WINERED: A warm near-infrared high-resolution spectrograph

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ABSTRACT

We are developing a new near-infrared high-resolution ($R_{\max} = 100,000$) and high-sensitive spectrograph WINERED, which is specifically customized for short NIR bands at $0.9-1.35$ μm. WINERED employs the following two novel approaches in the optical system: (1) portable design with a ZnSe immersion grating and (2) warm optics without any cold stops. These concepts result in several essential advantages as follows: easy to build, align, and maintain; these result in a short development time and low cost. WINERED employs a VIRGO HgCdTe 2k × 2k array by Raytheon as the detector. We are developing our own array control system that aims at a low readout noise ($<$ 10 e$^-$) with a readout time of about 3 sec. Our goal is to achieve a high sensitivity of $R = 100,000$ for a NIR spectroscopy of 15 mag and 17 mag point sources with 4 m and 10 m telescopes, respectively. We have just finalized the optical design and produced a proto-type electronics, which are described in the companion papers by Yasui et al.[1] and Kondo et al.,[2] respectively. We plan to complete this instrument by the end of 2008 and hope to attach it to various 4 to 10 m telescopes as a PI-type instrument.

Keywords: near-infrared, spectroscopy, high dispersion, immersion grating, VPH, ELT

1. INTRODUCTION

In recent years, the necessity for developing a near-infrared (NIR) high-resolution spectrograph with $R = \lambda/\Delta\lambda \geq 70,000$ has been increasing in the fields of astrophysics and cosmology. NIR high-resolution spectrometry is expected to be an essential diagnostic tool in the studies of the chemical evolution in the early universe with high-z QSO absorption systems, the search for extra-terrestrial planets around nearby low-mass stars & young stellar objects (YSOs), the kinematics of outflows and disks around YSOs & late-type stars, and the chemical abundance study of stars & star-forming regions.

In the last ten years, several cutting-edge NIR instruments that can provide high-resolution spectra have been developed for $8-10$ m telescopes, e.g., NIRSPEC[3] for Keck II: $R_{\max} = 23,000$, GNIRS[4] for Gemini-S: $R_{\max} = 18,000$, and IRCS[5] for SUBARU: $R_{\max} = 20,000$. These instruments have been yielding various scientific results[6,7] sometimes by a combination with the adaptive optics (AO) technology.[8] However, the maximum resolving power is still not compatible with the visible high-resolution spectrographs, which can steadily provide $R_{\max} \geq 100,000$ spectra (e.g., HIRES at Keck,[9] UVES at VLT,[10] and HDS at SUBARU[11]). To the best of our knowledge, only one instrument Phoenix for Gemini-S can provide the maximum resolving power of $R_{\max} = 75,000$ with a slit width of 0".17;[12] however, the wavelength coverage is limited ($\Delta v < 1,500$ km s^{-1} in the velocity unit) since the instrument is not equiped with a cross-disperser. The strong scientific needs have let to the development of CRIRES[13] by the ESO community; CRIRES is a state-of-the-art NIR high-resolution spectrograph for VLT, that enables $R_{\max} = 100,000$ spectroscopy with a 0".2 slit with a natural guide star AO system.

When designing and building a NIR high-resolution spectrograph ($R \geq 70,000$) for the existing $8-10$ m telescopes or extremely large telescopes (ELTs), we face a technical difficulty: the size of the collimated beam

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	Immersion grating mode	Normal echelle mode
Maximum resolution	$R_{\max} = 103,000$ (2-pix sampling)	$R_{\max} = 28,300$ (2-pix sampling)
Wavelength range	$\lambda = 0.9 - 1.35$ μm (z, Y, and J bands)	
Wavelength coverage	$0.90 - 1.07$ μm (z-mode)	
	$0.96 - 1.11$ μm (Y-mode)	$0.93 - 1.35$ μm
	$1.12 - 1.35$ μm (J-mode)	(obtained with a single exposure)
Instrumental volume	$<$ 1500 mm (L) × 500 mm (W) × 500 mm (H)	
Telescope diameter	$D = 4 - 10$ m	
Telescope f-number	$f > 11$ at Nasmyth focus	

Table 1. Specification of WINERED (see section 3.2 for the two modes).

ϕ. Therefore, the volume of the instrument must be very large to achieve high resolving power (see equation (1) in section 2.2.). Moreover, since a large optical system must be installed in a cryostat, the development is expensive and fine-consuming.

As an alternative solution to these problems, we are developing a new NIR high-resolution spectrograph WINERED (= Warm INfrared Echelle spectrograph to Realize Extreme Dispersion) by employing two novel approaches. First, WINERED employs an immersion grating[14, 15] of ZnSe ($n \sim 2.4$), resulting in a high resolving power of $R_{\max} = 100,000$, despite its compact volume of 1,500 mm × 500 mm × 500 mm (see Table 1). The second approach of WINERED employs warm optics with no cold stop, which can be realized by limiting the wavelength range to short NIR bands of $0.9-1.35$ μm (see the original idea of a non-cryogenic spectrograph by Joyce et al.[16]). These two approaches make WINERED portable and easy to build, align, and maintain; therefore. the total cost and time could be significantly reduced as compared to an entirely cooled "classical" echelle spectrograph. WINERED-type instruments may also be one of the promising solutions for a NIR high-resolution spectrograph for the future ELTs. In this paper, we introduce the concept, technical issues, current status, and future plans pertaining to WINERED. The optical design and array control system are described in greater detail in Yasui et al.[1] and Kondo et al.[2] in this volume.

2. CONCEPT OF WINERED

Our goal is to realize a *portable* NIR spectrograph with a *high resolving power of* $\geq 70,000$ and a *high throughput of* $\geq 25\%$ at *low costs and with a short development time.* The development could also be regarded as a basic study for NIR high-resolution spectrographs for ELTs. In order to achieve this goal, WINERED attempts the following two technical approaches.

2.1. Warm optics

Figure 1 shows the various background levels for ground-based NIR spectroscopy. In the short NIR region ($\lambda \leq 1.35$ μm), the ambient thermal and sky backgrounds are negligible as compared to the readout noise of the readout system. This means that the cooling of the entire optics is not necessary as long as we remain in this short NIR region. This could result in a significant reduction in the cost and the development time. Therefore, WINERED employs warm (room temperature) optics except for the camera system that include the detector array (see Figure 2).

The narrow wavelength range significantly increases the performance of the AR coating on the optical elements, e.g., $R < 1$ % per surface is possible, while $R > 5$ % per surface is inevitable at some wavelengths for $1.0-5.5$ μm broad band AR. This results in another advantage, significant throughput improvement, for WINERED, which uses a large number of refractive optics for the aberration-free design. Table 2 shows the efficiency of each optical element and the total throughput of WINERED. It is found that the total throughput of WINERED can be much higher than those of the existing NIR echelle spectrographs.[3–5, 12][*]

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[*] There is another reason for the improvement of the throughput; As the cross-disperser, we use VPH, which has a higher diffraction efficiency than classical reflective grating (see Yasui et al.[1]).

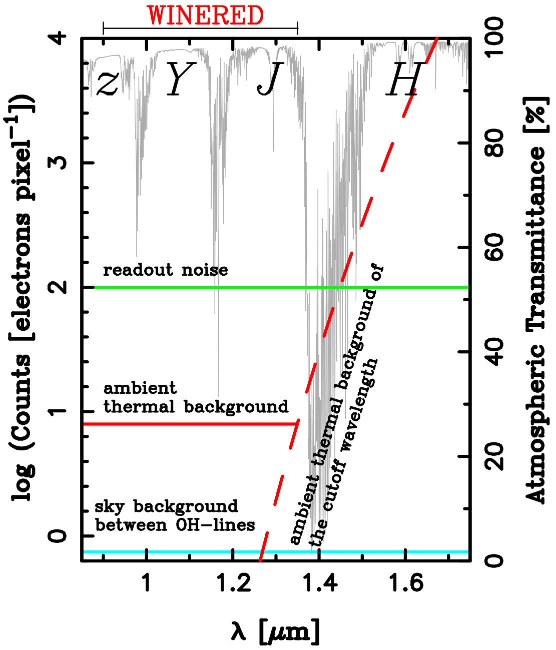

Figure 1. A comparison of the three background levels, readout noise of the array readout system, ambient thermal background, and sky background between OH lines in the wavelength range covered by WINERED. The horizontal axis shows the wavelength and the vertical axis shows the electron count rate. The dashed line shows the ambient thermal background if the cut-off wavelength is set as the wavelength. The top horizontal solid line shows the background level equivalent to the readout noise that is assumed to be 10 e^- rms pix^{-1}. The middle and bottom horizontal solid lines show levels of ambient thermal background (at 273 K) with a 1.35 μm cut-off and sky background between OH-lines, respectively. These are calculated assuming a telescope diameter of 6.5 m, a slit width of 0″.3, and an integration time of 1800 sec. In the short NIR regions (z, Y, and J bands), both backgrounds are negligible as compared to the readout noise (see Kondo et al.[2] for more details).

Optical element	$\eta_{\rm imm}$	$\eta_{\rm nor}$	Comments
Collimator mirror	98%	98%	Au coating
Echelle grating	60%	80%	target values
Cross-disperser	$> 80\%$	$> 70\%$	VPH grating (see Yasui et al.[1])
Camera lenses	$> 85\%$	$> 85\%$	total for 12 surfaces with AR coating
Dewar window	$> 98\%$	$> 98\%$	AR coating on CaF_2
Thermal-cut filter	$> 90\%$	$> 90\%$	
Detector	80%	80%	VIRGO HgCdTe (see Kondo et al.[2])
TOTAL	> 28 %	> 33 %	

Table 2. Estimated total throughput of WINERED. The efficiencies of the immersion grating mode ($\eta_{\rm imm}$) and the normal echelle mode ($\eta_{\rm nor}$) are shown separately.

Material	ZnSe ($n \sim 2.4$)
Clear aperture	90 mm × 90 mm
Blaze angle	70 deg.
Groove density	31.52 lines mm^{-1}
Coating	Anti-reflection coating on the entrance/exit surfaces Au or Ag coating on the grooved surface

Table 3. Optical parameters of the immersion grating for WINERED.

2.2. Immersion grating

The resolving power R of an echelle spectrograph is given by a simple equation with several instrumental parameters,

$$R = \frac{2n\phi \tan\theta}{Ds}, \tag{1}$$

where n is the refractive index of the material through which the incident and diffracted rays travel; ϕ, the diameter of the collimated beam; θ, the blaze angle of the echelle grating; D, the entrance pupil diameter of a telescope; and s, the slit width in radian. An immersion grating of an infrared material with a high refractive index ($n > 2$) can provide a higher resolution or reduce the size of the collimated beam to $1/n$ for the same resolving power.

As the main disperser, WINERED uses an immersion grating of ZnSe, which has a high refractive index ($n \sim 2.4$) and little absorption in the NIR wavelength. By adapting the ZnSe immersion grating, WINERED can realize a high resolving power with a very small instrumental volume and small optics (see Table 1). The specifications of the ZnSe immersion grating are listed in Table 3. The current status of the development is described in section 3.2.

3. OPTICAL SYSTEM

3.1. Overview of optical system

WINERED is a cross-dispersed-type echelle spectrograph that has a reflective parabola as the collimator, a ZnSe immersion grating, two (blue and red) Volume Phase Holographic gratings (VPHs) for the cross-disperser, and a cryogenic refractive lens system for the camera optics (Figure 2). The camera lens system and the detector array will be contained in a cryostat with a closed-cycle cooler. We employed this simplest and the most classical optical configuration because it provides the best balance between system throughput, alignment tolerances, and image quality, namely high spectral resolution. Although the white-pupil configuration,[17] which has become popular recently, is an alternative configuration, we did not employ it because either the throughput or the image quality must be sacrificed and the alignment tolerance becomes tight due to the larger number of optics. The details of the optical design are reported by Yasui et al.[1]

3.2. Development of ZnSe immersion grating

Our current trial of groove processing on ZnSe blocks uses a combination of a nano precision 3D profile grinding/turning machine and the electronic in-process dressing (ELID) grinding method.[18] The fabrication of a Ge ($n \sim 4.0$) immersion grating with the same method has been studied by a team of RIKEN, the Institute of Physical and Chemical Research, and Nagoya University.[19, 20] They reported a successful fabrication of a Ge immersion grating with nearly ideal groove profiles and acceptable wavefront errors at $\lambda \sim 10$ μm.

However, in order to complete the ZnSe immersion grating, we need to establish original technics to deal with two ather difficulties. One is the softness of ZnSe: it is much softer and brittler than Ge (the mechanical hardness is about 105 kg mm^{-1} for ZnSe while it is about 800 kg mm^{-1} for Ge.[21]). This implies that processing conditions, such as the typical size of diamonds on a grindstone, processing speed, and cutting depth into the block, are significantly different between ZnSe and Ge for obtaining smooth grooves without any chipping (= ductile mode) and a fine diffraction surface. Fortunately, our collaborators at RIKEN are finding suitable

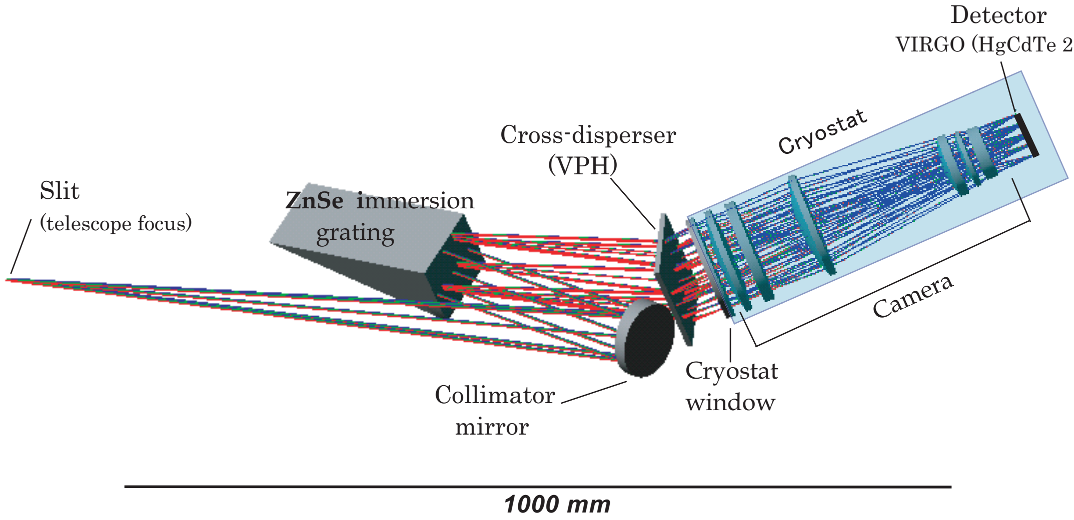

Figure 2. Optical layout of WINERED (see Yasui et al.[1] for more details).

conditions for ZnSe (see Figure 3). The other difficulty is obtaining the ideal echelle grating profile with a right angle particularly at the edges because the edge of a grindstone always has a round shape with $R > 5$ μm. Since the groove spacing of the ZnSe immersion grating is approximately seven times as small (~ 30 μm) as that of the Ge immersion grating,[19] the round shape of only a few μm is a serious problem for the diffraction efficiency of the ZnSe immersion grating used in the NIR region. At present, we are examining various possibilities such as the direct cut-off with a diamond tool and chemical/physical etching to eliminate the round shape. We are investigating the possibility of the use of ZnS. We expect the completion of the immersion grating to take about two or three years.

Because we anticipate a long leading time for the development of the ZnSe immersion grating, we plan to install a classical reflection echelle grating with a groove density of 31.6 lines mm^{-1} and a blaze angle of 63.9 deg, which will be switchable to the immersion grating. This "normal echelle mode" can have a spectra between 0.9$-$1.35 μm *simultaneously* with a resolving power of $R_{\rm max} = 28,300$ in one exposure (see Table 1). This mode serves as a full-science mode as well as a practice mode prior to the installation of the immersion grating. See Yasui et al.[1] for more details on the normal echelle mode.

4. ELECTRONICS

WINERED employs a 2048 × 2048 HgCdTe array VIRGO[22] by Raytheon, and a new array control system UTIRAC being developed by our team.[2] The most important spec of UTIRAC is a low readout noise (< 10 e$^-$) with speed of 200 kHz pix^{-1}. It has 4-channel readout ports that enable 3-sec readout time.[†] Any reduction in the readout noise brings a great advantage for high-resolution spectroscopy in the short NIR region because the readout noise becomes the most dominant noise source due to the low thermal background (see Figure 1). The details of UTIRAC are described in Kondo et al.[2] in the same volume.

5. OPERATION PLAN AND SYSTEM PERFORMANCE

All the WINERED components, including the optical system, electronics, and cryostat, occupy an area of only about $1,500 \times 500$ mm^2. Because of its portability, WINERED could be easily shipped to and mounted on

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[†] In the near future, we have a plan to extend the number of the readout ports from the current 4 channels to 16 channels, which will decrease the readout time to < 1 sec.

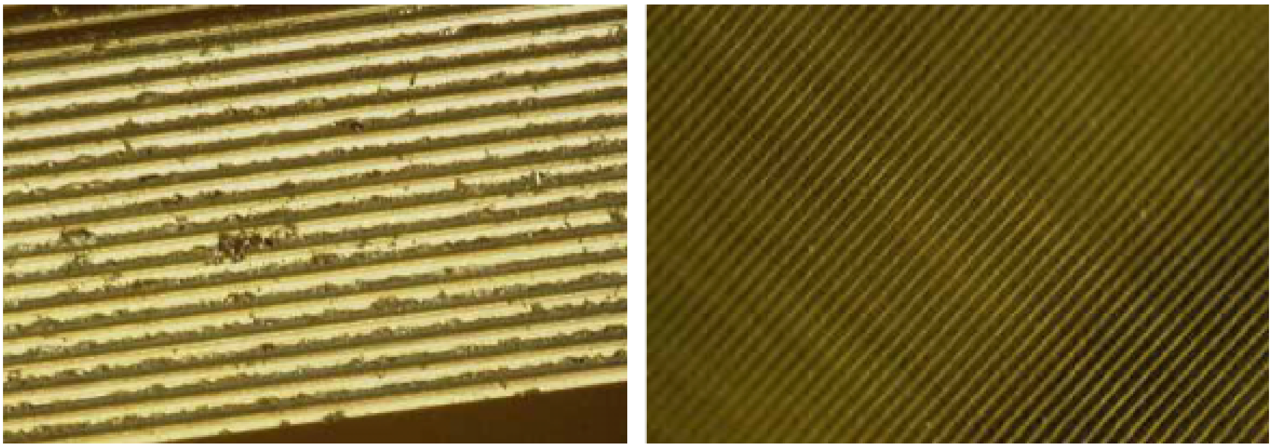

Figure 3. Results of the test groove processing on a ZnSe piece using a 3D grinding/turning profiler and the ELID grinding method. The left picture shows the grooves ground with a #4,000 cast iron bonded diamond-grinding cup under similar processing conditions that are successful for the Ge immersion grating;[19] there are many obvious chippings. The picture on the right shows the grooves with a #20,000 metal resin bonded polycrystallized diamond-grinding cup and newly searched conditions; no major chipping and defects can be seen on the edge of grooves.

	NTT	WHT	Magellan	VLT	Keck
Location	Cerro La Silla Chile	Canary Islands Spain	La Serena Chile	Cerro Paranal Chile	Mauna Kea Hawaii
Entrance pupil diameter (m)	3.58	4.2	6.5	8.2	10.0
f-number of Nasmyth port	$f/11$	$f/10.94$	$f/11$	$f/15$	$f/15$
Pixel scale (pix^{-1})	0”.27	0”.23	0”.15	0”.087 (0”.12)	0”.072 (0”.098)
Slit width for $R_{\rm max}$	0”.54	0”.47	0”.30	0”.17 (0”.24)	0”.14 (0”.20)
Maximum slit length	16”.3	14”.0	9”.0	5”.2 (7”.1)	4”.3 (5”.9)
$R_{\rm max}^{\rm imm}$	103,000	103,000	103,000	103,000	103,000
$R_{\rm max}^{\rm nor}$	28,300	28,300	28,300	28,300	28,300
$m_J^{\rm imm}$	15.6	15.9	16.4	16.4 (16.7)	16.8 (17.0)
$m_J^{\rm nor}$	17.2	17.4	18.0	18.0 (18.3)	18.4 (18.6)

Table 4. The estimated spectroscopic parameters of WINERED for various telescopes. The values in parentheses are those when using a focal reducer from $f/15$ to $f/11$. The notations of “imm” and “nor” represent “immersion grating mode” and “normal echelle mode”, respectively (see section 3.2). The limiting magnitudes at J-band ($m_J^{\rm imm}, m_J^{\rm nor}$) assume the natural seeing size of 0.”65 and S/N = 100 for a total integration time of 1800 sec × 16 exposures.

any telescope equipped with a Nasmyth port for visitor instruments. Our strategy is to install WINERED on a middle class telescope (D $\sim$ 4 m) as a home-ground, where regular scientific research, such as the Doppler search of planets and the survey of stars, YSOs, & QSO absorption systems, will be carried out. Because of the flexibility, the middle class telescopes are also a good home ground for observing "GRB (Gamma Ray Burst)" absorption systems that are similar to the QSO absorption systems but with GRB as the background source (see e.g., GRAASP project at *http://www.graasp.org*). In somecases, we can install WINERED in 8−10 m telescopes for fainter targets for a "campaign" of a few months. Table 4 summarizes the basic spectroscopic parameters and limiting magnitudes of WINERED for various telescopes. We found that WINERED can provide sufficiently high spectral resolution with seeing-limited wide slits and does not require the AO system for 4−6 m class telescopes.

6. SUMMARY

We presented an overview and the current status of the NIR high-resolution spectrograph WINERED, which is under development at the Institute of Astronomy, University of Tokyo. WINERED has various unique features: extremely high resolving power $\geq 100,000$ using an immersion grating, no cold stop, high throughput and low readout noise, portable size, low cost, and short development time. A WINERED-type spectrograph could be regarded as a prototype instrument for ELTs.

We have just finalized the optical design and completed a prototype of the readout system. We plan to complete the fabrication of the optics, except for the ZnSe immersion grating, by the spring of 2007. The noise testing of the readout system using a VIRGO multiplexer will be carried out immediately after this meeting and we hope to complete the testing of the final electronics for a science-grade array in the spring of 2007. At the end of 2007, we plan to perform the first light observations with the normal echelle mode using a middle class telescope. The first light observations with the ZnSe immersion grating will be conducted at the end of 2008 or later. We are constructing a website *http://www.ioa.s.u-tokyo.ac.jp/~winered* where you will soon find up-to-date information on WINERED. Using this website we hope to have fruitful discussions with those who are interested in this instrument.

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