WINERED: Optical design of warm infrared echelle spectrograph

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ABSTRACT

We are developing a short near-infrared ($\lambda = 0.9$–$1.35\,\mu$m) high-resolution ($R_{\max} = 100{,}000$) and high-sensitivity spectrograph "WINERED" by using several unique approaches. We adopt a classical cross-dispersed configuration for the optical system because it provides the best balance between the system throughput, alignment tolerances, and image quality (thereby producing high spectral resolution). Our design has four characteristics: (1) a ZnSe immersion echelle grating is used to realize a compact optical system even with $R_{\max} = 100{,}000$; (2) a volume phase holographic (VPH) grating is used as a cross-disperser (in comparison with the classical reflective grating, the VPH grating decreases the camera optics and provides higher throughput); (3) a cooled refractive lens system is used for the camera optics; and (4) a reflective echelle grating can be replaced with the above-mentioned immersion grating to cover a wider wavelength range with $R_{\max} = 28{,}000$. We have found a compact solution with high performance: all spots are well within 2×2 pixels throughout the entire detector array and the total throughput is more than 25% for all modes.

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

1. INTRODUCTION

Motivated by several scientific studies,[1] we are developing a near-infrared high-resolution spectrograph WINERED. The objectives of WINERED are to achieve (1) high spectral resolution ($R_{\max} = 100{,}000$), (2) high sensitivity (throughput $\geq 25\%$), and (3) portability. These objectives could be achieved by using warm (room temperature) optics and an immersion grating.

Warm optics in the short near-infrared region ($\lambda < 1.35\,\mu$m), the ambient thermal background is negligible in comparison with the noise of the readout system or OH airglow background (see Figure 1 in Ikeda et al.[1]). In this short wavelength range, it is not necessary to cool all optics. The limited wavelength range can significantly improve the performance of the antireflection (AR) coating on lenses (e.g., it is possible to achieve a reflectance of $R < 1\%$ per surface, while it is impossible to achieve $R < 5\%$ per surface in the case of 1–5.5 μm BBAR).

Immersion grating: The spectral resolution R of an echelle spectrograph is given by

$$R = \frac{2n\phi \tan\theta}{sD_{\rm tel}} \ , \tag{1}$$

where ϕ is the collimated beam diameter; s [rad], the slit width; $D_{\rm tel}$, the telescope diameter; θ, the blaze angle of the echelle grating; and n, the refractive index of the grating material. To obtain a higher value of R for a telescope, ϕ must be increased when a relief echelle grating in air ($n = 1$) is used; this increases the size of the instrument. An "immersion grating" with a high value of n can reduce ϕ by a factor of n.

To investigate the feasibility of the above-mentioned approaches, we have carried out the detailed optical design of WINERED. As a result, we obtained an effective solution for 4–10 m telescopes. In this paper, we present the optical design procedure and describe the optical performance of WINERED. The overall review and array control system of WINERED are described in companion papers by Ikeda et al.[1] and Kondo et al.[2]

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2. OPTICAL DESIGN

2.1. Paraxial design

First, we determined the best paraxial optical parameters for WINERED. We optimized their parameters for a telescope with an intermediate diameter of $D_{\rm tel} = 6.5$ m among our targeted 4–10 m telescopes and a popular Nasmyth f-number of $f/11$ for existing telescopes*. As the detector, we assumed a 2k $\times$ 2k VIRGO array developed by Raytheon; its pixel size is 20 μm^2. A pixel sampling of 2 pixels was assumed for $R_{\rm max} = 100{,}000$.

Immersion grating

We selected ZnSe ($n = 2.4$) or ZnS ($n = 2.3$) as the material for our immersion grating because their absorptions in the WINERED wavelength range of 0.9–1.35 μm are little compared to those of Si or Ge, which were first considered for infrared immersion gratings.[3] Because $D_{\rm tel}$ and n in equation (1) were already fixed, we determined the best balanced combination of ϕ, s, and θ under the following constraints:

- $\phi \leq 70$ mm, which is limited by the available block thickness of ZnSe or ZnS.
- $\theta \leq 72°$. A large blaze angle produces an extremely large difference in the resolving power in a free spectral range (FSR) because of the non linearity of the grating dispersion at high diffraction angles (see Loewen[4]).
- $s \geq 0''.3$ to detect 16 mag objects with $S/N = 100$ without the adaptive optics (AO) system.

The best combination was obtained as $\phi = 70$ mm, $\theta = 70$ deg, and $s = 0''.3$ (therefore, the pixel scale was $0''.15$ pix^{-1} for the array).

The groove density of the immersion grating was 31.8 gr mm^{-1}, which was determined as the FSR of the minimum order ($m = 109$, central wavelength $\lambda_0 = 1.346$ μm) completely falls into the array area.

Reduction ratio γ

The reduction ratio γ is defined as

$$\gamma \equiv f_{\rm col}/f_{\rm cam}. \tag{2}$$

It is uniquely determined from the telescope plate scale of $2''.88$ mm^{-1} and the array pixel scale of $0''.15$ pix^{-1}.

Collimator focal length $f_{\rm col}$

The collimator focal length $f_{\rm col}$ is calculated from $\phi = 70$ mm and $f/11$.

Camera focal length $f_{\rm cam}$

The camera focal length $f_{\rm cam}$ is estimated from $f_{\rm col}$ and γ using equation (2).

Cross-disperser

The distance between the spectral bands of adjacent orders on the detector array is proportional to the square of the central wavelength of each spectral band (${\lambda_0}^2$) when a grating is used as a cross-disperser.[5] This implies that the distance gradually increases with wavelength (decrease in the diffraction order). We have determined that the frequencies (groove densities) of the cross-disperses so that there is a clearance of at least 3 pixels between two spectral bands of the maximum order and the second maximum order.

The calculated paraxial optical parameters are listed in Table 1. The slit widths in radians and the pixel samplings for various 4–10 m telescopes are specified in Ikeda et al.[1] in this volume.

*The diameter and f-number of the Magellan telescope at the Las Campanas Observatory are the same as those of this model telescope.

Table 1. Optical parameters of WINERED.

		Immersion grating mode	Normal echelle mode
Telescope	f-number	$f > 11$ at Nasmyth focus	
	Wavelength range	0.9–1.35 μm	
	Wavelength coverage	0.90–1.07 μm (z-band)	
		0.96–1.11 μm (Y-band)	0.93–1.35 μm
		1.12–1.35 μm (J-band)	(obtained in a single exposure)
	Maximum resolution $R_{\max}$	103,000	28,300
	Reduction ratio γ $(= f_{\rm col}/f_{\rm cam})$	2.60	
Slit	Slit width	104, 208, 416 μm	
	Slit length	3.12 mm	
Collimator	Focal length $f_{\rm col}$	770 mm	
	Conic constant	−1 (offset parabola)	
	Offset angle	15 deg.	
Echelle	Blaze angle	70 deg.	63.9 deg.
	Groove density d	31.80 gr/mm	31.60 gr/mm
Cross-disperser (VPH grating)	Frequency	710 lines/mm (Y-mode)	280 lines/mm
		510 lines/mm (J-mode)	
	Bragg angle	20.8 deg. (Y-mode)	9.3 deg.
		17.8 deg. (J-mode)	
Camera	Focal length $f_{\rm cam}$	296.18 mm	
Detector	Array format	2k × 2k (Raytheon, VIRGO)	
	Pixel size	20 μm × 20 μm	

2.2. 3D modeling and optimization

We used a ray tracing software ZEMAX® for the 3D configuration modeling and optimization of the optical elements, particularly for the reduction of aberrations. The obtained optical layout is shown in Figure 1. The first parabolic off-axis mirror serves as a collimator for the telescope beam from the slit, thereby illuminating the echelle grating. Light dispersed by the echelle grating enters the VPH grating used as the cross-disperser. Finally, the beam enters the camera with six lenses. These lenses are cooled at 120 K, while all other optics are under room temperature at ∼293 K. Our model is based on the classical cross-dispersed configuration. Although the white-pupil configuration[6] has recently gained popularity, we have not adopted it because either the throughput or the image quality must be sacrificed and the alignment tolerance becomes tight due to a larger number of optics.

Figure 2 shows the wavelength coverage of four wavelength modes of WINERED along with the atmospheric transmission curve. The spectrum in the Y-band or J-band can be obtained in a single exposure. Hereafter, two wavelength modes of these bands are termed the Y-mode and J-mode, respectively. Wavelengths less than 0.96 μm (z-band) can also be observed in an exposure; in this case, the wavelength mode is termed the z-mode, which can be obtained by the rotation of the entire camera optics around the central axis of the VPH for the Y-mode. WINERED has an additional "N-mode", which uses a classical reflection echelle grating and covers 0.93–1.35 μm in a single exposure with $R_{\max}$ = 28,300 (see Table 1). It is possible to switch between the immersion grating mode and the normal echelle mode. The following is a more detailed discussion of some optical units.

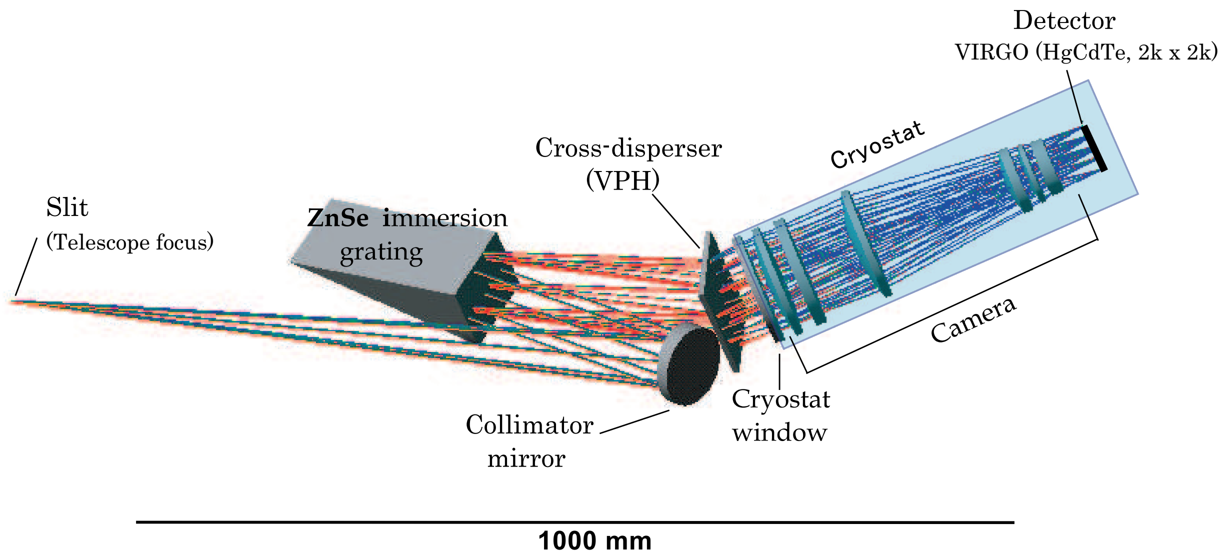

Figure 1. Optical layout of WINERED in the immersion grating mode. For the normal echelle mode, the immersion grating is replaced with a normal echelle.

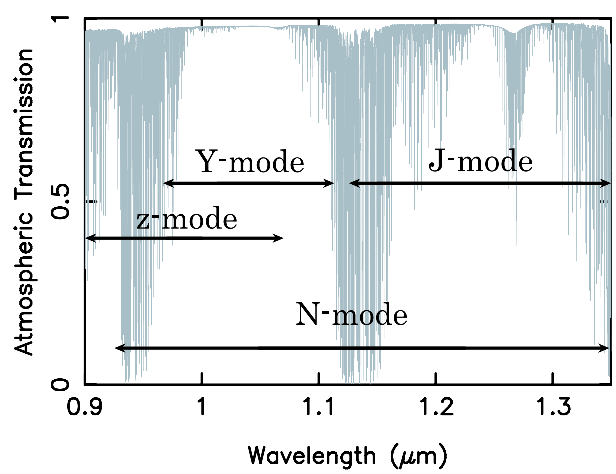

Figure 2. Atmospheric transmission curve and wavelength coverage by cross-disperser modes. The Y- and J-modes with the immersion grating cover 0.96–1.11 μm (m =154–133) and 1.12–1.35 μm (m = 131–109), respectively. There is an additional mode — z-mode — that covers 0.90–1.07 μm (m = 165–139, see text). The N-mode with a classical reflection echelle grating covers 0.93–1.35 μm (m = 60–42) in a single exposure.

Cross-disperser

VPH gratings are used as cross-dispersers. For the Y-, J-, and N-modes, the modulation frequencies of the index are 710 lines mm^{-1}, 510 lines mm^{-1}, and 280 lines mm^{-1}, while the Bragg angles at central wavelengths are 20.8 deg, 17.8 deg, and 9.3 deg, respectively. Since VPH grating is a transmission-type grating, the post optical elements can be placed close to the VPH, thereby resulting in compact post optics. The VPH could also provide higher diffraction efficiency since it can be used under the ideal condition equivalent to the Littrow configuration for a reflective grating; this is because the incident and diffracted rays do not overlap.

Camera

The existing near-infrared echelle spectrographs often employ reflective camera systems, which are free of chromatic aberrations, because they cover a wide wavelength range of 1–5.5 μm (e.g., CRIRES[7] for VLT, NIRSPEC[8] for Keck II, IRCS[9] for SUBARU). However, WINERED uses a "refractive" camera system because of the following advantages: (1) compact volume, (2) loose tolerances for fabrication and alignment, and (3) possibility of reducing aberrations by using only spherical surfaces and a coaxial configuration. Since WINERED covers a very narrow wavelength range (0.9–1.35 μm), chromatic aberrations can be easily corrected.

The camera optics are contained in a cryostat at 120 K in order to minimize the ambient thermal background radiation into the detector. The lens materials are selected from those used by Yamamuro et al.,[10] who measured the absolute refractive indices ($n_{\rm abs}$) under cryogenic temperatures for 20 types of infrared materials (see APPENDIX A for the derivation of $n_{\rm abs}$ from values estimated by Yamamuro et al.[10] for WINERED wavelengths and the operation temperature). By optimizing the lens shapes and thicknesses with ZEMAX, we obtain a feasible and effective solution for the camera optics by using six lenses of CaF_2, S-TIH14, BaF_2, S-TIH14, S-PHM52, and fused silica (see Figure 3). The diameter of the largest lens (CaF_2) is only 130 mm.

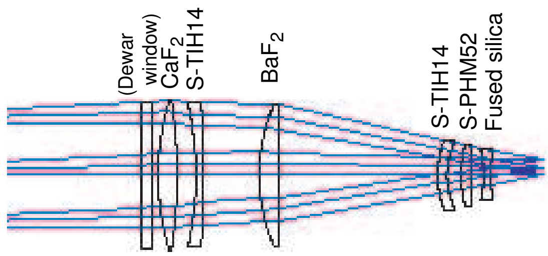

Figure 3. Optical layout of WINERED camera system. The leftmost flat of the figure shows a dewar window of CaF_2.

3. PERFORMANCE

Figures 4, 5, and 6 show the echelle formats and spot diagrams for the Y-, J-, and N-modes, respectively. We have obtained high image quality for the three modes: all spots are well within 2×2 pixels throughout the entire detector array. The efficiencies of all elements and the total throughput of WINERED are listed in Table 2. The target throughput of $\leq$25% can be reasonably achieved for both the immersion grating and the normal echelle modes.

Table 2. Estimation of the total throughput of WINERED.

Optical element	Immersion grating mode	Normal echelle mode	Comments
Collimator mirror	98%	98%	Au coating
Echelle grating	60%	80%	Target value
Cross-disperser	$> 80\%$	$> 70\%$	VPH grating
Camera lenses	$> 85\%$	$> 85\%$	Total for 12 surfaces with AR coating
Dewar window	$> 98\%$	$> 98\%$	
Thermal-cut filter	$> 90\%$	$> 90\%$	
Detector	80%	80%	VIRGO HgCdTe (see Kondo et al.[2])
TOTAL	$> 28\%$	$> 33\%$	

4. SUMMARY

We have carried out the optical design of WINERED and successfully obtained a feasible solution for achieving high spectral resolution and high sensitivity with a compact volume: all spots on the detector array are well

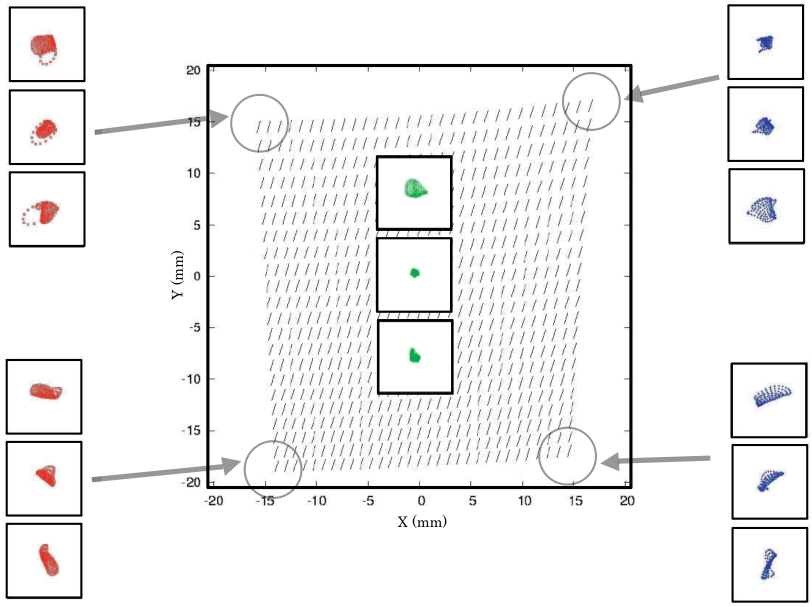

Figure 4. Echelle format and spot diagrams for the Y-mode. We obtained the spot diagrams at five detector positions, thereby at five wavelengths. The three boxes at each detector position show the spot diagrams at the upper edge, center, and lower edge of the slit, respectively. The boxes represent 2×2 pixels.

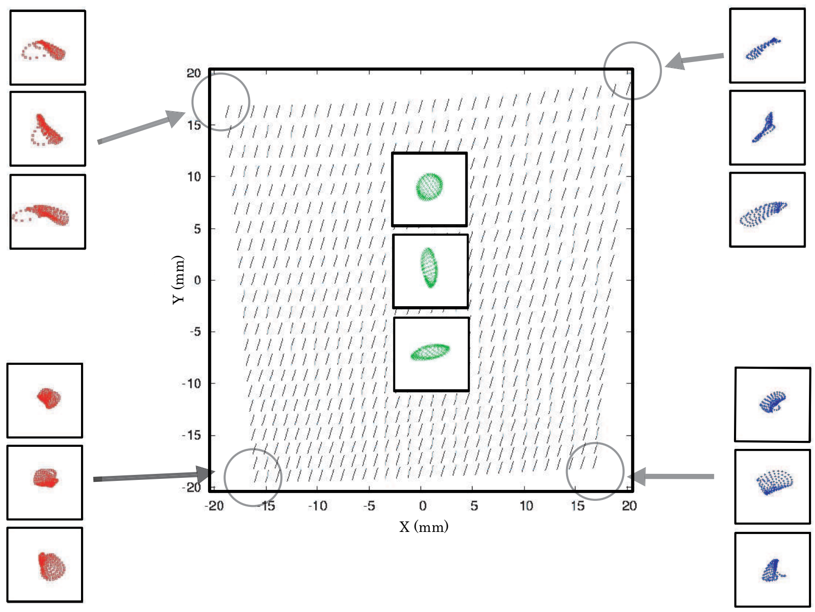

Figure 5. Echelle format and spot diagrams for the J-mode.

within 2×2 pixels, the throughput is >25 % for all modes, and the volume of the optics is within 1500 mm (L) $\times$ 500 mm (W) $\times$ 500 mm (H). We plan to perform tolerance and ghost analyses and fabricate the optical elements, except for the immersion grating, by spring of 2007. The immersion grating would be completed by the end of 2008. Before installing the immersion grating, we plan to conduct observations in the N-mode by using the classical reflection echelle grating (see Ikeda et al.[1] for a detailed explanation of our observation strategy).

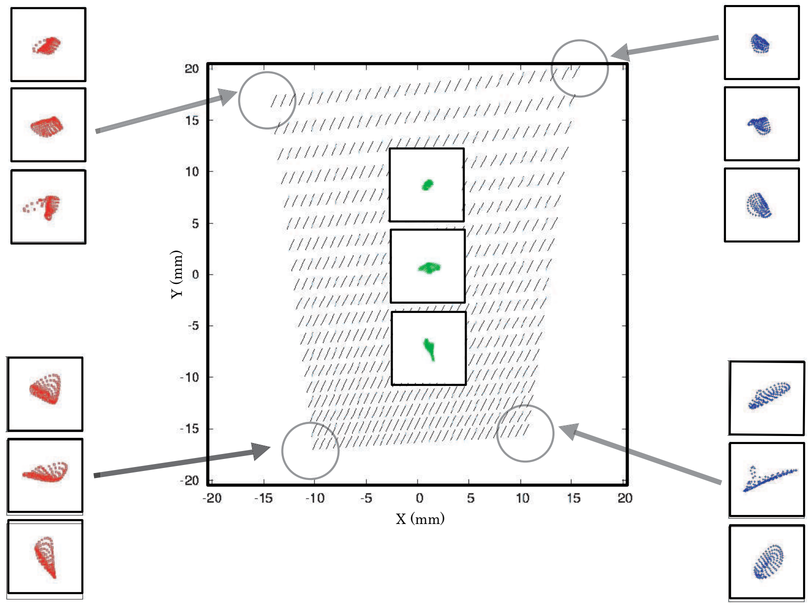

Figure 6. Echelle format and spot diagrams for N-mode.

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APPENDIX A. DERIVATION OF REFRACTIVE INDICES FOR COOLED CAMERA LENSES

Yamamuro et al.[10] have measured the absolute indices $n_{\rm abs}$ of 20 materials at 293 K and the index differences Δn for cryogenic temperatures at seven wavelengths between 365.02 nm and 3298 nm. By using the values of Δn at 1013.98 nm and 1529.58 nm at 120 K, we interpolate Δn at $\lambda = 0.9, 1.0, 1.1, 1.2, 1.3, 1.4$, and 1.5 μm. To convert $n_{\rm abs}$ at 120 K, we do not use $n_{\rm abs}$ at 293 K given by Yamamuro et al; rather, we calculate $n_{\rm abs}$ with the relative index of each material initially considered in ZEMAX and the absolute index of air $n_{\rm air}$:[11]

$$n_{\rm air} = 1 + \frac{\left(6432.8 + \frac{2949810\lambda^2}{146\lambda^2-1} + \frac{25540\lambda^2}{41\lambda^2-1}\right) \times 10^{-8} \times P}{1.0 + (T-15) \times 3.4785 \times 10^{-3}}, \tag{3}$$

where T is the temperature in °C, P is the relative air pressure in atm, and λ is in μm. This is because Yamamuro et al. state that their $n_{\rm abs}$ values would include systematic errors of 1.3–1.8 $\times$ 10^{-4} due to the characteristics of their equipment.

In order to assign these $n_{\rm abs}$ values to the private glasses in ZEMAX, we obtain the coefficients (K_1, K_2, K_3, L_1, L_2, and L_3) of the "Sellmeier 1 formula" defined by ZEMAX:

$$n^2 - 1 = \frac{K_1\lambda^2}{\lambda^2 - L_1} + \frac{K_2\lambda^2}{\lambda^2 - L_2} + \frac{K_3\lambda^2}{\lambda^2 - L_3}, \tag{4}$$

by least squares fitting. Table 3 lists the calculated values of $n_{\rm abs}$ of materials that are used for WINERED camera lenses.

Table 3. Absolute refractive indices of optical materials at 120 K.

	Wavelength [μm]						
Glasses	0.9	1.0	1.1	1.2	1.3	1.4	1.5
CaF_2	1.43168	1.43095	1.43030	1.42978	1.42927	1.42879	1.42832
BaF_2	1.47217	1.47138	1.47076	1.47024	1.46980	1.46940	1.46904
S-TIH14	1.73907	1.73551	1.73267	1.73027	1.72817	1.72626	1.72457
S-PHM52	1.61048	1.60888	1.60751	1.60627	1.60511	1.60399	1.60288
Fused silica	1.45973	1.44964	1.44843	1.44727	1.44614	1.44500	1.44385

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