First high-efficiency and high-resolution (R=80,000) NIR spectroscopy with high-blazed echelle grating: WINERED HIRES modes

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ABSTRACT

WINERED is a PI-type 0.9 – 1.35 μm high-resolution spectrograph developed by the Laboratory of Infrared high-resolution Spectrograph (LiH) of the Koyama Astronomical Observatory at Kyoto Sangyo University, Japan. The scope of WINERED is to realize a high-resolution near-infrared (NIR) spectrograph with both wide coverage and high sensitivity. WINERED provides three observational modes called as the Wide, Hires-Y and Hires-J modes. The Wide mode simultaneously covers the z, Y and J-bands in a single exposure with $R \equiv \lambda/\Delta\lambda = 28{,}000$ and was commissioned for the 1.3 m Araki Telescope of Koyama Astronomical Observatory in 2013. We have been building alternative observational modes "Hires-Y" and "Hires-J", providing R = 80,000 spectra in the Y- and J-bands, respectively. There are two choices for realizing a compact spectrograph with a high spectral resolution of $R \geqq 50{,}000$: an immersion grating (IG) or a high-blazed echelle grating (HBG). Investigating the availabilities of both optical devices, we selected an HBG solution for $\lambda <$ 1.5 μm because can be realized with currently available technology in earlier time. The optical parameters of WINERED's HBGs are as follows: groove pitch = 90.38 μm, blaze angle = 79.32 °, and apex angle = 88 °, which are determined to minimize vignetting in the optical system as well as aberrations with the spectral resolution of R = 80,000. Custom HBGs were made by CANON Inc. Because of the size the size limitation in fabrication process, we decided to use a mosaicked grating consisting of two HBGs. The alignment tolerances of the two HBGs are very tight (< 0.5 arcsec for the parallelism between grooves of the two gratings and 1.5 arcsec for the flatness between the two grating surfaces). To enable these fine alignments, we designed a grating holder with an adjustment mechanism with sub-μm positional resolution. We adapted cordierite CO-220 as the material for the grating holder, thereby reducing the misalignment generated by thermal expansions/compression with extremely low coefficient of thermal expansion (CTE $< 2.0 \times 10^{-8}$ K^{-1} at 23 ℃). As a result of the measurement of the two HBGs installed in the grating holder, we confirmed the parallelism of < 0.1 arcsec. Finally, we evaluated the total optical performances of the Hires modes with the HBGs. The widths of the monochromatic slit-images obtained with a Th-Ar lamp were measured to be 1.7 – 2.3 pixels, which agreed well with the designed values (1.6 – 2.6 pixels). These results should guarantee the spectral resolution (R = 78,000) estimated from the measurement of the linear dispersion [pix / μm]. Because there was an avoidable degradation in reducing the two-dimensional spectrum using HBGs with a large γ angle, the final spectral resolution of the reduced one-dimensional spectrum results in R = 68,000.

Keywords: Infrared, Spectroscopy, High resolution, High efficiency, Echelle grating, Non-cryogenic optics

1. INTRODUCTION

1.1 NIR HIGH-RESOLUTION SPECTROGRAPH, WINERED

Near-infrared high-resolution spectrometry is an essential tool for astronomy because it provides information on the chemical abundances and dynamics of astronomical objects imbedded in the circumstellar and/or interstellar media, or located at cosmological distances. Recently, NIR high-resolution spectroscopy has been applied to various objects in the wide fields of astronomy including high-z QSO absorption systems, the exo-planets, the kinematics of the circumstellar matters of LBVs, YSOs, AGB stars including proto-planetary nebulae (PPNs), novae and supernovae, and late-type stars and stars embedded in the star-forming regions and around the galactic center. We have been developing a next generation NIR high-resolution spectrograph, WINERED, which has three features: “no cold stop,” “wide spectral coverage” and “high sensitivity”. WINERED provides three observational modes; the Wide mode, which covers the z, Y and J-bands simultaneously with R = 28,000 and the Hires-Y and Hires-J modes, which cover the Y and J-bands, respectively, with R = 80,000 (Table 1). The total throughputs are unprecedentedly high among the optical or NIR high-resolution spectrometers; > 50 % for the Wide mode and > 35 % for both Hires modes. The Wide mode has already been commissioned for the 1.3 m Araki telescope of the Koyama Astronomical Observatory, Japan, since 2013 (see Ikeda et al. 2016 for more detail)[1]. On the other hand, the Hires-Y and Hires-J modes are under development and are scheduled to be completed in the summer of 2016.

Table 1. Specifications of WINERED.

	Wide mode	Hires-Y mode	Hires-J mode
Wavelength coverage	0.90–1.35 µm	0.95–1.11 µm	1.14–1.36 µm
Nominal spectral resolution	28000	80000	80000
Total throughput	> 50 %	> 28 %	> 35 %
Slit width	100 µm, 200 µm, 400 µm		
Slit length	3.12 mm		
Magnification factor	0.346		
Volume	1750 mm(L) × 1070 mm(W) × 500 mm(H)		
Operation temperature[1]	270–300 K		

1. Except for the camera lens and the infrared array

1.2 IMMERSION GRATING AND HIGH-BLAZED ECHELLE GRATING

The maximum spectral resolution of an astronomical spectrograph under the seeing limit condition is given by,

$$R = \frac{\lambda}{\Delta\lambda} = \frac{2n\Phi\tan\theta_B}{sD} \quad (1)$$

where Φ is the collimated beam diameter, θ_B is the blaze angle, n is refractive index in the grating surface, s is the silt width, and D is the telescope diameter. This equation suggests that the spectral resolution is inversely proportional to the aperture size of the telescope. Historically, a higher resolution spectrograph ($R \geqq 50{,}000$) for $8-10$ m-class telescopes has been realized with a larger beam size, Φ i.e., with a larger instrument. However, the high-resolution spectrographs for the coming 30 m-class telescopes cannot be realized using the same strategy because it is technically and financially difficult to build much larger cryogenic instruments. In order to solve this problem, several authors have proposed concepts for high-resolution spectrometers with small beam sizes over the last 30 years (e.g., Dekker et al. 1992, Lacy et al. 2006)[2,3]. One is immersion grating (IG), which realizes high resolution with a high refractive index material ($n > 2$), and the high-blazed echelle grating (HBG) with a highly blaze angle ($\theta > 75$ °, see Figure 1).

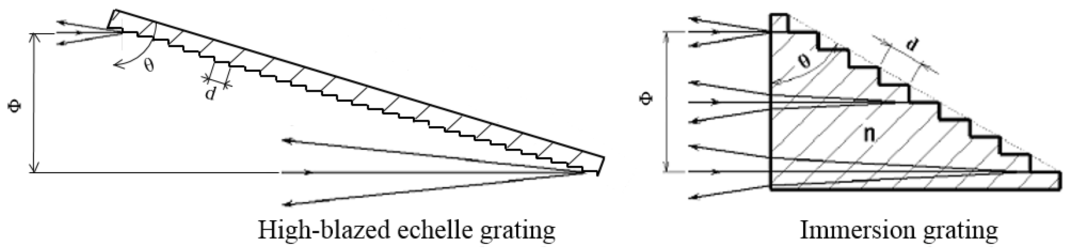


Figure 1. High-blazed echelle grating and immersion grating.

Our group, which belongs to the Laboratory of infrared spectroscopy (LiH), Koyama Astronomical Observatory of Kyoto Sangyo University, has also studied these new grating technologies (e.g., Ikeda et al. 2008a, 2008b, 2009, 2010, 2014, and 2015, Kaji et al. 2014, Sarugaku et al. 2012, 2016)[4-12]. For the Hires-Y and Hires-J modes of WINERED, both the ZnSe IG and the HBG were considered as candidates. We have already manufactured a large ZnSe IG with a grating surface area of 50 mm × 80 mm as a trial, and found that it suffers problems with degradation of its diffraction efficiency, probably generated by the reflective Cu coating on the groove surface. On the other hand, the high-efficiency HBG could be realized in cooperation with Photocoding Co. and Canon Inc., of Japan (see Section 3.2). Therefore we decided to employ HBGs for the high-resolution modes of WINERED. In this paper, we report the technical details and the current status of the Hires-Y and Hires-J modes. We describe the optical design of the two Hires modes in Section 2, introduce the design and evaluation results of both our HBGs and the extremely fine-alignment grating holder in Section 3, and report on the preliminary results with the Hires-J mode in Section 4. Finally, we summarize the future plan for these Hires modes in Section 5.

2. OPTICS

2.1 DESIGN

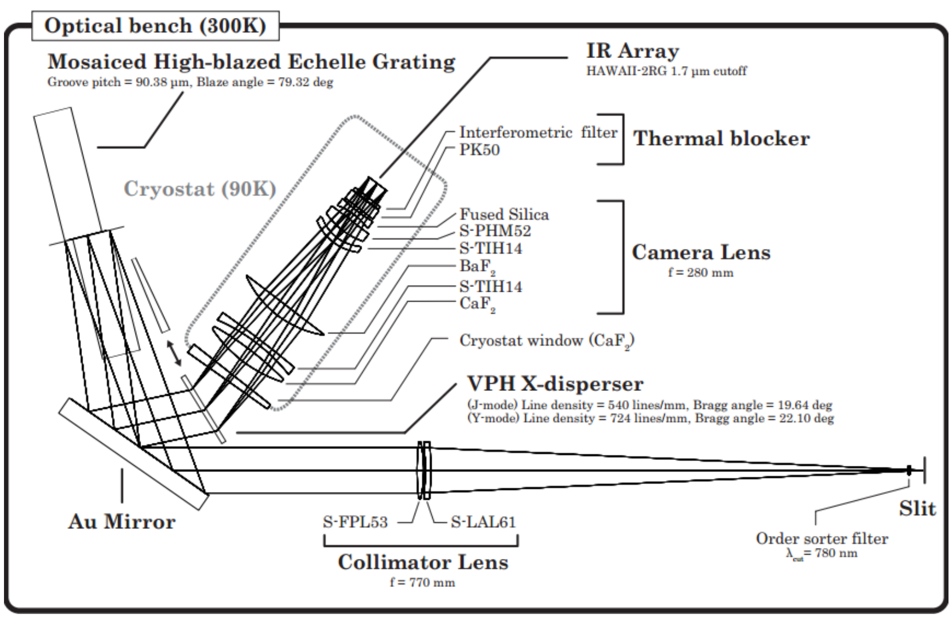


Figure 2. Optical layout of the Hires-Y and Hires-J modes.

Figure 2 shows the optical designs of the Hires-Y and Hires-J modes, which are almost the same as that of the Wide mode except for using a different main disperser, cross-dispersers, and an additional fold mirror located after the collimator-lens unit. The physical size of the fold mirror is 265 mm × 130 mm × t30 mm (the clear aperture of 253 mm × 119 mm) with Au coating. The light reflected by the fold mirror enters the mosaicked HBG unit consisting of two HBGs.

Each HBG has a physical size of 200 mm × 60 mm × t60 mm (and a clear aperture of 198 mm x 58 mm). The dispersed light by the mosaicked HBG is reflected by the fold mirror again, and enters the VPH cross-dispersers. WINERED uses different VPH cross-dispersers for the Hires-Y and Hires-J modes (Table 2), which are designed to be switchable by the remote control. The VPH cross-disperser for the Hires-Y mode has an N-BK7 prism with an apex angle of 8.15 ° on the exit surface which refracts the exiting beam and matches the direction to that from the Hires-J mode. We can easily switch from the Wide mode to the two Hires modes by inserting a fold mirror into the optical train. The optical parameters of the fold mirror, the HBG, and the cross-dispersers for the Hires modes are summarized in Table 2.

Table 2. Optical parameters of gratings and mirrors for the Hires-Y and Hires-J modes.

Components	Items	Specifications	Remarks
Fold mirror	Physical size	265 mm × 130 mm × t20 m	Octagonal shape and with chamfering of 40 mm × 20 mm at the four corners
	Clear aperture	253 mm × 119 mm	
	Material	N-BK7	
	Reflective coating	Au	
	Surface irregularity	0.3λ (PV), 0.05λ (RMS) @633nm	As measured
High-blazed echelle grating	Blaze angle	79.32 deg	As measured
	Apex angle	87.95 deg	As measured
	Groove pitch	90.38 μm	
	Physical size	60 mm × 200 mm × t59 mm	For a single piece
	Clear aperture	59 mm × 198 mm	For a single piece
	Material of substrate	ULE	
	Reflective coating	Protected Ag	
	Manufacturer	CANON Inc.	
X-disperser for Hires-Y mode	Type	Transmission VPH grism	With a prism on the exit surface
	Line frequency	724.80 line/mm	
	Bragg angle	22.1 deg	
	Physical size	135 mm × 130 mm × t10 mm	The thickness is define at the center
	Clear aperture	125 mm × 120 mm	
	Apex angle of prism	8.15 deg	See text for detail
	Material of substrate	N-BK7	
	Manufacture	Wasatch Photonics	
X-disperser for Hires-J mode	Type	Transmission VPH grating	
	Line frequency	540.48 line/mm	
	Bragg angle	19.65 deg	
	Physical size	135 mm × 130 mm × t10 mm	
	Clear aperture	125 mm × 120 mm	
	Material of substrate	B270	
	Manufacture	Wasatch Photonics	

2.2 PERFORMANCE

Figure 3 shows the designed spot-diagrams and echellograms for the Hires-Y and Hires-J modes. The spot-diagrams, in which the effects of vignetting are considered (see Section 2.3), are evaluated in nine different fields namely the different wavelengths, of the detector for each mode. The three different spot-diagrams for each field show the different positions on the slit i.e., the upper edge, the center, and the lower edge. We can confirm that all spots fall within the boxes of 2 pixels x 2 pixels. The echellograms show that both modes continuously cover all required wavelength regions given in Table 1. The shortest gaps among the orders are calculated as 3.0 pixels between m = 183 and 184 for the Hires-Y mode, and 3.6 pixels between m=155 and 156 for the Hires-J mode, which are sufficient for estimating the flux of the inter-order scattered light in reduction.

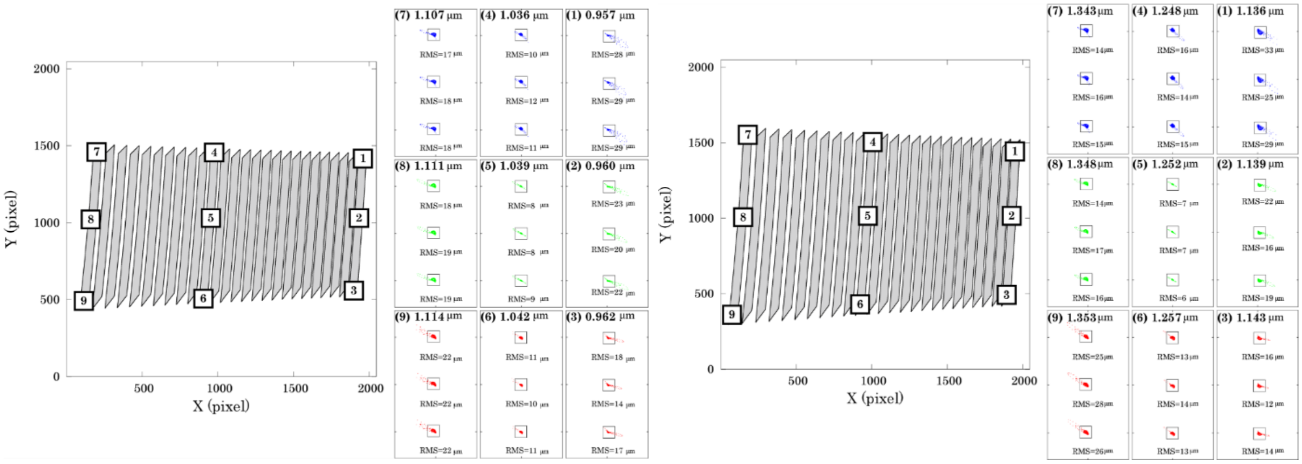


Figure 3. Spot-diagrams and simulated echellograms of Hires-Y and Hires-J modes. Spots are evaluated in nine positions (wavelengths) on the array, indicated in echellograms numbered of 1–9. The box size for each spot corresponds to 2 pixels × 2 pixels of the array.

2.3 VIGNETTING AND THROUGHPUT

There are avoidable vignettings for the Hires modes, originating from the size limitation of the HBG during fabrication and the slight changes from the original optical design. Figure 4 shows the footprints on the mosaicked HBG, the cross-dispersers, and the first lens of the camera system.

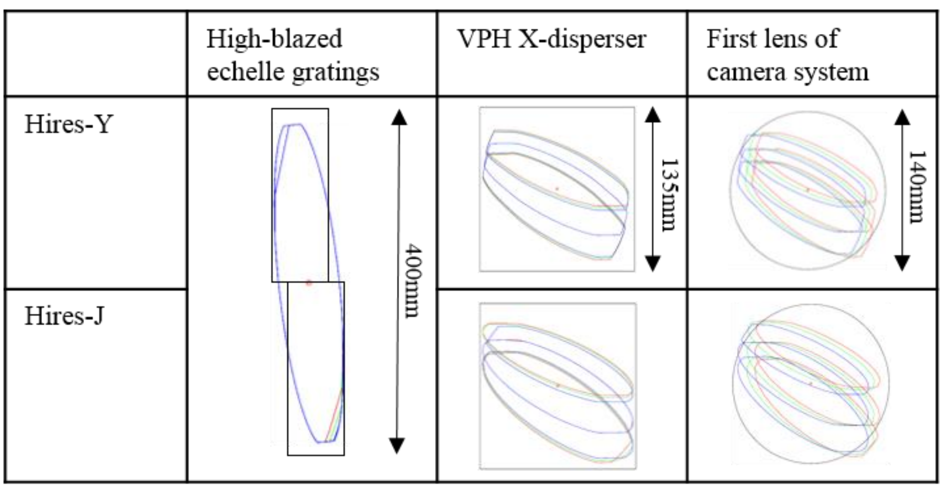


Figure 4. The footprints on the high-blazed echelle grating, the VPH gratings (for Hires-Y and Hires-J modes), and the first lens of the camera system. The rectangles and circles surrounding the footprints represent the clear apertures. Each color of footprint shows a light beam forcing a different position on the infrared array assumed in Figure 3.

The different colors indicates the cross section of light beams focusing different position on the infrared array. The vignetting on the HBG is due to the size limitation for fabrication, which is 60 mm in width, although the collimated beam size of WINERED is 70 mm. Since the HBGs are aligned with an angle (γ = 6 degrees, see Section 3.1), the footprint on the grating surface is not formed as a purely oval shape, but as a sheared oval. This deformed beam cannot be completely covered by a rectangular grating surface, even with the same width as the collimated beam diameter (Φ70 mm). Thus, we shift one HBG 8.5 mm along the grooves of the other to cover the footprint as widely as possible. Using this idea, vignetting can be reduced to approximately 7.6 % on the mosaicked HBGs. 4 % vignetting also occurs at the maximum on the first lens of the camera system. This originates from the change of the grating from IG to HBG in design. The HBG has to be located farther from the collimator lens and the cross-dispersers to avoid mechanical interference among the optical elements because the HBG is longer than the IG (the blaze angle of 70 °). This produces larger beams and, consequently vignettings on the optics downstream of the HBG. The total energy loss due to vignetting, which considerably varies depending on the wavelength, is estimated to be 9 % at maximum. Table 3 shows the calculated total throughput of the Hires-Y and Hires-J modes. While it is low for the Hires-Y mode due to the low QE of the array at 1 μm, it shows a higher total throughput (>38.7 %) than the requirement (>35 %) for the Hires-J mode.

Table 3. Total throughput including the vignetting for Hires-Y and Hires-J modes.

Element	Hires-Y mode	Hires-J mode	Remarks
Order-sorter filter	0.98	0.98	As measured
Collimator	> 0.985	> 0.985	As measured
Fold mirror	0.96	0.96	Total reflectivity of the beam incoming to and outcoming from the echelle grating
High-blazed echelle grating	0.63	0.63	Including the vignetting
VPH X-disperser	0.91	0.91	As measured
Dewer window	0.99	0.99	As measured
Camera lens system	0.90	0.89	Including the vignetting
Thermal blocker	0.95	0.95	Total transmittance two filters H-band filter and PK50
Deterctor	0.63	0.87	Measured by Teledyne Inc. at 1.00 μm for the Y-mode and at 1.23 μm for the J-mode
Total[1]	> 0.283	> 0.387	

[1] These throughputs does not include a slit loss.

3. HIGH-BLAZED ECHELLE GRATING

3.1 DESIGN

The optical parameters of the HBGs for the Hires modes can be uniquely determined with slight free because added to the Wide mode which already has been completed. At first, with s collimator beam diameter of 70 mm and the spectral resolution of R = 80,000, a blaze angle can be given by equation 1. The second, free spectral range ($\Delta\lambda_{FSR} = \lambda_m$/m), consequently the minimum diffraction order *m*, could be determined based on the condition that all wavelengths in the free spectral range must fall in the used the 2k x 2k infrared array, $\Delta\lambda_{FSR}$ / (2 R) <N_{PIX}, where N_{PIX} is the usable number of pixels in the dispersion direction on the array N_{PIX} = 2,048 (for the case of HAWAII-2RG). With a combination of the blaze angle, θ_B, and the minimum diffraction order, m, the groove pitch, *d*, could be derived with the grating equation ($m\lambda = d(\sin\alpha + \sin\beta)\cos\gamma$) under the Littrow condition ($\alpha = \beta = \theta_B$, $\gamma = 0$). However, the actual HBG was not used in the perfect Littrow condition because the incident and diffracted lights must be spatially divided. The γ angle was determined by optimization on the ray-tracing software based on the constraint that optical vignetting should be minimized under good optical performance (small aberration). Once a γ angle was set, the spectral resolution was slightly degraded compared to its original value. To improve the spectral resolution, we adjusted the groove pitch and diffraction order, iteratively. As a result of these processes, we derived a blaze angle of 79.32 ° (R5.3) and a groove pitch of 90.38 μm for the HBG.

Among the optical parameters, only the apex angle was determined based on the requirement for the diffraction efficiency. The diffraction efficiency of HBG was more sensitive to the apex angle than that of the classical echelle grating because the shadow effect can be easily influenced by the long counter facets on the groove. We set the apex angle to 88 ° to obtain a higher diffraction efficiency. In addition, we decided to use the protected Ag coating, which showed the highest reflectance in the WINERED wavelength range, on the grating surface to maximize the absolute diffraction efficiency. We employed ULE glass (with CTE ~ 5 x 10^{-8} K^{-1}) as the grating substrate, thereby preventing shift of the spectra on the infrared array under temperature variation. To achieve fine alignment (mosaicking) of two gratings, we produced reference surfaces on the side of the substrates, which were optically polished to achieve an orthogonality to the grooves of <1 μm. The detailed specifications of the HBG are shown in Table 4.

Table 4. Specifications and production results of high-blazed echelle gratings

Items	Specifications	Grating #A	Grating #B	Remarks
Physical size	200mm × 60mm × t59.3 ±0.2mm			
Orthogonality	< 1 μm	0.7 μm	0.5 μm	
Blaze angle	79.32 deg	79.32 deg	79.32 deg	
Apex angle	88 ± 0.2 deg	87.95 deg	87.95 deg	
Groove pitch	90.38 μm			Not measured
Random pitch error	< 8 nm (rms)	4.9 nm(rms)	4.9 nm(rms)	
Surface irregularity	< 150 nm (PV) < 30 nm(rms)	54.1nm(PV) 5.6 nm(rms)	45.4nm(PV) 6.0 nm(rms)	
Rowland ghost	< 0.1 %	< 0.01 %	< 0.01 %	
Diffraction efficiency	> 70 %	68.6 %	68.8 %	Average of TE and TM waves

3.2 FABRICATION

Our HBGs were fabricated by Canon Inc., which has much experience in the fabrication of diffraction gratings for UV excimer lasers and immersion gratings. The evaluation results of the completed HBGs are summarized in Table 4. It was found that the HBGs almost fulfill the specifications, although the absolute diffraction efficiencies slightly fail to meet the requirements. Figure 5 shows the wavefront error maps of the diffracted light measured with the visible light. Excellent wavefronts are obtained at 50 nm (PV) for 90 % of the groove area.

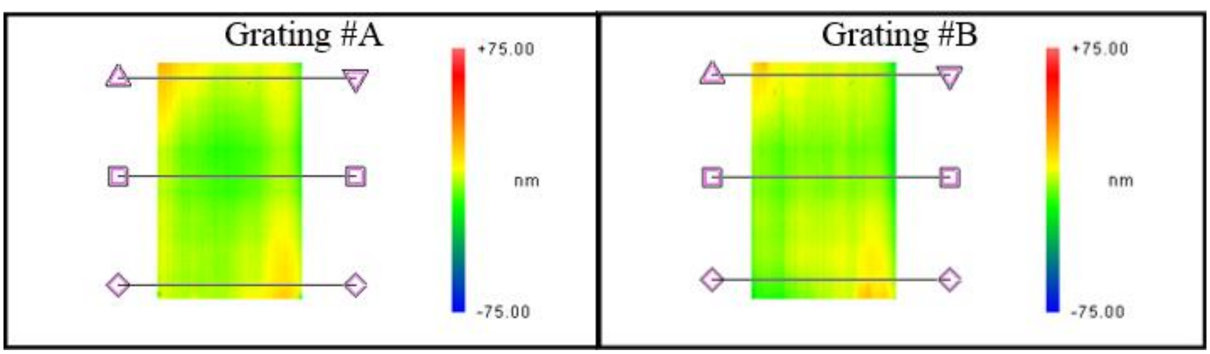
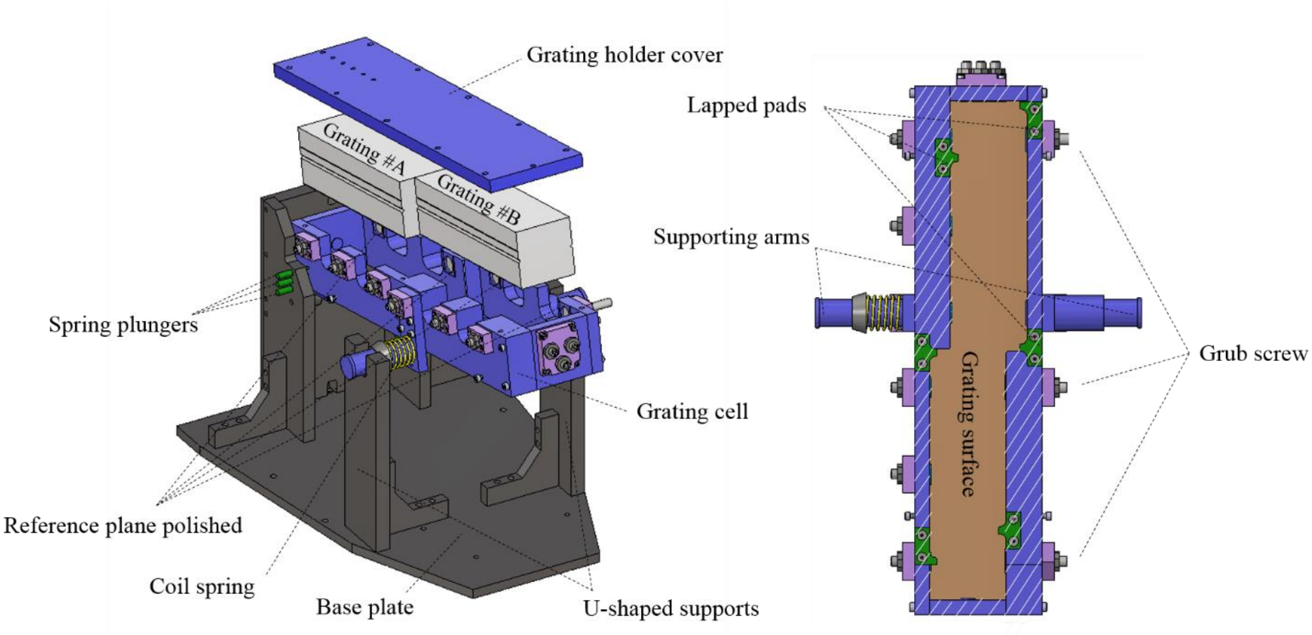


Figure 5. Wavefront maps of the fabricated HBGs, measured at 633 nm (m=201) by the interferometer.

3.3 MOSAICING MECHANICS

As mentioned in Section 2, we employed the optical design with the mosaicked grating of two HBGs. The misalignment of two gratings can degrade the spectral resolution produced by the blurred images because two monochromatic images of the slit diffracted from each grating can be focused on different position of the array. If the acceptable shift among the monochromatic images was set to less than 1/10 pixel, the tolerances of the alignment became 1.5 arcsec in the plane of the grating surfaces and 0.5 arcsec in the perpendicular plane of the grooves. In addition, these alignments must be maintained in an environment with ΔT ± 10 K, which is anticipated the maximum temperature variation during a night. Figure 6 shows the designed grating holder, which fulfills these stringent requirements. This grating holder consisted of aluminum and ceramic (cordierite CO-202, produced by Kyocera corporation), components, which are colored in black and in blue, respectively. The cordierite CO-202, which is a new structural material with an extremely low CTE (2 x 10^{-8} K^{-1}) and which can easily be polished with the surface flatness and roughness achieved for optical glasses, was used for the parts holding the gratings.

Figure 6. A design of the grating holder for the mosaicked high-blazed echelle gratings. The left is a bird's eye view and



the right is viewed from the grating surfaces.

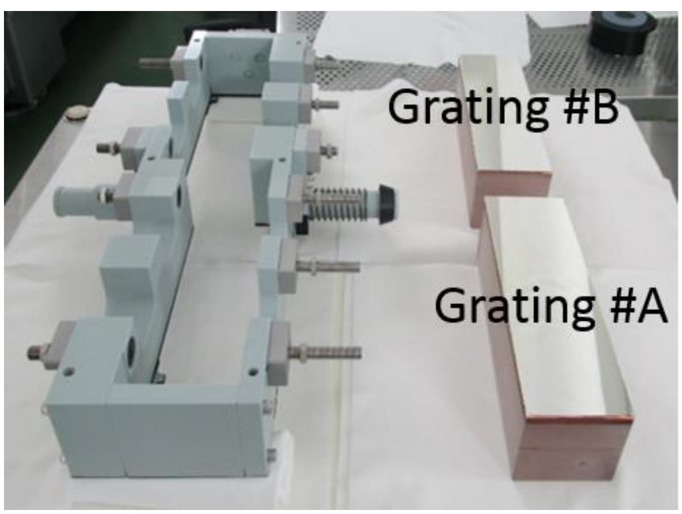


Figure 7. A grating holder (left) and the gratings (right).

Since the CTEs of both the ULE for the grating substrate and the cordierite CO-202 are negligibly low, a robust mechanism can be realized without any thermal stresses or alignment errors due to the thermal expansion/contraction of the holder during the observations. The inner surfaces of the grating holder are polished to a flatness of less than 1 μm. This polished surface is used as a reference surface for aligning the two gratings (the datum planes are also produced on the side surfaces of the gratings, and are guaranteed to be perpendicular to the grooves to within 0.1 μm). These are realized with cordierite CO-202, which can be easily processed into a complicated form similarly as to machine metric parts. To compensate for possible sight machining or assembly errors, we made several tap holes on the side of the holder for the grub screws, with which the parallelism of the grating was made adjustable (Figures 6 and 7). The surfaces of the gratings were supported at three points with lapped pads to achieve non-stressed support and minimize thier vignetting effects. As for the base structure of the grating holder, we used the aluminum A5052, which is the same material as that out of which the optical bench was constructed. The supporting structure had two U-shaped plates that supported the arms extended from the grating holder (see Figure 6). The coil spring was inserted between the U-shaped plate and the arm on one side, and it absorbed the difference between the CTEs of cordierite and aluminum. In this situation, the grating moved along grooves, which, in principle, should not change spectral images in any way, including image.

Since cordierite has a non-negligible reflectance for infrared light, the reflected or scattered lights on the grating holder could generate unexpected stray light. To suppress this effect, we applied the black paint CS037 (produced by Canon-kasei Inc.) to the hatched surfaces in Figure 6. This paint was developed for commercial cameras with low reflectance of 1 % including both specular and scattered components.

After installing two HBGs into the completed grating holder, we examined the wavefront errors of the mosaicked gratings using a Zygo interferometer. Figure 8 shows the measured diffracted-wavefront maps at 633 nm (m = 201), which achieves a wavefront error of <250 nm (PV) and the parallelism of <0.1 arcsec after careful adjustments. We also checked the stability of the alignment for the two cases. Under the condition of a constant temperature with $\delta T <\pm 0.5$ K, both the wavefront error and the parallelism did not change within the measurement accuracy, even after 24 hours. On the other hand, after passive temperature variation with $\Delta T = 5$ K, the parallelism increased to 1.0 arcsec over a short time. This variation of the parallelism does not affect the spectral resolution because it is still within requirements (<2 arcsec).

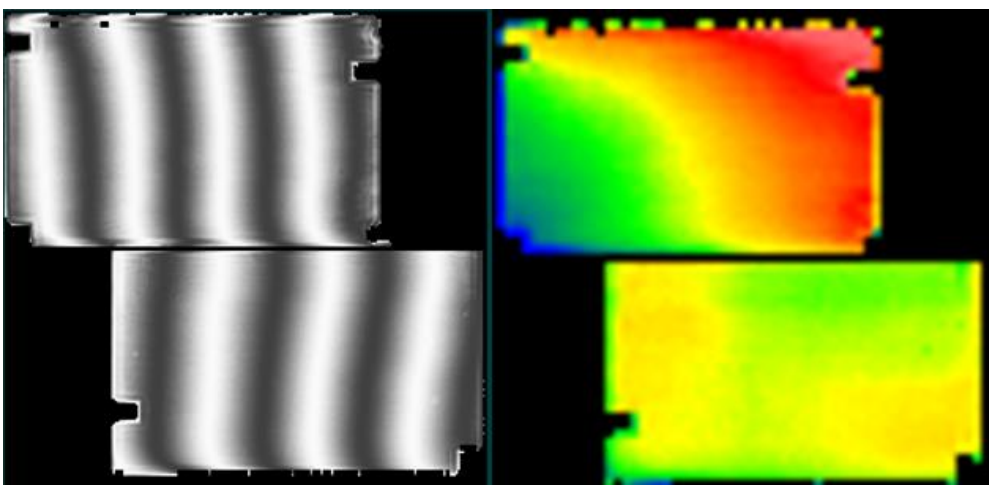


Figure 8. Interference fringe patterns (left) and the wavefront error map (right) of the mosaicked HBG using the ZYGO interferometer.

4. VERIFICATION OF THE HIRES MODES

We evaluated the spectroscopic performances of the mosaicked HBG units installed in WINERED (the two pictures in Figure 9). The two images at right in Figure 9 are the raw images of the flat lamp and comparison lamp (Th-Ar) obtained with the Hires-J mode. Both images correspond well to the simulated echellograms shown in Figure 3.

First, we investigated the image qualities and the linear dispersion [pix μm^{-1}] with the two-dimensional image of the Th-Ar lamp. The full widths at half maximum (FWHMs) of the emission lines were measured as 1.7 – 2.4 pixels at various of the array, agreeing with the designed values (1.6 – 2.6 pixels). We measured the linear dispersions with several pairs of strong emission lines, which were also consistent to within 0.5 % with those that were designed (but smaller than the specifications). These results confirm that we obtained good image qualities for the two-dimensional spectra, as had been expected with the optical ray tracking.

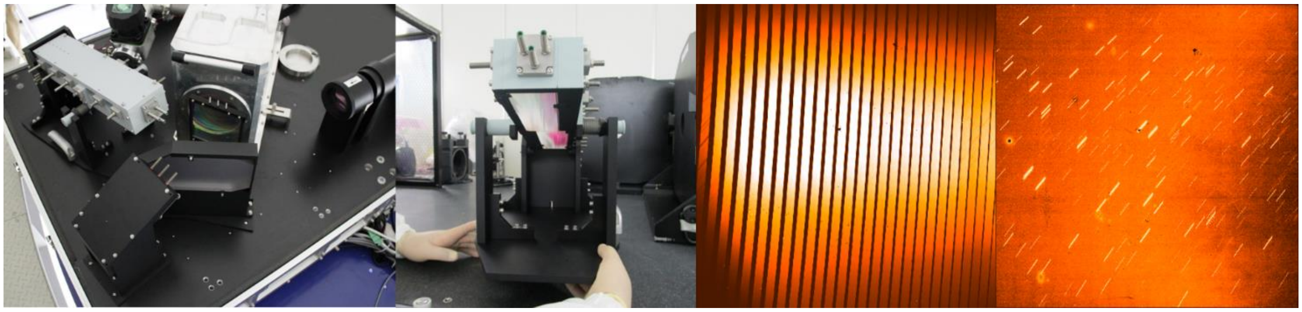


Figure 9. Mosaicked HBGs installed into WINERED and images of the flat lamp and the Th-Ar lamp obtained with the Hires-J mode.

Subsequently, we checked the spectral resolutions by measuring the FWHMs of the emission lines in one-dimensional spectrum of the Th-Ar lamp (Figure 10), which was reduced by the automatic reduction software for WINERED. The degradation of the spectral resolution was clearly seen at >1.3 μm. This may have originated from the slight tilting of the infrared array from the optical axis of WINERED, which could be recovered by realignment. The averaged spectral resolution from 1.23 to 1.28 μm (m = 143 – 137), without the influence of the tilting if the array is R = 67800 ± 700. The obtained spectral resolution still degraded by 15 % from R = 78,000, which was the value expected from the measurement of linear dispersion. This degradation can be partially interpreted as the large γ angle of the echelle grating (see section 3.1). The HBG of WINERED is located with γ = 6 °, which produces large tilted slit images on the infrared array. If the monochromatic slit images were to not be perpendicular to the dispersion direction seen in the WINERED spectrum, it can be shown with a simple algebraic calculation that the unavoidable degradation of the final spectral resolution would be generated in the extraction of one-dimensional spectra. Although these degradations are unavoidable for the reduced the one-dimensional spectra obtained by echelle spectrographs with a large γ angle, they become prominent only for spectrographs employing the HBGs with the large blaze-angle. However, the estimated degradation due to this effect (the red line in the Figure 10) is about 10 % and there was a remaining degradation of 5 %. This should not be attributed to the aberration of the optics but to the reduction process because the optical performance of the array was well consistent with simulation. We continue the investigation to reveal the cause.

Figure 11 shows the normalized spectrum of alpha Boo (K1.5III) obtained with the Hires-J mode. The spectra obtained with the Wide mode are superimposed with the black line. In the Hires mode spectrum, some blended lines can be clearly resolved and some weak lines, which are not seen in the Wide mode spectrum can be detected.

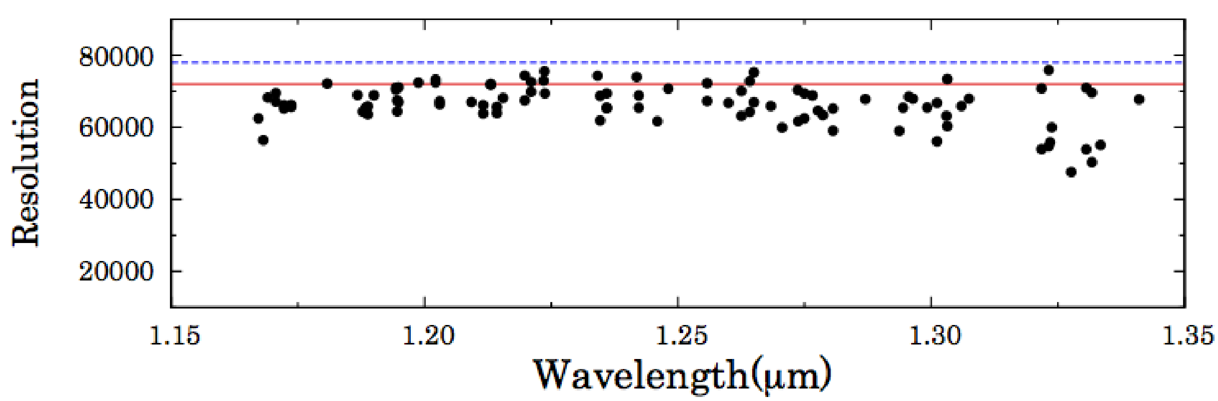


Figure 10. Measured spectral resolution of the Hires-J mode. The blue line is the spectral resolution expected from the measurements of the linear dispersion.

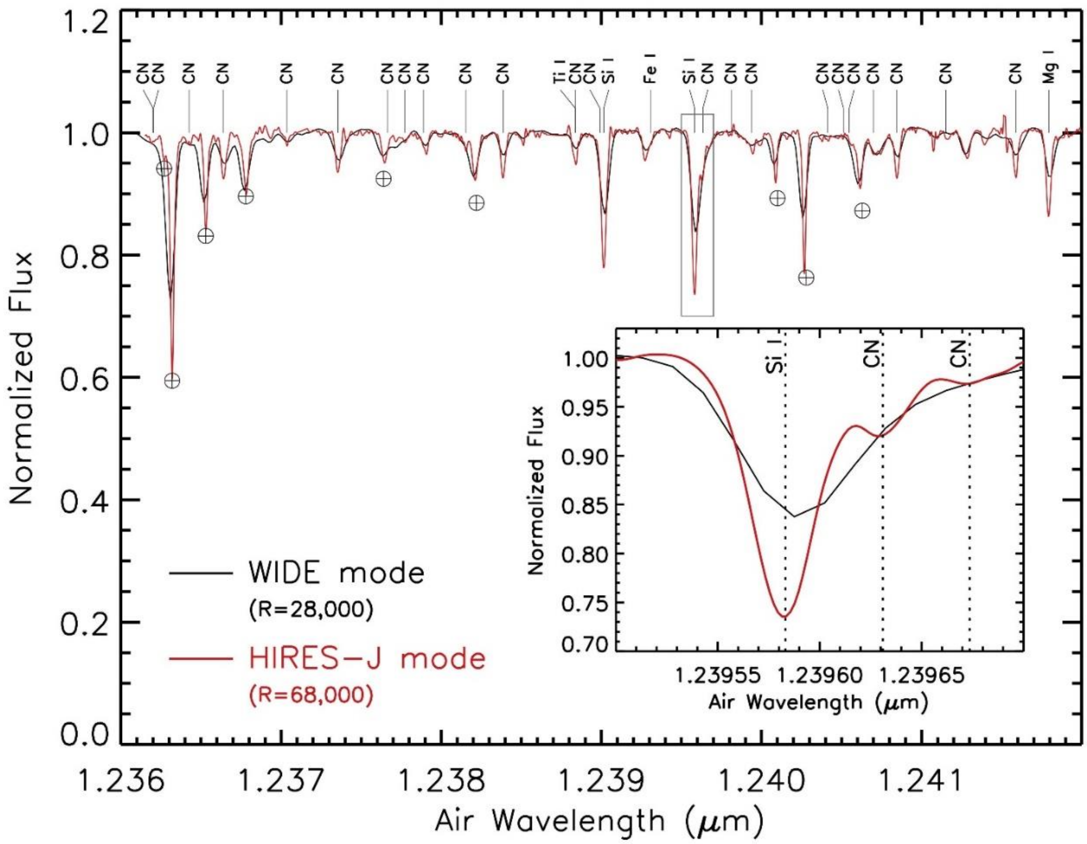


Figure 11. A preliminary spectrum of α Boo(K1.5Ⅲ) with Hires-J mode.

5. SUMMARY

We developed the alternative observational channels the "Hires-Y mode" and the "Hires-J mode" with R = 80,000 for WINERED. To realize high resolution, we made use of an HBG instead of an IG. By optimizing the optical layout so as to minimize vignetting and optical aberrations, we obtained an optical design using mosaicked HBGs, which provided the required spectral resolutions with total throughputs of ~35 % for both Hires-Y and Hires-J modes. We also designed a grating holder for mosaicking two HBGs with positional accuracy of sub-μm order. By adapting an extremely low CTE ceramic cordierite CO-220, we realized a stable grating holder with an extremely low temperature aberration, which achieved an alignment of <0.1 arcsec in the parallelism of two gratings. Evaluation of the total optical performance using of the assembled HBG units confirmed that the designed optical performances were fulfilled with monochromatic slit images of the Th-Ar lamp. A slight degradation of the spectral resolution observed in the reduced one-dimensional spectrum may have partially originated from an avoidable effect in the reduction process.

We plan to complete the development of the Hires-Y and the Hires-J modes by the summer of 2016. Afterwards, we will commence scientific observations accompanied by continuous improvements of the reduction procedures.

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