Development of a Cryogenic Far-infrared Grating Spectrometer for a Post-dispersed Fourier Transform Spectrometer

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Abstract—Recent advances in far-infrared detector technology have led to increases in raw sensitivity of more than an order of magnitude over previous state-of-the-art detectors. With such sensitivity, photon noise becomes the dominant noise component, even when using cryogenically cooled optics, unless a method of restricting the spectral bandpass is employed. One method is to use a low-resolution diffraction grating spectrometer to post-disperse the signal from a high-resolution instrument, such as a Fourier transform spectrometer (FTS). This concept has been adopted for the SAFARI instrument on the SPICA mission. This paper discusses the development of a prototype cryogenic grating spectrometer that has been used to evaluate the concept of a post-dispersed polarizing FTS over the range from 285 - 500 µm.

I. INTRODUCTION

The SPace Infrared telescope for Cosmology and Astrophysics (SPICA) is a joint ESA/JAXA space observatory class mission [1] in which the primary mirror will be actively cooled below 8 K to minimize self-emission. The SpicA FAR-infrared Instrument (SAFARI) is based on a Post-Dispersed Polarizing Fourier Transform Spectrometer (PDPFTS) design, which limits the instantaneous spectral bandwidth falling on its ultra-sensitive detectors (NEP ~2×10⁻²² W/√Hz). This paper presents the design and verification of a prototype cryogenic grating spectrometer that will serve to post-disperse the output of a room temperature polarizing FTS to form an analog of SAFARI and allow the instrument concept to be studied for the first time in a realistic environment [2].

II. GRATING CONCEPT

The prototype diffraction grating spectrometer is based on the Czerny-Turner monochromator configuration which is governed by the grating equation [3]:

\[ m \lambda = 2d \sin \theta \cos \varphi, \]

where \( m \) is the order of diffraction, \( d \) is the slit spacing, \( \lambda \) is the wavelength of the incident light, \( \theta \) is the angle of incidence, and \( 2\varphi \) is the deviation angle. The design of the grating spectrometer extends the work of Veenendaal et al. [4] who developed a cryogenic post-dispersed grating to order sort the output from a Fabry-Perot interferometer. In the new design, the grating is mounted in a monolithic aluminum housing on a pivot driven by a cryogenic stepper motor [5] through worm gear reduction. The incident collimated beam is reflected by a fold mirror onto the grating which disperses the radiation onto a 15° off-axis parabolic mirror, which in turn focuses the light on the exit slit of the spectrometer located on the feedhorn of a 0.3 K composite bolometer detector [6].

The grating was designed to operate over a wavelength range from 285-500 µm chosen close to the long-wavelength end of SAFARI and for which an extensive suite of test equipment is available. The theoretical resolving power, \( R \), was calculated under the assumption that it was slit width limited [7]:

\[ R = \frac{m \lambda}{w \cos (\varphi + \theta)}, \]

where \( w \), the width of the entrance slit, was chosen to achieve a resolving power of \( R \sim 100 \) near the middle of the wavelength range (392.5 µm). The design specifications for the grating, which is used in the first order, are listed in Table 1.

Table 1: Specifications for the grating spectrometer designed to operate over the range of 285 – 500 µm.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order of diffraction, ( d )</td>
<td>312 µm</td>
</tr>
<tr>
<td>Deviation angle, ( 2\varphi )</td>
<td>15°</td>
</tr>
<tr>
<td>Entrance slit width, ( w )</td>
<td>5.0 mm</td>
</tr>
<tr>
<td>Exit slit width, ( w'' )</td>
<td>4.0 mm</td>
</tr>
<tr>
<td>Blaze angle, ( \theta_B )</td>
<td>39.4°</td>
</tr>
</tbody>
</table>

The grating was fabricated from RSA 6061 aluminum and ruled with a single point diamond machine under a specialized thermalization process to minimize internal stress [8]. The grooves embodied a sawtooth profile to maximize the efficiency of the grating. The angle of each triangular groove was made to satisfy the blaze condition [7]:

\[ \lambda_B = 2d \sin \theta_B, \]

Fig. 1: Cut-away view of the prototype grating spectrometer CAD model. Improvements from the previous design include: a monolithic grating enclosure (teal); a larger diameter filter (50 mm) (brown); a new diffraction grating (yellow) that features a plane mirror mounted to the rear side (red) to allow determination of the grating efficiency; and a retractable baffle (blue) mounted to the aluminum shield surrounding the enclosure. A thermal filter (pink) is mounted at the interface between the 4 K and 0.3 K enclosures. The exit slit (green) is mounted on the feedhorn of a 0.3 K composite bolometer detector (gold). The cryogenic stepper motor (orange) drives the worm and gear system and rotates the grating around the axis indicated by the black arrow. The grating assembly is clamped to the 4 K baseplate of a test-facility cryostat [9]. See text for details.
where $\theta_B$ is the angle between the grating plane and the face of the groove. The grating was designed to achieve a maximum efficiency at 392.5 $\mu$m, corresponding to a blaze angle of 39.4°.

The new grating design, shown in Fig. 1, incorporates a larger aperture entrance filter (50 mm) and a retractable baffle to block stray light within the grating enclosure from reaching the detector. The monolithic design and choice of material of the enclosure minimize misalignments (e.g., gear drive and optics) as the system is cooled to cryogenic temperatures. The bottom of the enclosure has three extruded square pads that serve as a three-point contact between the enclosure and the 4 K plate. To measure the efficiency of the grating spectrometer, a mirror is mounted onto the back of the grating in such a way that the assembly is free to rotate completely around its axis. When the system is coupled to a Fourier transform spectrometer (FTS) as the system is cooled to cryogenic temperatures, the FTS was post-dispersed the signal from a room temperature polarizing FTS, described in a companion paper [2], with one port viewing a ~1200 K blackbody source and the other viewing a room temperature blackbody. The grating was stepped through angular positions in 0.12° (0.57 µm) increments around the terahertz band. For a given setting of the photomixer frequency, the grating was scanned in 0.03° (0.1425 µm) increments at ± 2.0° (± 9.5 µm) around the corresponding photomixer wavelength, in order to determine the spectral response function (SRF) of the grating as a function of angle (wavelength). Measurements at six photomixer frequencies were obtained. Fig. 2 shows the SRF for two photomixer frequencies. Gaussian profiles were fitted to each measurement to determine the center wavelength, $\lambda_c$, and the standard deviation, $\sigma$, which were used to determine the resolving power, $R$, and full-width-half-maximum, $\Delta\lambda$.

$$R = \frac{\lambda_c}{\Delta\lambda} \quad \Delta\lambda = 2\sqrt{2 \ln(2\sigma)}$$  \hspace{1cm} (4)

The measured (4) and theoretical (2) resolving powers are compared in Fig. 3. The tunable range of the photomixer depends on the center wavelengths of the individual lasers that are used. In these preliminary tests, the lasers allowed tuning over the range of (0.878 – 1.04 THz). New lasers that have been acquired will be able to produce radiation over the entire range of the grating, 285 – 500 $\mu$m (1.05 – 0.600 THz). Moreover, since the output from the photomixer is polarized, the method described above can be used to determine the grating efficiency as a function of input polarization.

Finally, preliminary measurements were obtained with the grating coupled to a polarizing FTS. The grating was used to post-disperse the signal from a room temperature polarizing FTS, described in a companion paper [2], with one port viewing a ~1200 K blackbody source and the other viewing a room temperature blackbody. The grating was stepped through angular positions in 0.12° (0.57 µm) increments around the atmospheric water absorption line at 32.954 cm$^{-1}$. The FTS was operated with a resolution of 0.0343 cm$^{-1}$. The measured spectrum is compared with a theoretical atmospheric model [10] for the conditions in the laboratory in Fig. 4. These measurements illustrate the capability of the post-dispersed FTS to reconstruct a broad spectral feature by stitching together individual grating profiles.

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**REFERENCES**