ABSTRACT

This paper presents the results of refractive index measurements of CdZnTe at the wavelength range of 10.6, 11.4, 14.0, and 17.1 μm and in the temperature range between 4 and room temperature, and the development of a high-precision cryogenic mid-infrared refractive index measurement system. We show how these results have influenced the detailed optical design of HRS (High Resolution Spectrometer, wavelength range between 10 and 18 μm, spectral resolution $R = \lambda/\Delta\lambda > 25,000$, operating temperature $T < 20$ K), one of the instruments on board GREX-PLUS (Galaxy Reionization EXplorer and PLanetary Universe Spectrometer).

GREX-PLUS is an ambitious mission designed to explore a wide range of astrophysical phenomena, including the formation of galaxies and planetary systems, and to make detailed studies of planetary atmospheres and the potential for life beyond Earth. One of the science topics of particular interest is the observation of H_2O snow lines in protoplanetary disks. We are developing a CdZnTe immersion grating for a compact high-dispersion mid-infrared spectrometer GREX-PLUS/HRS. One of the key challenges in the design of high-dispersion spectrometers for space-based infrared astronomy is the need to miniaturize components without sacrificing performance. Immersion gratings are a promising solution to this problem. By using an immersion grating, the spectrometer size can be reduced to $1/n$ ($1/n^3$ in volume, n: refractive index) compared to conventional diffraction gratings. This allows the spectrometer to be significantly smaller and lighter, which is crucial for space missions where weight and size are limiting factors. CdZnTe is promising as a material for immersion gratings for the wavelength range between 10 and 18 μm.

Immersion gratings are useful for miniaturization of spectrometers, but have not been established in the mid-IR due to the lack of materials with well-known optical constants at cryogenic temperatures. CdZnTe has been proposed as a promising material, but its refractive index and its temperature dependence in the wavelength range between 10 and 18 μm, which are important for optical design, have not been directly measured. The refractive index is a crucial parameter for the spectral resolution and optical design of the spectrometer. In the GREX-PLUS/HRS design, refractive index values with a

measurement accuracy of $\Delta n_{\mathrm{req}} < 1.0 \times 10^{-3}$ are required to maximize efficiency at certain wavelengths (e.g., 17.754 mum).

In this study, we developed a high-precision cryogenic mid-infrared refractive index measurement system that operates at wavelengths of 10.6, 11.4, 14.0, and 17.1 μm and in a temperature range between 12.4 and 300 K. The measurement system is characterized by its innovative features, including the realization of a highly efficient optical system, the construction of a cooling system capable of achieving cryogenic temperatures, and the establishment of a minimum deviation measurement method utilizing a single-element detector.

Using the measurement system, two experiments were performed to obtain the refractive index of CdZnTe. In the first experiment, the apex angle of the prism was measured using visible autocollimation. The second experiment was a declination measurement in the mid-infrared at cryogenic temperatures.

From the results of the two experiments, the refractive index of CdZnTe at wavelengths of 10.6, 11.4, 14.0, and 17.1 μm and temperatures between 12.4 K and 292.84 K was obtained with an accuracy of $\Delta n_{\mathrm{total}} < 1.3 \times 10^{-3}$. Using these refractive indices and their measurement accuracy, three topics were discussed. First, the temperature dependence of the refractive index of CdZnTe at low temperatures for each wavelength was revealed, indicating a difference in temperature dependence between CdZnTe and CdTe. Second, it was demonstrated that the previously estimated refractive index of CdZnTe, based on the temperature dependence of CdTe, does not meet the required precision of $\Delta n_{\mathrm{req}} < 1.0 \times 10^{-3}$, suggesting the importance of measuring refractive indices at cryogenic temperatures in the mid-infrared region. Finally, the impact of the system's measurement precision on the design of immersion gratings was examined. For ground-based high-dispersion spectrometers, the diffraction efficiency could drop to 75–85%, while for GREX-PLUS, the influence is considered negligible due to its lower diffraction order and wider free spectral range. The current accuracy of $\Delta n_{\mathrm{total}} < 1.3 \times 10^{-3}$ is considered sufficient for GREX-PLUS.

The results of this research are expected to play a key role in refining the optical design of the HRS and ensuring the success of the GREX-PLUS mission. Moreover, the techniques and findings presented in this thesis can be applied to the study of other materials and wavelength ranges, potentially benefiting a wide range of future space missions in the field of infrared astronomy.