2022 47th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz) | 978-1-7281-9427-1/22/$31.00 ©2022 IEEE | DOI: 10.1109/IRMMW-THz50927.2022.9896015

Development of a cryogenic far-infrared post-dispersed polarising Fourier transform spectrometer

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***Abstract*—The sensitivity of state-of-the-art superconducting far-infrared (FIR) detectors is such that wideband spectroscopic observations will require techniques to reduce the spectral bandwidth of a detector to limit the photon noise from an astronomical source. The leading instrument concept features grating spectrometers to post-disperse the light that has been modulated by a polarising Fourier transform spectrometer (FTS) onto a detector array, thereby reducing the photon noise on each detector. While the principles of this method are understood, to date an integrated system has not been realized in the laboratory. We present the development of a fully cryogenic post-dispersed polarising FTS (PDPFTS). To assess the data processing challenges posed by this hybrid spectrometer realistic astronomical spectra are generated by combining line emission from a tunable THz photomixer source with continuum emission from a variable blackbody source.**

I. INTRODUCTION

The continued improvement in the sensitivity of superconducting far-infrared bolometers has required scientists to reconsider the design of cryogenically cooled spectrometers to fully exploit the potential of such detectors. While Fourier transform spectrometers (FTS) have an illustrious history in astronomical research, the sensitivity of modern detectors is such that the multiplex disadvantage of FTS is prohibitive unless the spectral bandpass can be restricted to a few tenths of one percent. The most widely considered method is to use a reflection diffraction grating as the post dispersing component [1]. Unlike a typical FTS, in which a single detector simultaneously measures a broad spectral band, a post-dispersed detection system requires multiple detectors, each with their own unique spectral, spatial and temporal responses. Moreover, the narrow spectral band viewed by each detector results in an interferogram having a large coherence length; the signal is heavily modulated, yet truncated. While simulations play a useful role in modeling instrumental performance, there is no substitute for data obtained from a real implementation of an instrument concept. In this paper we describe the current status of the development of a cryogenic, far-infrared post-dispersed, polarising FTS (PDPFTS). The end-to-end performance of the PDPFTS is evaluated in a large cryogenic test facility to simulate a space environment. The results provide valuable insight into the spectral calibration and data processing challenges that will be faced by hybrid spectrometers employing a post-dispersed component.

II. PDPFTS CONCEPT

The prototype PDPFTS is designed to cover a wavelength range from 285 to 500 µm (20 to 35 cm^{-1}) chosen to match existing test hardware including tunable THz photomixer line sources and variable blackbody sources. The cryogenic grating spectrometer [2], is mounted in a test-facility cryostat (TFC) [3], which is coupled to an evacuated room temperature polarising FTS, the Calibration FTS (cFTS) [4]. A blackbody and a tunable photomixer line source are coupled to the two mutually orthogonal input ports of the cFTS. In this scheme, by varying the temperature of the blackbody and frequency of the line source it is possible to simulate astronomical spectra consisting of unresolved emission or absorption lines superimposed on a continuum. A basic schematic of the fully cryogenic PDPFTS configuration is shown in Fig 1.

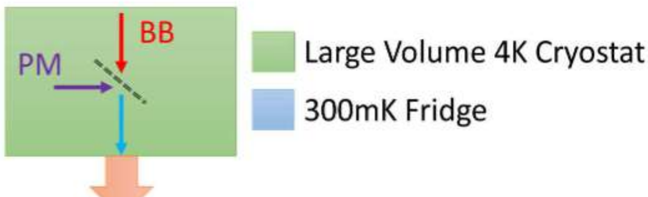

Fig 1. An overview of the PDPFTS configuration. The system is characterized by four modules: the source, a polarising FTS, a reflection diffraction grating and a bolometric detector. The source module consists of a cryogenic photomixer (PM) and blackbody (BB). The source, FTS and diffraction grating all operate within a large volume cryostat at 4K. The composite bolometer detector [5] operates within a ^4He:^3He:^3He closed cycle refrigerator at 0.3K.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The current state of the PDPFTS incorporates a source module and polarising FTS which operate at room-temperature. The diffraction grating spectrometer operates at 4K in the TFC and the sensitive bolometer detector operates at 0.3K [5]. Continuum emission was produced by a silicon carbide (SiC) gas igniter which was placed at the input of the cFTS and

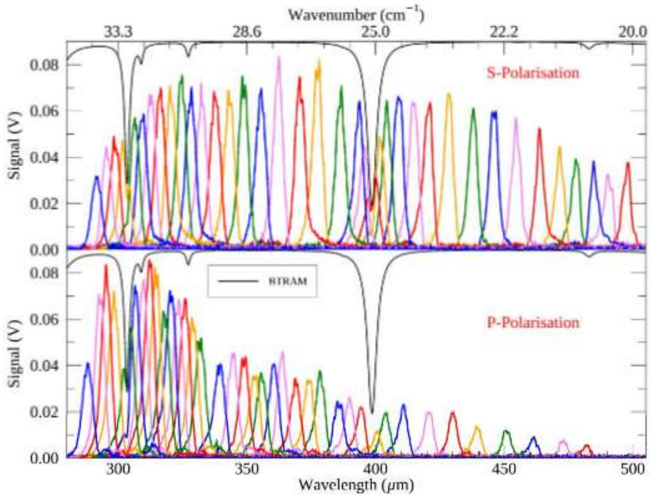

Fig 2. Measurements of the PDPFTS with a blackbody source placed at the input of a room-temperature polarising FTS. Each coloured figure represents a diffraction grating spectral response function obtained by scanning the polarising FTS at each angular position of the grating. The output polarisation of the FTS was orientated parallel to the grating grooves (P-polarisation) in the bottom figure and perpendicular to the grooves (S-polarisation) in the top figure. The black curve is the transmission of a ~1500 K blackbody through 2 m of atmosphere at 5% relative humidity [4].

operated at a temperature of ~1500K. Spectral measurements of the SiC source were taken by incrementally rotating the grating and obtaining interferograms at each grating angle with the cFTS. Fig 2 shows the power spectra of the grating spectral response at each angular (wavelength) position. An atmospheric model was generated using BTRAM v3 [4] and is added to the figure to show the location of atmospheric absorption features.

The diffraction efficiency of a blazed grating depends strongly on the polarisation state of the incident light [6]. By utilizing a polarising FTS, the PDPFTS can exploit the high efficiency achieved over the broad spectral band when operating in the S-polarised orientation as shown in Fig. 2.

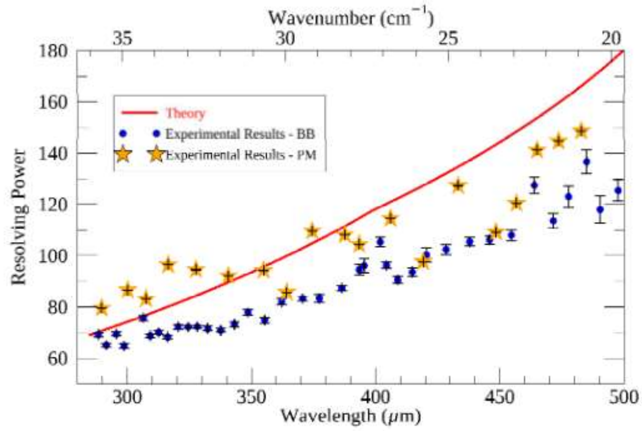

Fig 3. Experimental resolving power (blue points) calculated from grating spectral response profiles with the blackbody source compared with measurements with the photomixer source (yellow stars). Both experimental data were collected with the output polarisation of the FTS configured parallel to the grating grooves (S-polarised). The error bars are calculated from errors in the Gaussian fits to the measured data. The theoretical slit limited resolving power (red) is shown for comparison.

Each grating spectral response curve was fitted with a Gaussian function:

$$f(\lambda) = A_o e^{\frac{-(\lambda-\lambda_c)^2}{2\sigma^2}} + A_1 \qquad (1)$$

to determine the center wavelength, λ_c, and the standard deviation, σ, from which the full-width-half maximum, $\Delta\lambda$, was used to determine the resolving power, R, where:

$$R = \frac{\lambda_c}{\Delta\lambda}, \qquad \Delta\lambda = 2\sqrt{2\, ln(2\sigma)} \qquad (2)$$

The results are shown in Fig. 3.

An alternate method of measuring the resolving power used a tunable monochromatic source. A photomixer was illuminated by two continuous-wave lasers operating in the 1550 nm band such that their difference frequency occurred in the terahertz region. The frequencies of the individual lasers were adjusted by varying their current and temperature to enable tunable radiation across the terahertz band. For a given setting of the photomixer frequency, the grating was scanned in 0.06° increments (~0.285 µm) around the corresponding photomixer wavelength, to determine the spectral response function of the grating as a function of angle/wavelength. At each grating angle, the FTS was scanned to produce a high-resolution spectrum which was fitted with equation 1 to determine the experimental resolving power as a function of wavelength.

The resolving power calculated from these independent techniques: the continuum source (blue points) and with the photomixer (yellow stars) are compared in Fig. 3. The theoretical curve (red) is the resolving power limited by the exit and entrance slit widths [6].

IV. Summary and Future Work

Experimental spectra obtained with the PDPFTS using a room temperature source module and FTS and have been presented. The spectral response function of the grating shows good agreement with theory. The sensitivity of the grating to the polarisation of incident light was explored using the polarising FTS, the results agree well with theory [2].

Future work will incorporate a cryogenic source module and cryogenic FTS module (FTSM) [7] which will be operated in a large facility cryostat. A cryogenic photomixer module and tunable 780 nm lasers have already been procured along with a cryogenic blackbody source which will allow the complete validation of the grating spectrometer at cryogenic temperatures. The culmination of this project will be achieved upon the successful integration of the FTSM to realize a fully cryogenic PDPFTS.

Acknowledgements

The authors acknowledge support from ARIF, CFI, CMC, CSA, and NSERC.

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