Cryogenic Performance of High-efficiency Germanium Immersion Grating

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ABSTRACT

Immersion gratings will play important roles for infrared astronomy in the next generation. We have been developing immersion gratings with a variety of kinds of materials and have succeeded in fabricating a high-efficiency germanium (Ge) immersion grating with both a reflection coating on the grating surface and an AR coating on the entrance surface. The grating will be installed in a K-, L-, and M-bands (2-5um) high-resolution (R=80,000) spectrograph, VINROUGE, which is a prototype for the TMT MIR instrument. In this paper, we report the preliminary results on the evaluation of the Ge immersion grating. We confirmed that the peak absolute diffraction efficiency was in the range of 70-80 %, which was as expected from the design, at both room and cryogenic temperatures.

Keywords: immersion grating, infrared, high-resolution spectroscopy, VINROUGE, TMT

1. INTRODUCTION

Immersion grating is a diffraction grating wherein the diffraction surface is immersed in a material with a high refractive index ($n > 2$, see Figure 1).[1] The maximum spectral resolution of an immersion grating at a wavelength λ is given by

$$R_{max} = \lambda/(\Delta\lambda)_{min} = \begin{cases} \frac{2n\phi\tan\theta}{\lambda} & \text{(diffraction-limited case)} \\ \frac{2n\phi\tan\theta}{sD} & \text{(slit}-\text{limited case)} \end{cases}, \quad (1)$$

where ϕ is the collimated beam diameter, θ is the incident angle to the grating surface (which corresponds to the blaze angle θ_B under the Littrow condition), s is the slit width measured in celestial coordinates, and D is the entrance pupil diameter of the telescope. These equations indicate that immersion grating can provide n times higher spectral resolution compared to classical reflective grating of the same clear aperture, thus it enables us to realize compact spectrographs without changing the spectral resolution. This new device will play important roles for infrared astronomy in the next generation (see Intro. in Ikeda et al.[1]).

Although immersion gratings are invaluable for infrared astronomy, realizing a practical immersion grating with high diffraction efficiency is challenging. Since high grating efficiency is as effective as large telescope diameter, diffraction efficiency is the critical indicator of gratings for astronomical use. Recently, we succeeded in fabricating a cadmium zinc

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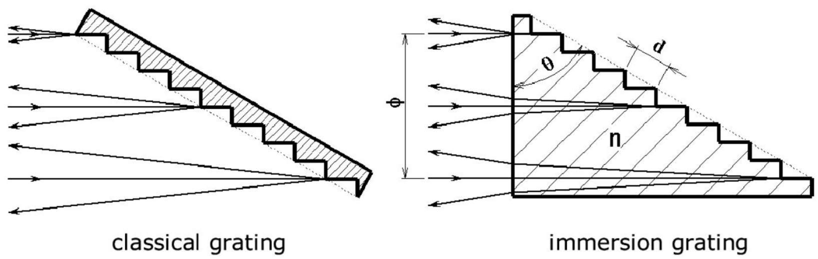

Figure 1. Classical reflective grating and immersion grating. *n*: refractive index, ϕ: collimated beam diameter, θ: blazed angle, *d*: groove pitch.

telluride (CdZnTe) immersion grating with perfect groove shapes,[1] which showed the theoretically predicted relative diffraction efficiency, by planing process with an ultrahigh-precision five-axis processing machine developed by Canon Inc.[2] This technique enables us to process ideal groove shapes on any kind of infrared materials including Ge. As a next step, practical Ge immersion gratings with both a reflection coating on the grating surface and an AR coating on the entrance surface have been completed.[3] We are going to install a Ge immersion grating in a K-, L-, and M-bands (2-5um) high-resolution (R=80,000) spectrograph, VINROUGE,[4] which is a prototype for the TMT MIR instrument. Since Ge has very high refractive index (n = 4), which is the highest among the available infrared optical materials for immersion grating, the optical system of the spectrograph is designed unprecedentedly compact (600 mm x 600 mm x 600 mm) for the spectral resolution in this wavelength region. In this paper, we report the preliminary results on measuring diffraction efficiency of the Ge immersion grating at both the room and cryogenic temperatures.

2. GE IMMERSION GRATING

Figure 2 shows the appearance of the Ge immersion grating for VINROUGE and Table 1 summarizes properties of the grating. We set the apex angle to 86° to maximize the integrated diffraction efficiency as a result of a simulation based on the rigorous coupled-wave analysis. The entrance/exit surface was tilted at 5° from the optical axis so that the ghost ray generated at this surface deviates from the correct optical path. There are recesses with a width of 2 mm at both sides of the diffraction surface for holing the grating without any thermal stresses on the diffraction surfaces.

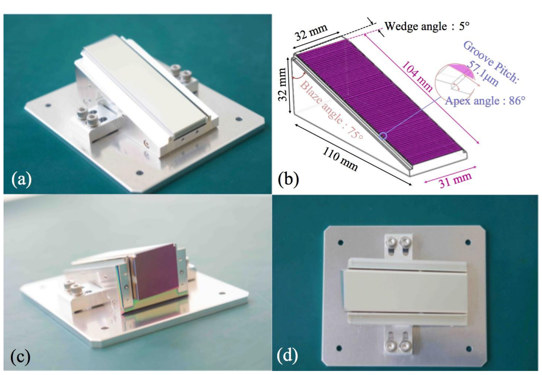

Figure 2. Ge immersion grating for VINROUGE.
(a) Diffraction surface. (b) Schematic diagram.
(c) Entrance/exit surface. (d) Diffraction surface (top view)

Table 1. Properties of Ge immersion grating

Geometrical parameters	
Material	Single-crystal Ge (n = 4.0)
Blaze angle	75°
Apex angle	86°
Groove Pitch	57.1 μm
Tilt angle of entrance/exit surface	5°
Area of entrance/exit surface	32.0 mm x 32.0 mm
Area of diffraction surface	31.0 mm x 104.0 mm
Diffraction surface	
Surface roughness	< 8 nm (RMS)
Surface irregularity	< 65.6 nm (PV), < 18.7 nm (RMS)
Rowland's ghost	< 0.1 %
Coating	Ag (with protective coating)
Entrance/exit surface	
Surface irregularity	< 175 nm (PV)
Coating	Broadband anti-reflective coating

3. MEASUREMENT SYSTEM

Figure 3 shows an in-house equipment to measure the light diffracted by immersion gratings in the infrared wavelength range under both the immersion and reflection configurations at room and cryogenic temperatures. For the light source, this system employs a single-mode quantum cascade tunable laser (TLS-41047, Daylight Solutions, Inc.), whose wavelength range is 4.30-5.11μm and the band width is < 6.8 x 10^{-6} μm. Linearly polarized beam is emitted from the laser, and TE or TM modes can be selected by rotating a half-wave plate. The selected beam is cleaned up, expanded, and collimated by a spatial filter. The diameter of the collimated beam is reduced by a variable diaphragm aperture. We set the diameter of the collimated beam to 3 mm for this experiment. The reduced beam is split by a beam splitter of a CaF_2 plate, which is wedged to prevent interferences within it and ghosts. One of the split beams enters and is diffracted back by the immersion grating in the Littrow configuration, being focused on a two-dimensional (80 x 80 arrays) photoconductive detector (Tachyon 6400 core, New Infrared Technologies, Ltd), whose wavelength detection range is 1-5 μm. The other split beam enters and is reflected back by a mirror, being also focused on the detector, but at the different location. By monitoring the reflected beam and the diffracted beam simultaneously, we can compensate the time variation of the laser output. Both an immersion grating and a reference mirror are switchable without changing the light path. Comparing the intensities of beams diffracted by the immersion grating and reflected by the reference mirror, we obtain the absolute diffraction efficiency of the immersion grating. When we measure the diffraction efficiency at the cryogenic temperature, the immersion grating and the reference mirror are installed in a cryostat, and they are mechanically switchable without breaking the vacuum condition with a motion feedthrough. The detail of the cryostat is described in Kaji et al.[5] From measurements at various wavelengths, we obtained the wavelength dependence of the diffraction efficiency. Since the direction of the diffracted beam changes with the wavelength, we put the IR detector and the focusing lens on a movable plate to be able to follow it.

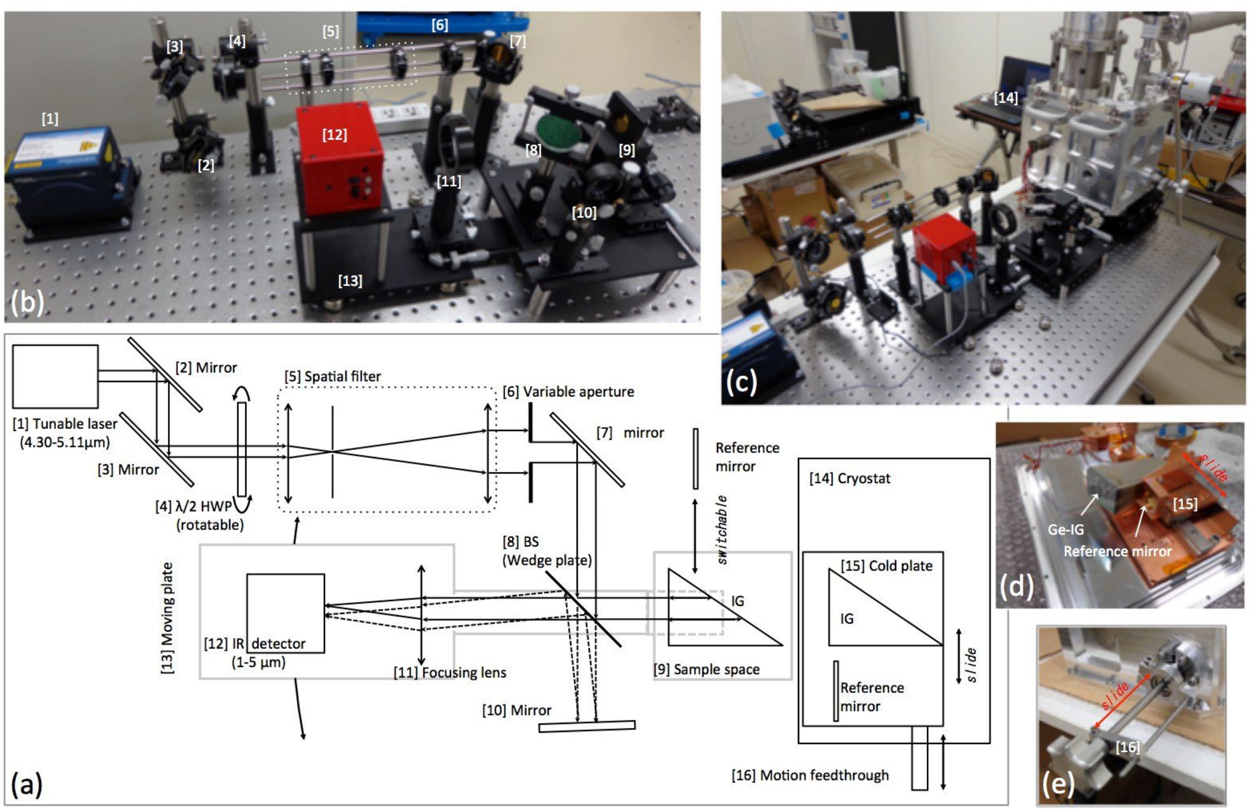

Figure 3. An in-house equipment to measure the diffraction efficiency of immersion gratings. (a) Schematic diagram of the optical configuration. (b) Setup for measurement at the room temperature. (c) Setup for measurement at the cryogenic temperature. (d) The Ge immersion grating and the reference mirror on the cold plate. (e) Motion feedthrough.

4. DIFFRACTION EFFICIENCY

We measured the diffraction efficiency of the Ge immersion grating at room and cryogenic (~28 K) temperatures. The measurements were made at $\lambda \sim 4.25\mu m$ for both TE/TM modes. A beam with a diameter of 3 mm entered at the center of the entrance/exit surface. The entrance/exit surface of the grating was tilted by 10° relative to the beam axis so that the beam was diffracted back by the diffraction surface in the Littrow configuration when the wavelength was a blaze wavelength.

Figure 4 shows the diffraction efficiency of the Ge immersion grating. We measured beam intensities at several positions of the IR detector and took the average of them to reduce the uncertainty due to the pixel-to-pixel sensitivity variation. The error bars in the figure show the standard deviations of the measured efficiency. The horizontal line shows the peak efficiency expected from the designs of grooves and coating. The Ge immersion grating is found to have high efficiencies (80% for TE and 70% for TM) as expected from the design at both room and cryogenic temperatures. The data measured at the cryogenic temperature is under detailed analysis, but the efficiency at the cryogenic temperature is roughly the same as that at room temperature.

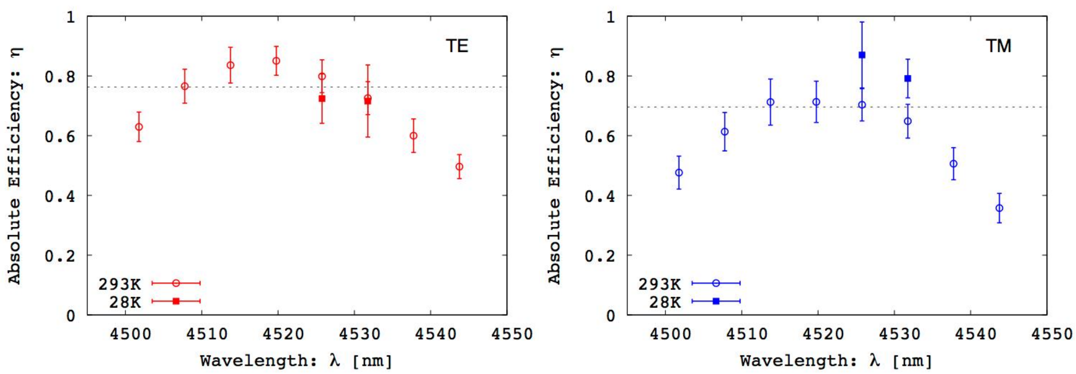

Figure 4. Measured absolute diffraction efficiency at room and cryogenic temperatures (left: TE mode, right: TM mode). The horizontal line shows the peak efficiency expected from the design.

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