄氏には素早い対応をしていただき、短期間に劇的な技術革新と微細な深い矩形格子に対する多くの知見が得られた。本研究の回折格子や光学部品等の試作や測定は主に国立天文台先端技術センターの設備を利用させていただいている。本研究は日本科学技術振興機構の A-Step 探索タイプ予算および、科学研究費 挑戦的萌芽研究、国立天文台共同開発研究経費、TMT 戦略的基礎開発研究経費の支援により推進された。

文献