VINROUGE : a very compact 2-5 μm high-resolution spectrograph with Germanium immersion grating

Takayuki. Arasaki[a], Naoto. Kobayahsi[a,b], Yuji. Ikeda[a,c], Sohei. Kondo[a], Yuki. Sarugaku[d], Sayumi. Kaji[e], and Hideyo. Kawakita[a,e]
[a] Laboratory of Infrared High-resolution spectroscopy (LiH), Koyama Astronomical Observatory, Kyoto Sangyo University, Motoyama, Kamigamo, Kita-ku, Kyoto 603-855, Japan; [b]Institute of Astronomy, University of Tokyo, 2-21-1 Osawa, Mitaka, Tokyo 181-0015, Japan; [c]Photocoding, 460-102 Iwakura-machi, Sakyo-ku, Kyoto 606-0025, Japan; [d] Kiso Observatory, Institute of Astronomy, University of Tokyo, 10762-30 Mitaka, Kiso-machi, Kiso-gun, Nagano 397-0101, Japan; [e] Faculty of Science, Kyoto Sangyo University, Motoyama, Kamigamo, Kita-ku 603-8555, Kyoto, Japan

ABSTRACT

The infrared high-resolution and highly-sensitive spectroscopy can provide new and deep insights in many fields of astronomy. The 2.0-5.5 μm region is a very unique and important wavelength region for astrochemistry and astrobiology, because the vibrational transitions of C-H, N-H, O-H, C-O, and C-N bonds in many molecules, which are of astrophysical interest, concentrate in this wavelength range. To advance the study in this wavelength range, we are developing a new near-infrared spectrograph: VINROUGE (= Very-compact INfrared high-ResOlUtion Ge-immersion Echelle spectrograph). The instrumental concepts of VINROUGE are “high-resolution”, “highly-sensitive”, and “very-compact instrumentation”. With (i) Germanium immersion grating, (ii) white pupil spectrograph design, (iii) reflective optics using the integrated off-axis mirrors and the optical bench by ceramic (cordierite CO-220), and (iv) highly-sensitive array (HAWAII-2RG 5.3μm cutoff array), we could obtain a solution of optical design with a spectral resolution of 80,000, total throughput of > 0.28, and a compact volume that is smaller than 600 mm×600 mm×600 mm even for 10-m class telescope. We have already completed the development of Germanium immersion grating. In this year, we plan to fabricate a set of integrated off-axis ceramic mirrors together with the ceramic optical bench to demonstrate that the reflective optics was an athermal performance. The first light of VINROUGE is expected in 2019.

Keywords: Infrared, High-resolution, High-sensitivity, Very compact instrumentation, Immersion grating, Spectrograph

1. INTRODUCTION

Infrared wavelength region from 2-20 μm is so unique that there are rovibrational transitions of various kinds of molecules (including the symmetric molecules without permanent electric moment, which cannot be observed in the radio domain). Therefore, it is considered as the key wavelength region for astronomy, astrochemistry, and astrobiology. Especially, the vibrational transitions (e.g., for C-H, N-H, O-H, C-O and C-N stretching vibration modes) for the astrophysically interested molecules concentrate on the near-infrared wavelength region from 2.0-5.5 μm (Figure 1). High-resolution spectroscopy exhibits a great power for observing minor molecules (e.g., more complicated molecules, deuterated molecules or minor isotopologures including such as ^{13}CO and $C^{15}N$, and the molecules including minor but important elements such P) in this spectral region, because the “high-resolution” can allow us to distinguish the weak lines from the strong ambient background radiation and other atomic or molecular lines. The high-resolution can also realize highly-sensitive for the lines of which intrinsic widths are narrower compared to the spectra resolution, such as the interstellar absorption lines. For example, although H_3^+ and CH_3^+ are important pivotal ions in the chemical network for astrophysical plasmas (Herbst & Klemperper 1973[1]), CH_3^+ (which is a starting point of the chemistry for complex organic molecules including carbons) is not yet detected in 3.2 μm region due to their weak transition probabilities while H_3^+ is well observed in ~ 3.6 μm region under various environments in the universe (e.g., Geballe *et al*. 1996[2], McCall *et al*. 2002[3], Oka 2013[4]). Thus, high-resolution and highly-sensitive spectroscopy of the molecules with large telescopes will provide the deep insights for astronomy. Using large telescopes are essential for observing weak lines because not only it is necessary to collect a large number of photons but also the thermal background noise is extremely reduced by the improvement of the spatial resolution.

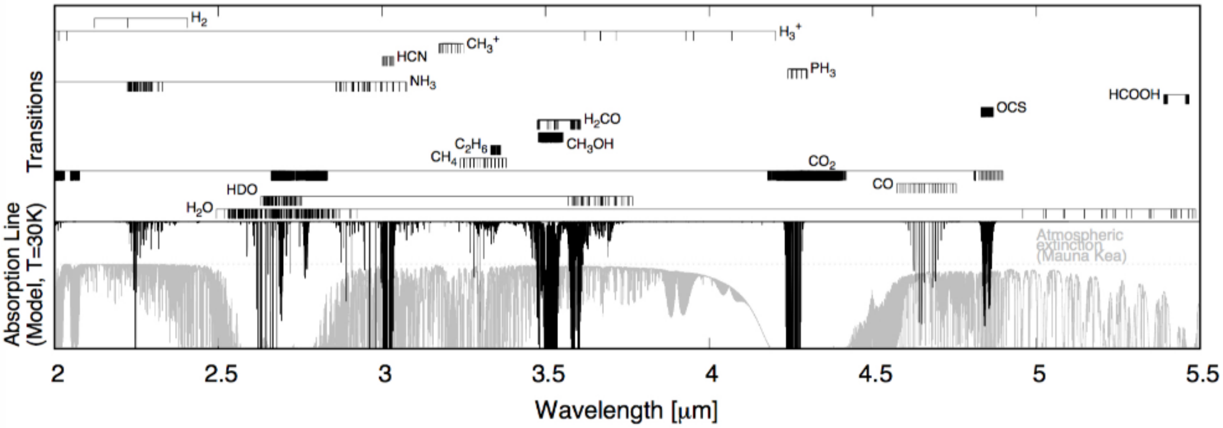


Figure 1. Model spectra of various molecular absorption lines in the wavelength range of 2.0-5.5 μm.

However, there are various technical issues on the development of infrared high-resolution spectrographs attached to large telescope. Among them, the instrument size is the biggest one.

The maximum spectral resolution of a diffraction grating for the slit-limited case is given by

$$R = \frac{2n\varphi_{col}\, tan\theta_B}{sD_{tel}} \tag{1}$$

where n is the refractive index of which the grooves are immersed (n = 1 for the classical grating), φ_{col} is the collimated beam diameter, θ_B is the blaze angle, s is the slit width, and D_{tel} is the entrance pupil diameter of the telescope. It is found from Eq. (1) that the collimated beam diameter, that is the size of optics, is proportional to the spectral resolution and the entrance pupil diameter of the telescope equipped with it. Therefore the high-resolution spectrograph in the coming 30-m telescope ages requires the much larger optics and vacuum chamber enveloping them than those currently attached to 10-m class telescopes. To realize these extremely large instruments, some technological innovations are strongly required on fabrication of the extremely large optics and cryostat, resulting in that it takes a great cost for time and money. Under these circumstances, we start the project of a new near-infrared high-resolution spectrograph: VINROUGE. VINROUGE uses a Germanium immersion grating with which the instrument can be dramatically reduced in size, similar to or smaller than the spectrographs using classical echelle gratings (see Eq. (1)).

VINROUGE is a PI-type infrared high-resolution spectrograph which is developed by LiH (= Laboratory of Infrared High resolution spectroscopy) funded by the Koyama Astronomical Observatory of Kyoto Sangyo University, Japan. We describe the design concepts of VINROUGE in section 2, and we introduce a preliminary optical design for realizing the concepts in section 3 and the fabrication and alignment strategy on the designed reflective optics in section 4.

2. CONCEPTUAL DESIGN

Table 1 summarizes the specifications of VINROUGE. The instrumental concepts of VINROUGE are to aim "high-resolution (R_{max} = 80,000)", "very-compact instrumentation" attachable to the Cassegrain focus, and "highly-sensitive (the total throughput > 0.25)". To achieve these concepts simultaneously, we decided to employ (i) Germanium immersion grating, (ii) white pupil spectrograph, (iii) reflective optics with the integrated off-axis mirrors and the optical bench by ceramic, and (iv) highly-sensitive array (HAWAII-2RG 5.3μm cutoff).

The high-resolution and the very-compact instrumentation are realized with a Germanium immersion grating and the white pupil spectrograph design. Immersion grating is a reflection type grating of which the diffraction surface is immersed in the material with a high refractive index (n > 2). It provides an n times higher spectral resolution compared to a classical reflective grating if using the same collimated beam in diameter, or reduces the size of optics to *1/n* if the spectral resolution is maintained (see Eq. (1)). Since Germanium has the highest refractive index (n = 4) among available infrared optics same materials for immersion grating, we can obtain an extremely compact high-resolution spectrograph as never before in this wavelength region. The white pupil spectrograph also contributes to compactification of the size of optics because it reduces the collimated beam diameter on the gratings and camera unit by producing the second pupil image where is a conjugate position to the surface of the first disperser.

Highly-sensitive is achieved with a Germanium immersion grating, a highly-sensitive infrared array, and the reflective optics. The absorption in the material is very important for immersion grating, because even small absorption coefficient α [cm^{-1}] which is negligible for general applications such as lenses should influence the absolute diffraction efficiency due to the long traveling path in the immersion grating ($\alpha < 0.01$ cm^{-1} is needed for keeping the absorption loss in < 0.1 for a Germanium immersion grating with R = 100,000 at 8 μm). The single crystal Germanium shows ideally low absorption coefficients ($\alpha < 0.001$ cm^{-1}) between 2 and 10 μm (see Kaji *et al*. 2014[5] and 2016[6]). With the same ingot, we have succeeded to fabricate the large Germanium immersion grating with the high diffraction efficiency (> 0.7) even under the cryogenic condition (see section 3.2). As for the infrared array, we use the HAWAII-2RG 5.3 μm cutoff array for VINROUGE, which is the most sensitive array in this wavelength region at present. It has the high QE of > 0.8 and the low readout noise of < 16 e$^-$ (from the catalog of Teledyne Inc.). Finally, the reflective optics provides the continuously high throughput optics in the wide spectral range of the infrared region by using Au or the protected Ag coating as the reflective materials. Recently, the higher (spatial or spectral) resolution instruments has been increasing using the large format arrays like a 2K×2K array and/or Adaptive Optics (AO) technology. Consequently, the refractive optics tends to be preferred for these instruments because it is easier to correct the aberrations (although the chromatic aberrations is generated), and to align lenses high-precisely by using the axial symmetric lenses and barrels. However, since the white pupil spectrograph, which is also often used for the modern high-resolution spectrographs, needs a large number of lenses, the total throughput is considerably degraded due to the reflection loss on the lens surfaces. For instance, if we assume an spectrograph consisting of 15 lenses with the Broad-Band AR coating (BBAR) of R < 3% from 2 to 5.5 um (= 3 lenses for a collimator, 3 lenses for a re-imager, 4 lenses for a relay, and 5 lenses for camera), the throughput of lens systems is estimated to be 0.40 ($= 0.97^{15\times2}$) in total. On the other hand, the reflective optics can be expected to be the high throughput of > 0.77 for 13 reflective surfaces with the reflectance of > 0.98 per one surface (= 3 surfaces for a collimator, 3 surfaces for a re-imager, 3 surfaces for a relay, and 4 surfaces for a camera) with a very slow wavelength dependence. The difficulties of the aberration correction and alignment for the reflective optics can be overcome with the integrated off-axis mirrors and the optical bench made from the same material to the mirrors, which could provide an athermal optics. This technology had been often used with aluminum for infrared instrument (e.g., CRIRES+ (Follert *et al*. 2014[7]), iSHELL (Rayner *et al*. 2012[8])), but the aluminum mirrors are not applicable for the high-resolution instruments because they are easy to be deformed by the inner remaining stress when they are cooled down, and linear scars produced by the machining process degrade the image qualities. Instead, VINROUGE employs a low CTE ceramic, cordierite CO-220, for the materials of mirrors. The CO-220, which is provided by Kyocera Corporation, Japan, shows an extremely low CTE ($< 2.0 \times 10^{-8}$@23℃) similar as Zeroduar and ULE. It is not only easy to be polished and but also easy to be proceeded to any forms as obtained with metals. This means that the highly accurate integrated off-axis mirror system could be assembled with this material, as they had been tried with aluminum. See details of this athermal reflective optics in section 4.

Table 1. Specifications of VINROUGE.

Items	Specifications
Wavelength coverage	2.1–5.3 μm
Maximum spectral resolution	80,000
Total throughput	> 0.25
Instrumental volume	600 mm×600 mm×600 mm
Slit width×length	0.13 mm×3.64 mm*1 (0.18”×5.0”)*2
Pixel scale	0.07 [arcsec/pixel]*2
Array	HAWAII-2RG 5.3 μm cutoff

*1 More wider and longer slits will be available as options.
*2 For 10-m with f/15 telescope.

3. OPTICAL DESIGN

The optical layout of VINROUGE is shown in Figure 2. The main optical train of VINROUGE consists of two individual units: the fore optics and the spectrograph. The fore optics play a role as suppressing of the ambient thermal background radiation by the cold stop located on the pupil image produced in the optics. The focal plane images of telescope are refocused on the slit of spectrograph by the fore optics. The spectrograph produces the final echellogram spectrum of R_{max} = 80,000. Table 2 summarizes the optical parameters of optical elements used in VINROUGE.

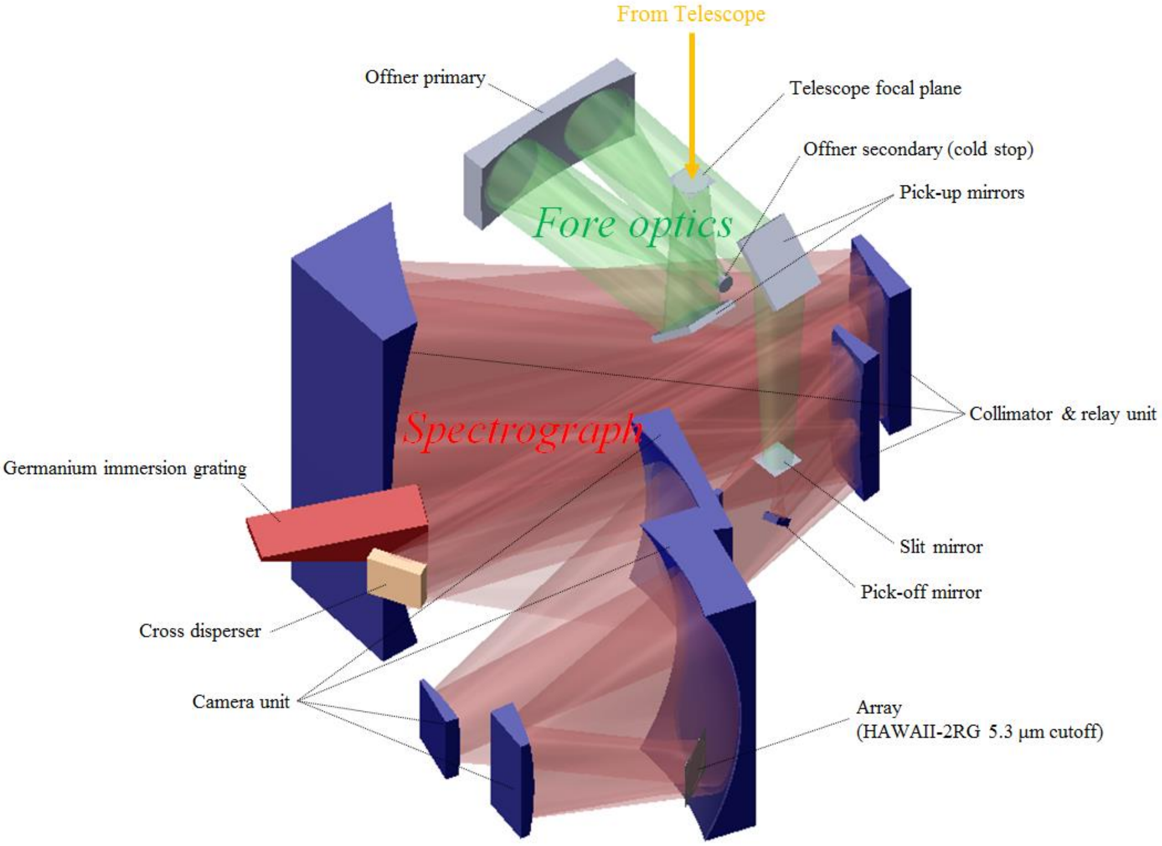


Figure 2. Optical layout of VINROUGE.

3.1 Fore optics

The optical layout of the fore optics is shown in Figure 3. We employ the Offner type optics as the fore optics. It is a re-imaging optics consisting two mirror (the primary and secondary mirrors), producing the image with the lateral magnification of one. The curvatures of two spherical mirrors are 314.7 mm for the primary and 156.7 mm for the secondary. The *f*/15 beam from the telescope is reflected by the primary, which produces the pupil of the entrance aperture of the telescope. The secondary mirror, which plays a roll on the cold stop, has a hole at the center and is cut with the sharp edge at the circumference. The former excludes the radiation reflected by the center cone on the secondary mirror, and the latter also prevents the thermal sky background radiation which directly goes to the optics through the side of the telescope secondary mirror. The reflected lights from the Offner secondary mirror is re-focused by the primary mirror. The field of view of the fore optics is 60”×60” (for the 10-m telescope with *f*/15). The classical Offner optics, in which the centers of radius of the primary mirror perfectly corresponds to that of the secondary mirror, produces a little astigmatism. In order to correct this aberration, we slightly shift the positon of the Offner secondary mirror by 0.35 mm away from the Offner primary mirror.

Table 2. Optical parameters of optical elements in VINROUGE.

Optical unit	Component	Item	Specification	Remarks
Fore optics	Offner optics	Material	Cordierite CO-220	CTE < 2.0×10^{-8}
		Curvatures of primary mirror	314.7 mm	
		Curvatures of secondary mirror	156.7 mm	
		Cold stop diameter	φ12 mm	On the secondary mirror
		Magnification factor	1.0	Offner type optics
Spectrograph	Entrance slit	Physical size	0.13 mm × 3.64 mm	
	Collimator and relay optics	Type	TMA	
		Material	Cordierite CO-220	CTE < 2.0×10^{-8}
		Effective focal length	348.1 mm	
	Main disperser (immersion grating)	Material	Single crystal Ge	
		Entrance/exit aperture	φ28 mm	
		Grating area	31 mm × 104 mm	
		Groove pitch	57.1 μm	
		Blaze angle	75°	
		Apex angle	86°	
		Reflective coating	Protected Ag	
	Cross disperser I	Groove density	250 lines/mm	K_s and M -mode
		Blaze angle	37.8°	
	Cross disperser II	Groove density	625 lines/mm	K_l -mode
		Blaze angle	50.7°	
	Cross disperser III	Groove density	476 lines/mm	L_s -mode
		Blaze angle	46.3°	
	Cross disperser IV	Groove density	400 lines/mm	L_m -mode
		Blaze angle	43.8°	
	Cross disperser V	Groove density	323 lines/mm	L_l -mode
		Blaze angle	40.6°	
	Camera	Configuration	FMA	
		Material	Cordierite CO-220	CTE < 2.0×10^{-8}
		Effective focal length	119.7 mm	
	Detector	Format	2048 × 2048 pixels	HAWAII-2RG 5.3 μm cutoff (Teledyne Inc.)
		Pixel size	18 μm	
		QE	> 0.8	From a catalog by Teledyne Inc., measured at 2.0, 3.5, and 4.4 μm
		Dark current	< 0.05 e^-/s	From a catalog by Teledyne Inc.
		Readout noise	< 15.5 e^-	
		Cut-off Wavelength	5.3 μm	

3.2 Spectrograph

The optical layout of the spectrograph is shown in Figure 4. The spectrograph is the full reflective optics consisting of the combination of the three-mirror anastigmat (TMA) and the four-mirror anastigmat (FMA). At the re-focal plane of the fore optics, slit mirrors are located. The size of a slit is 0.13 mm in the width and 3.64 mm in the length (0.18”×5.0” for 10-m telescope with *f*/15). The much wider or longer slits will be prepared for various purpose of observations. The stellar light passing through the slit is collimated by the TMA collimator unit with the effective focal length of 348.1mm. The collimated beam size is φ23.2 mm. The collimated light is dispersed by the Germanium immersion grating with the blaze angle of 75 degrees, the groove pitch of 57.1 μm, and the apex angle of 86 degrees. The entrance/exit clear aperture is φ28 mm and the grating surface is 31 mm×104 mm, (see Table 2 and section 3.3). The dispersed spectra by the Germanium immersion grating is re-focused near the slit, where the flat mirror is located and reflects back to the TMA.

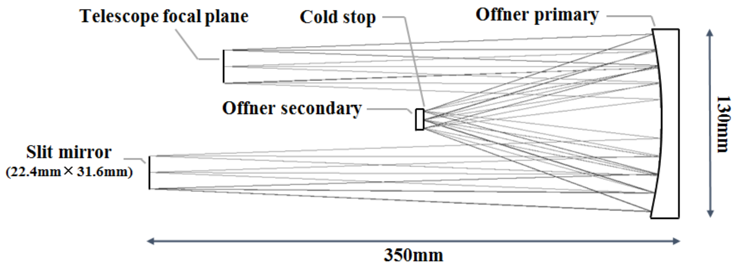


Figure 3. Optical layout of the fore optics of VINROUGE.

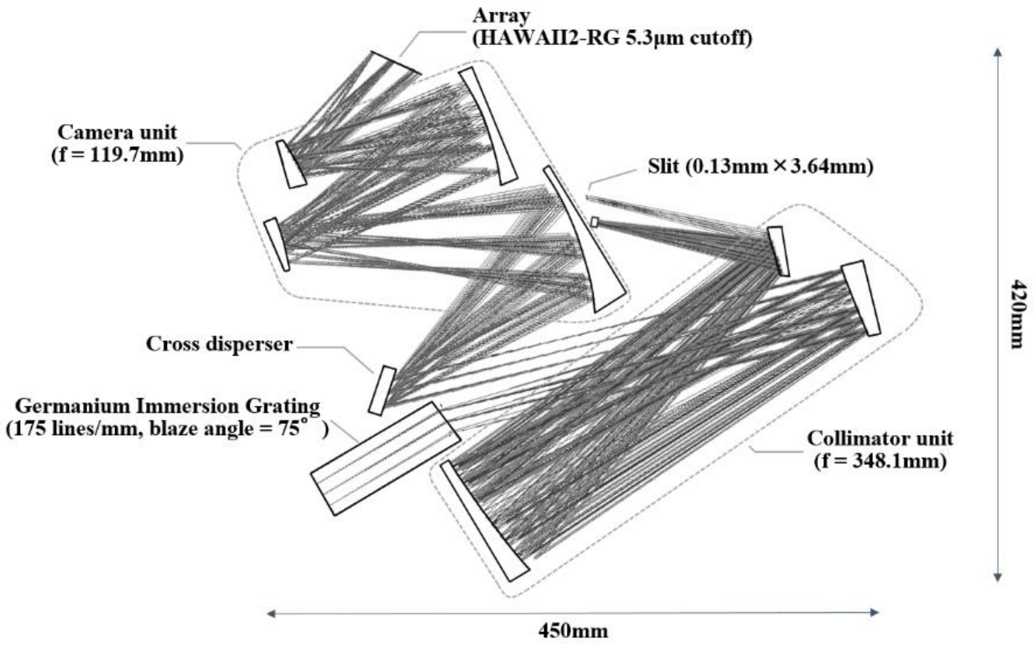


Figure 4. Optical layout of the spectrograph of VINROUGE.

The TMA produces the second pupil image spatially away from the immersion grating to work as the relay optics. The cross-dispersers are located on the second pupil position (that is the white pupil). VINROUGE employs five kinds of reflective gratings as the cross-dispersers. Each grating covers the half of K-band (K_s-band and K_l-band) or one third of L-band (L_s-band, L_m-band, and L_l-band), or M-bands.

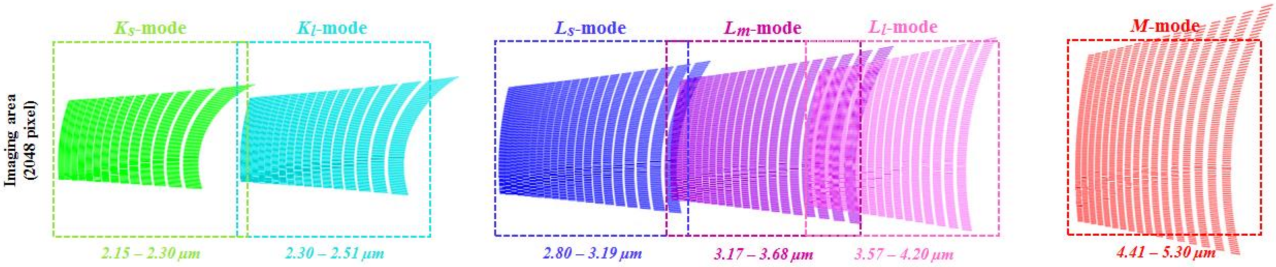
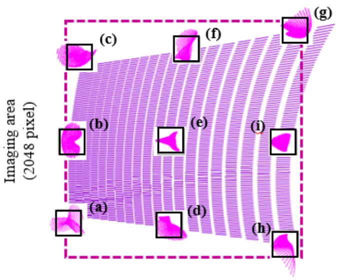


Figure 5. Simulated echellograms from K- to M-bands. VINROUGE provides six wavelength regions by changing five reflective grating as the cross-dispersers. K_s-mode and M-mode are obtained by one cross-disperser with the different diffraction order. The other wavelength regions are obtained by the individual cross-dispersers (see Table 2).

One grating among five cross-dispersers is used for both K_s-band and M-modes with the different diffraction orders $m = 3$ and 1, respectively. The other four gratings are used for K_l-, L_s-, L_m, and L_l-modes with $m = 1$ (see Table 2). The diffracted spectra by the cross-dispersers are separated into different orders, which are focused on the infrared array by the camera optics. The camera optics is the FMA with the effective focal length of 119.7 mm. The final echellograms are shown in Figure 5. The spectral resolution is achieved to be $R = 80,000$ with the sampling of 2.5 pixels. The spot diagrams of L_m-mode are also shown in Figure 6.



	Spot diagram diameter (RMS)	λ	Diffraction order (m)
(a)	30.4μm	3.171μm	140
(b)	27.9μm	3.183μm	140
(c)	29.3μm	3.194μm	140
(d)	28.9μm	3.436μm	129
(e)	23.7μm	3.449μm	129
(f)	32.9μm	3.463μm	129
(g)	27.5μm	3.658μm	122
(h)	30.4μm	3.658μm	121
(i)	28.7μm	3.673μm	121

Figure 6. Spot diagrams at various positions on the array for L_m-mode. The alphabets on the left figure show the evaluated positions of the spot diagrams. The spot diagram diameters (RMS) are measured in μm and given in the right table together with the corresponding wavelengths and the diffraction orders. The sizes of the boxes surrounding the spots are equivalent with 2.5 pixels × 2.5 pixels of the infrared array.

3.3 Germanium immersion grating

Figure 7 shows the Germanium immersion grating for VINROUGE. The designed optical parameters of Germanium immersion grating are described Table 2. The sharp apex angles of 85 degrees maximizes the diffraction efficiency by reducing the shadow effect caused by the counter groove surface. It is optimized using the RWCA method with an assumption of Ag coating on the groove surface. We designed the tilted wedge with 5 degrees on the entrance surface to prevent the reflected light on the entrance surface from directly going to the array. We prepare the steps with the 2 mm width at both sides of grating surface, which are used for holing the grating without any thermal stresses on the groove surfaces under the cryogenic condition.

We have already completed the Germanium immersion grating, which was fabricated by Canon Inc. We adapt the BBAR (< 3% at 2.0-5.5 μm) on the entrance/exit surface and the protected Ag coating on the grating surface. The careful evaluations confirm that the completed Germanium immersion grating achieves a high absolute diffractive efficiency of 0.75 at 4.52 μm in both room and cryogenic temperatures (Sarugaku *et al*. 2016[9]).

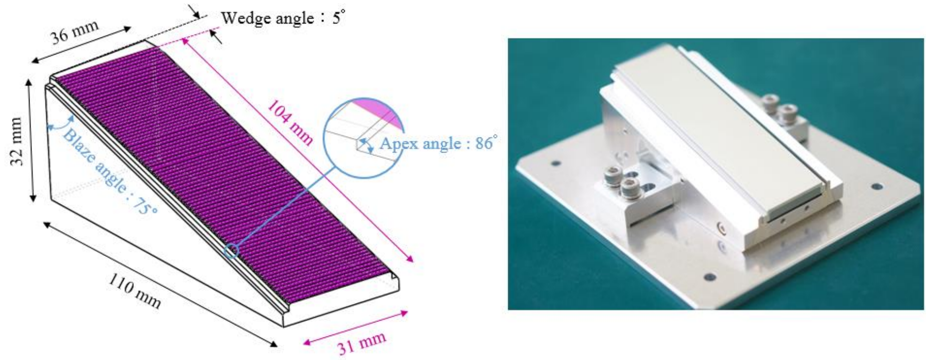


Figure 7 3D model (right) and the fabricated Germanium immersion grating (left).

3.4 Total throughput

Table 3 summarizes the estimated total throughput of VINROUGE. We also show the efficiencies of individual optical elements used for this estimation. The reflectance of Au mirrors are assumed as 0.98 per one surface. The diffraction efficiency of the immersion grating is a value measured in the cryogenic condition by Sarugaku *et al*. (2016)[9]. This table does not include any slit losses because they are dramatically changeable for the telescopes, the performance of the AO system, and the weather or site conditions. The final total throughput is estimated as ≥ 0.28 which fulfills the requirements in Table 1.

Table 3. Estimated total throughput of VINROUGE.

Optical component	**Transmittance or efficiency**	**Remarks**
Fore optics	0.904	3 spherical mirrors and 2 pick-off mirrors
Collimator	0.868	3 aspheric mirrors (including reciprocating path) and 1 pick-off mirror
Relay optics	0.922	3 aspheric mirrors and 1 pick-off mirror
Immersion grating	≥ 0.75	As measured under the cryogenic condition
Cross disperser	≥ 0.70	
Camera	0.922	4 aspheric mirrors
Detector	≥ 0.80	From the catalog of Teledyne Inc. at 3.5μm
Total throughput	**≥ 0.28**	Not including any slit losses

4. ATHERMAL REFLECTIVE OPTICS USING CORDIERITE

In general, it is a critical issue for infrared instruments including high resolution spectrographs to realize the highly accurate alignment of the optics under the cryogenic condition. The optical elements such as lenses and glass mirrors often are held by the metallic holders. However, since there is a large difference of the CTEs between the optical elements and the holder, the relative positional relations among the optical elements are changed under the cryogenic condition, and the resultant optical performances are degraded. To compensate this degradation, the optical elements are previously aligned with the displacements, which are predicted by the optical and the mechanical-thermal analyses, in the room temperature. Since this often used method requires the interactive alignments accompanied with frequent thermal cycles until the optical performances are satisfied, it could provide the much time and the cost for development. Additionally, because the mechanisms which are applied on the holder for releasing the thermal stress onto the optical elements under the cryogenic condition often have irreversible properties, the alignment becomes more difficult.

In order to solve such problems, athermal reflective optics had been classically employed for the infrared instrument. This optical system uses only a single material like aluminum alloys for all optical and opt-mechanical parts like the mirrors, the mirror holders, and the optical bench. Because of the self-similar expanding or shrinking of the optics for any temperature variations, it shows no temperature dependence on the aberration in principles. However, this athermal optics with aluminum alloys has disadvantages that aluminum mirrors produce many ghost or flare images diffracted by the processing traces, and they often never shrinks with the self-similarity as expected because of the remaining inner stresses.

Under this situations, we propose alternative athermal reflective optics using ceramic. It consists of the integrated off-axis mirrors and the optical bench, made of only ceramic, cordierite CO-220 produced by Kyocera Co. This material is easy to be polished like glasses and to be processed to any complicate forms like metals. And, it also has an extremely low CTE (< 2.0×10^{-8} @23℃). The easiness of polishing enables the ghost free and high performance mirrors because of no processing trace. The free-formability by machining enables to not only the athermal but also the alignment-free reflective optics even for the cryogenic condition, because we can directly produce holes on the integrated mirror structure for the gauge pins, which are directly stuck through the optical bench made of the same material (see Figure 8). We plan to produce a testing bench with the off-axis cordierite mirrors and the optical bench, and demonstrate the optical performances, the athermlity, the effect of hysteresis, and the durability of the metal coating under the cryogenic conditions.

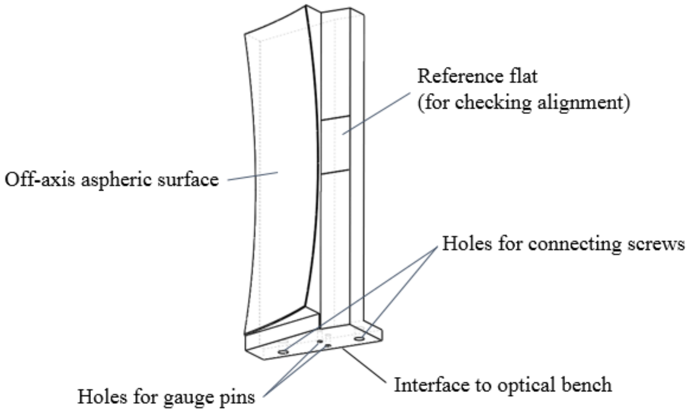


Figure 8. 3D model of the integrate off-axis mirror made by cordierite.

5. SUMMARY

We are developing a new NIR high-resolution, highly-sensitive, and very-compact spectrograph, VINROUGE. By employing a Germanium immersion grating, the white pupil spectrograph, HAWAII-2RG 5.3 μm cutoff array, and the integrated reflective optics using a ceramic (cordierite CO-202), we derive a preliminary optical design which achieves the spectral resolution of $R = 80{,}000$, the total throughput of > 0.28, and the instrument size is smaller than 600 mm×600 mm×600 mm even for 10-m class telescope. We have already completed the development of Germanium immersion grating and confirmed that it shows the highly absolute diffraction efficiency of approximately 0.75 at 4.52 μm in both room and cryogenic temperatures. In this year, we plan to fabricate a set of integrated off-axis ceramic mirrors together with the ceramic optical bench to demonstrate that the reflective optics was an athermal performance. The first light of VINROUGE is expected in 2019.

ACKNOWLEDGEMENTS

We would like to thank all staff of Koyama Astronomical Observatory of Kyoto-Sangyo University for supports throughout the production of this work. This study was financially supported by Ministry of Education, Culture, Sports, Science and Technology (MEXT) of the Japanese government and Kyoto-Sangyo University in Japan (2014-2018).

REFERENCES

[1] Herbst, E. and Klemperer, W., "The Formation and Depletion of Molecules in Dense Intersteller Clouds," Astrophysical Journal, 185, 505-534 (1973).

[2] Geballe, T. R. and Oka. T., "Detection of H_3^+ in interstellar space," Nature 384, 334-335 (1996).

[3] McCall, B. J.; Hinkle, K. H., Geballe, T. R., Moriarty-Schieven, G. H., Evans, N. J.; Kawaguchi, K., Takano, S., Smith, V. V., Oka, T., "Observations of H_3 in the Diffuse Interstellar Medium," Astrophysical Journal, 567, 391-406 (2002).

[4] Oka. T., "Interstellar H_3^+", Chemical Reviews, 113, 8738-61 (2013)

[5] Kaji, S., Sarugaku, Y., Ikeda, Y., Kobayashi, N., Nakanishi, K., Kondo, S., Yasui, C., and Kawakita, H., “The precise measurement of the attenuation coefficients of various IR optical materials applicable to immersion grating,” Proc. SPIE 9147, 914738 (2014).

[6] Kaji, S., Sarugaku, Y., Ikeda, Y., Kobayashi, N., Nakanishi, K., Kondo, S., Yasui, C., and Kawakita, H., “The development of a cryogenic FTIR system for measuring very small attenuation coefficients of infrared material,” Proc. SPIE 9912 (2016)

[7] Follert, R., Dorn, R. J., Oliva, E., Lizon, J. L., Hatzes, A., Piskunov, N., Reiners, A., Seemann, U., Stempels, E., Heiter, U., Marquart, T., Lockhart, M., Anglada-Escude, G., Löwinger, T., Baade, D., Grunhut, J., Bristow, P., Klein, B., Jung, Y., Ives, D. J., Kerber, F., Pozna, E., Paufique, J., Kaeufl, H. U., Origlia, L., Valenti, E., Gojak, D., Hilker, M., Pasquini, L., Smette, A., Smoker, J., “CRIRES+: a cross-dispersed high-resolution infrared spectrograph for the ESO VLT,” Proc. SPIE 9147, 914719 (2014)

[8] Rayner, J., Bond, T., Bonnet, M., Jaffe, D., Muller, G., Tokunaga, A., “iSHELL: a 1-5 micron cross-dispersed R=70,000 immersion grating spectrograph for IRTF,” Proc. SPIE 8446, 84462 (2012)

[9] Sarugaku, Y., Ikeda, Y., Kaji, S., Kobayashi, N., Sukegawa, T., Arasaki, T., Kondo, S., Nakanishi, K., Tasui, C., Kawakita, H., “Cryogenic performances of high-efficiency Germanium immersion grating,” Proc. SPIE 9906 (2016)