Development of a Millimeter Wave Grating Spectrometer for TIME-Pilot

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***Abstract*—Instantaneous wideband spectral coverage with background-limited sensitivity requires a grating-type spectrometer or filter bank as opposed to a Fourier transform spectroscopy (FTS) or Fabry–Perot. Previously, millimeter wave gratings presented a technological challenge, because conventional echelle grating spectrometers are too large and bulky for cryogenic operation. A unique approach is to use a curved grating in a parallel-plate waveguide to focus and diffract broadband light from a feedhorn to a detector array. This approach markedly reduces the total volume of the spectrometer. The Tomographic Ionized-carbon Mapping Experiment (TIME)-Pilot measures 3-D [CII] fluctuations from $5 < z < 9$ galaxies by using 32 independent spectrometers. We designed, prototyped, and tested a waveguide grating for TIME-Pilot. Each grating has 190 facets and provides a resolving power in excess of 140 over the full 183–326 GHz range.**

I. INTRODUCTION

The Tomographic Ionized-carbon Mapping Experiment (TIME)-Pilot [1] was designed to measure the red-shifted 157.7-µm line of singly ionized carbon [CII] from the Epoch of Reionization (EoR), when the first stars and galaxies formed and ionized the intergalactic medium. For 3-D intensity mapping, TIME-Pilot uses an imaging spectrometer to measure a spatial–spectral data cube, in which the intensity is mapped as a function of the sky position and frequency. The data cube is then analyzed to produce a 3-D power spectrum. Spectral measurements incorporate redshift information that is needed to distinguish faint EoR signals from bright low-red-shift galaxies along the line of sight. [CII] is an energetic emission line in galaxies and a bolometric marker for total star formation activity. [CII] is also well matched to the 1-mm atmospheric windows for z between 5 and 9. As shown in Fig. 1, the instrument is housed in a closed-cycle 4K–1K–300mK cryostat. Thirty-two waveguide grating spectrometers are assembled into two stacks of 16, coupling the same 1-D linear field on the sky through an array of feedhorns illuminated through a polarizing grid. Each grating is similar to that used in Z-Spec [2], but smaller to operate at a lower resolving power. The dispersed light is detected with 2-D arrays of transition edge sensor (TES) bolometers. The spectrometers and detectors are cooled with a dual-stage 250/300-mK refrigerator.

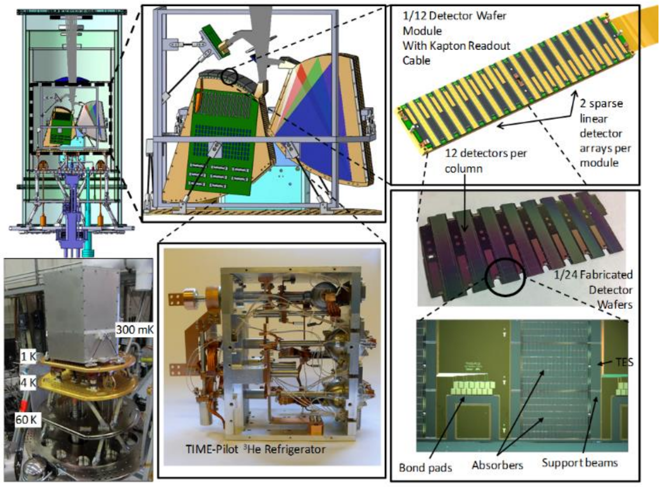


Fig. 1. TIME-Pilot instrument overview.

II. WAVEGUIDE SPECTROMETER DESIGN

The TIME-Pilot spectrometer uses a Waveguide Far-IR Spectrometer (WaFIRS) [3] architecture that employs a curved diffraction grating in a parallel-plate waveguide. Facets on the grating arc both diffract and focus the radiation to locations on a focal curve. Light propagates in the TE_1 mode of parallel-plate waveguide with two degrees of freedom. The grating design begins with a Rowland geometry, as shown in Fig. 2, and then each facet of the grating is positioned such that the total path from the center of the input feed to the facet to the output position changes by exactly one wavelength as the number of facets is incremented at two stigmatic frequencies. Propagation is confined between parallel plates to achieve efficient coupling to the detectors.

For TIME-Pilot, the initial Rowland circle radius is 13.3 cm, and the input position and stigmatic frequency output positions are selected on this circle. The distribution of facets is not centered relative to Rowland's vertex; 35 more lie on the side opposite the input position, because centering the grating does not provide adequate illumination for the upper facets. The blaze angles for the facets vary along the grating arc to accommodate the fact that the input and output angles are varying. They are ranging between 22° and 26°, according to simulations of S polarization blaze efficiencies with the software toolkit PCGrate. The parallel-plate spacing is a compromise between minimizing waveguide propagation loss and avoiding scattering into unwanted waveguide modes. We selected 3 mm for our 183–326-GHz system, which is over-moded by a factor of 4–6. The preliminary grating spectrometer design has 190 facets, with the longest dimension of 31 cm, and provides a resolving power of 140–250. The output arc is approximated by six linear facets so that when the spectrometers are stacked in the two groups of 16, each stack creates six planes, on which the 2-D detector arrays are mounted.

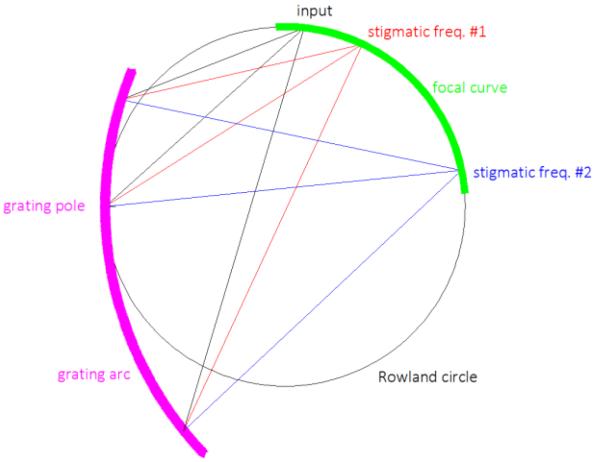


Fig. 2. Rowland geometry.

III. COUPLING STRUCTURES

The waveguide gratings couple to the incoming radiation through multiple flare-angle (MFA) feedhorns. The MFA feeds are spaced 2.2 f λ apart to balance the desire to couple to the sky with the optimal efficiency per beam, and to pack a large number of horns into the fixed field of view. Light from the feedhorn couples into the grating through a bent split-block waveguide section. The waveguide gratings are single polarization devices, and a polarizing diplexer placed in front of the focal plane feeds two 16-element grating stacks. The waveguide in one stack includes a 90° twist to align the polarization vector of the grating with that of the polarizing grid.

The MFA feeds are smooth-walled, easy-to-machine horns that perform comparably to traditional corrugated feed horns [4]. For TIME-Pilot, we designed a three-section horn that was optimized by varying the positions and magnitudes of these flare angle discontinuities to match the beam widths to an f/3 beam and suppress the sidelobes across the desired band. The simulations were performed with HFSS, a commercial 3-D electromagnetic (EM) simulator, as shown in Fig. 3. The initial geometry of the optimized horn is given in Table I. The initial waveguide radius R_0 was fixed to 0.56 mm, and the aperture radius R_3 was kept less than 3.9 mm to fit the 8-mm separation between horns. The six parameters of the horn design became variables to be determined. Fig. 4 shows the expected far-field beam patterns for the horn design. Because of the very wide bandwidth, the patterns exhibit better beam circularity and low sidelobes at higher frequencies. The cross polarization remains 30 dB lower across the whole band of interest.

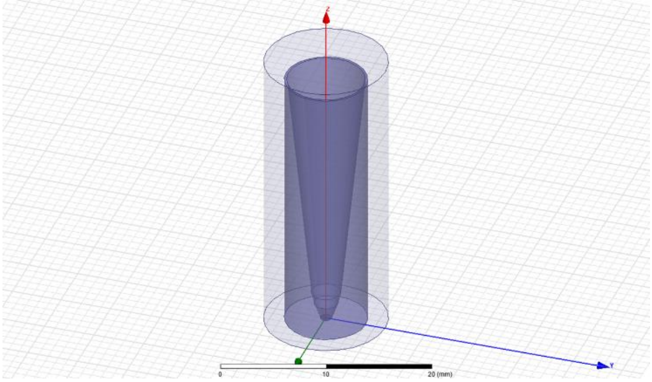


Fig. 3. HFSS model of the three-section MFA horn.

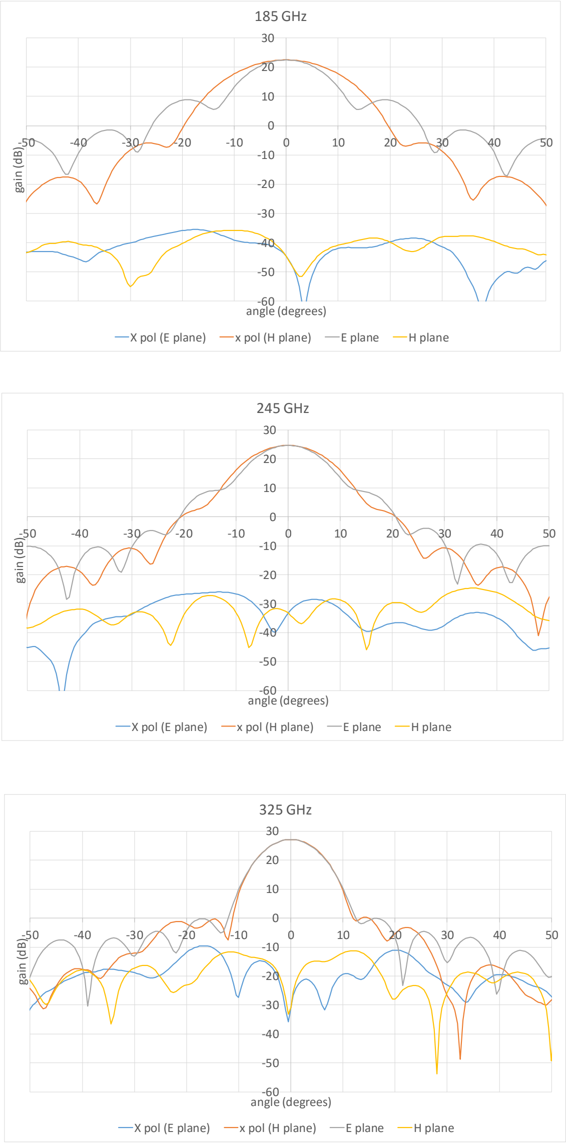


Fig. 4. Beam patterns (E-plane, H-plane, and cross-polarizations) simulated using HFSS at 185, 245, and 325 GHz, respectively.

The MFA feed tapers to a single-mode rectangular waveguide. The rectangular waveguide tapers gradually in height and width and then connects to the spectrometer input horn. Light enters the parallel-plate waveguide through the input horn and illuminates the diffraction grating. Because some portions of the waveguide are over-moded, special care was taken to minimize excitations of the higher order modes. A single-mode section of the waveguide ensures that only one mode propagates, and the higher order modes are cut off within the design bandwidth.

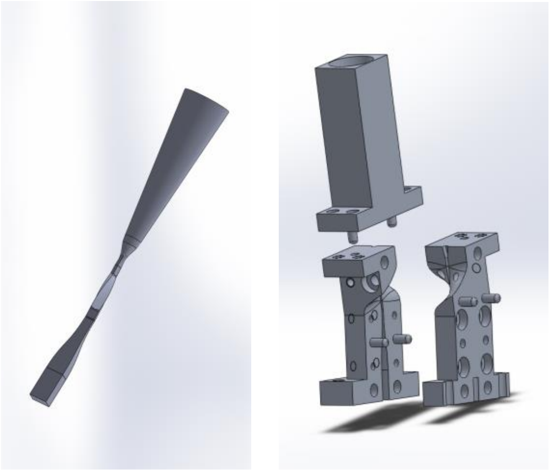


Fig. 5. [Left] 3-D EM simulation model of the MFA feed and waveguide twist, bend, and taper. [Right] Split block design.

TABLE I
GEOMETRICAL PARAMETERS FOR THE THREE-SECTION MFA FEED DESIGN

Parameter	Length (mm)
R_0	0.56
R_1	1.173
R_2	1.511
R_3	3.824
L_1	1.750
L_2	1.236
L_3	25.566

IV. SPECTROMETER TESTING

The prototype spectrometer has two gratings in a ministack and is a simple machined, bolted aluminum assembly, as shown in Fig. 6. The spectrometer requires global tolerances of λ/10 (approximately 100 µm) and low surface roughness on the waveguide plates. The 190 facets on each grating were cut using a wire electrical discharge machine. Operation of the spectrometer requires that the correct spacing be maintained across the entire region to ensure that the same dispersion relation holds throughout.

Preliminary testing of the spectrometer was performed at room temperature. The spectral profile was measured using a sweep-able coherent source and a diode detector in a single-mode waveguide. Several spectra are shown in Fig. 7. The measured profiles represent the convolution of the intrinsic resolving power of the spectrometer with the width of the detector waveguide feed. The spectra show approximately 25%–45% transmission, depending on the width of the output feeds. After deconvolution from the output waveguide width, the measured resolving power is comparable to that is predicted. The warm measurements are affected by some standing waves or multiple reflections because the detector and the source are not well matched. Based on the known sources of loss listed in Table II, the spectra show that the efficiency measurements match expectations within 10%.

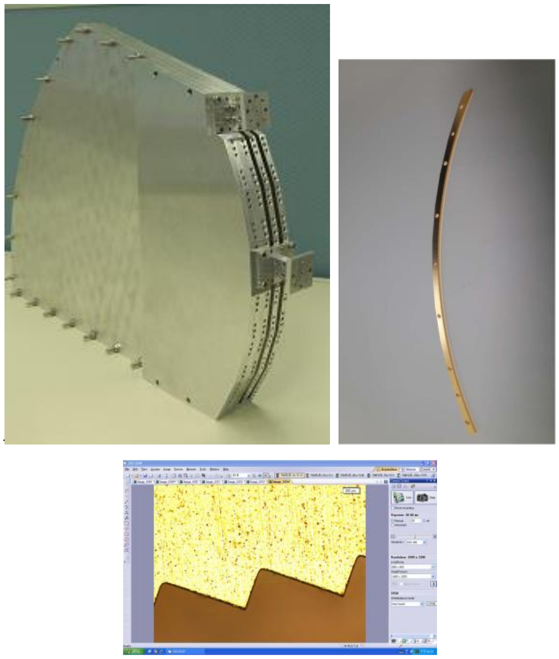
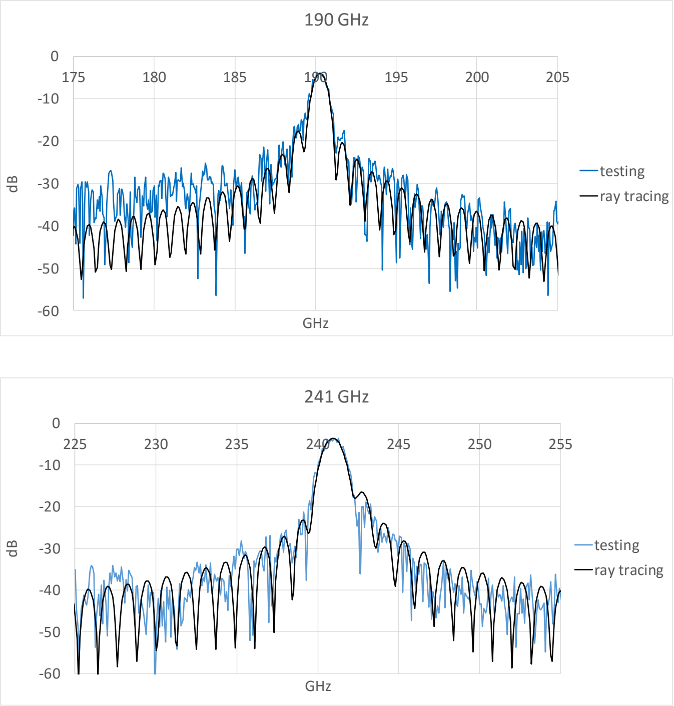


Fig. 6. Two-channel grating spectrometer stack with input and output feeds connected. The 190 facets on the grating were wire-cut. A close-up view of the grating facets is also shown.



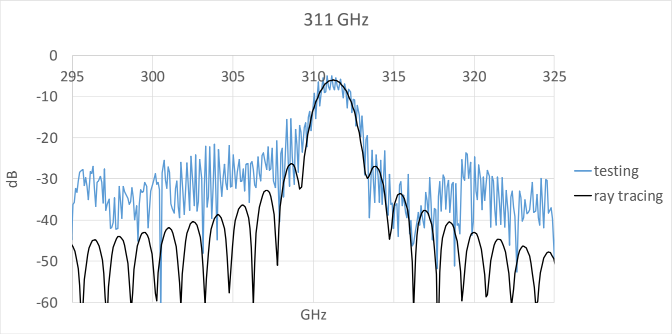


Fig. 7. Spectrometer room temperature test results and responses calculated through ray tracing around 190 GHz, 241 GHz, and 311 GHz, respectively.

TABLE II
SPECTROMETER EFFICIENCY ESTIMATES

Frequency (GHz)	**190.3**	**241**	**311.3**
Grating illumination	0.76	0.85	0.89
Blaze efficiency	0.92	0.97	0.88
WG propagation loss	0.97	0.98	0.99
Output coupling	0.55	0.57	0.33
Product	**0.37**	**0.46**	**0.26**
Measure	0.40	0.45	0.25
Measure/expected	1.08	0.98	0.96

V. CONCLUSION

We present the design and testing of a millimeter-wave grating spectrometer based on the waveguide grating spectrometer architecture WaFIRS for TIME-Pilot. Room temperature testing shows that the efficiency measurements match expectations within 10% with a resolving power above 140. Integration and testing with TES bolometers will follow to verify the performance at cryogenic temperatures.

ACKNOWLEDGMENT

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