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TIME Millimeter Wave Grating Spectrometer

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ABSTRACT

The Tomographic Ionized-carbon Mapping Experiment (TIME) utilizes grating spectrometers to achieve instantaneous wideband coverage with background-limited sensitivity. A unique approach is employed in which curved gratings are used in parallel plate waveguides to focus and diffract broadband light from feed horns toward detector arrays. TIME will measure singly ionized carbon fluctuations from $5 < z < 9$ with an imaging spectrometer. 32 independent spectrometers are assembled into two stacks of 16, one per polarization. Each grating has 210 facets and provides a resolving power *R* of ~ 200 over the 186–324 GHz frequency range. The dispersed light is detected using 2-D arrays of transition edge sensor bolometers. The instrument is housed in a closed-cycle 4K–1K–300mK cryostat. The spectrometers and detectors are cooled using a dual-stage 250/300 mK refrigerator.

Keywords: millimeter wave, spectroscopy, diffraction grating, reionization, intensity mapping

I. INTRODUCTION

TIME [1] is aimed to build a millimeter-wave imaging spectrometer for detecting 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 intergalactic media. Detecting the primordial galaxies responsible for reionization individually is difficult as they are intrinsically low-mass, low-luminosity objects. Intensity mapping measures the total bolometric light production integrated over all galaxy populations, including those faint ones. 3-D intensity mapping of spectral lines can provide red shift information. TIME will measure a spatial–spectral data cube, where 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. [CII] is an energetic emission line in galaxies and a bolometric marker for total star forming activity. [CII] emission from the EoR is red shifted into the 1 mm atmospheric window.

II. WAVEGUIDE GRATING SPECTROMETER

To realize a multi-beam millimeter-wave spectrometer, TIME employs the Waveguide Far-IR Spectrometer (WaFIRS) [2] architecture, which uses curved diffraction gratings inside parallel plate waveguides. This architecture is more compact than those conventional free-space grating spectrometers, and no mirrors or lenses are used in the instrument. The design is similar to Z-Spec [3], but with a smaller resolving power. The curved grating not only disperses but also focuses the incoming signal to various locations on the focal curve, as displayed in Fig. 1. Transition edge sensor (TES) [4] detectors are mounted along the output curve to measure the intensity of each frequency bin. Signals coupled to each spectrometer are confined and propagate within the parallel plate region in the TE_1 mode, with two degrees of freedom. The distance between the parallel plates is 3 mm. The waveguide is over moded with a factor of 4–6 to minimize propagation loss.

TIME employs 32 spectrometers and assembles them into two stacks, one per polarization. For each stack, 16 spectrometers are packed to form a 1-D spectrometer array, coupling a linear field on the sky through an array of feed horns. Signals of different polarizations were separated using a polarizing grid located in front of the input feeds, as illustrated in Fig. 2.

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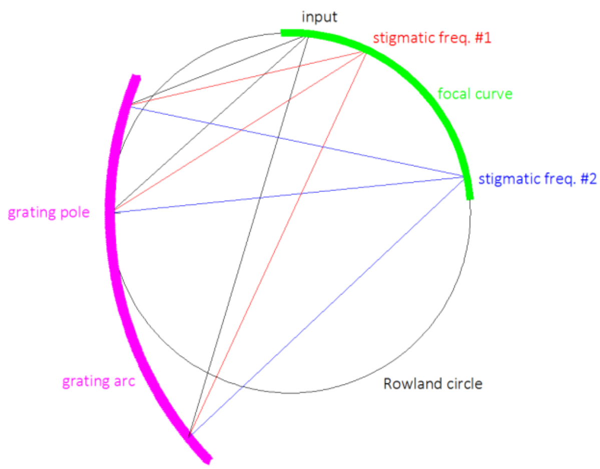


Fig. 1. WaFIRS geometry. Facets on the grating arc diffract and focus radiation onto the focal curve. Signals are confined to propagate between parallel plates for easy and efficient coupling to detectors.

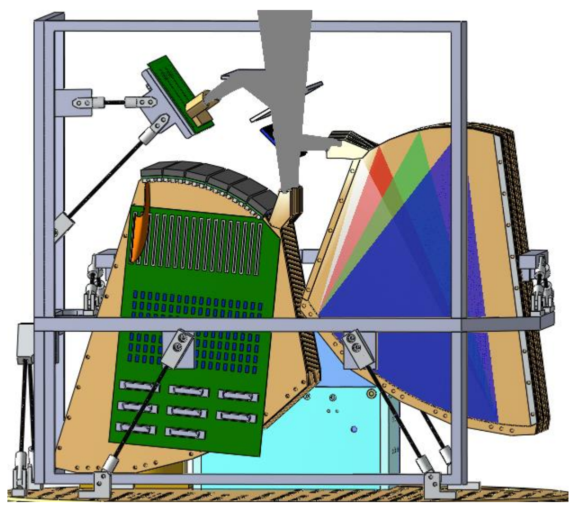


Fig. 2. Multi-beam, dual polarization spectrometer for TIME. TIME employs 32 waveguide grating spectrometers that are assembled into two stacks, one per polarization. A polarizing grid is placed in front of the spectrometer array to separate two polarizations.

A. Design and fabrication

The grating has 210 facets, providing a resolving power of ~ 200. Each facet is situated along the grating arc such that the grating has aberration free performance at two frequencies near either edge of the band; that is, the total path from the center of the input feed to each facet and then to the output position differs by one wavelength for subsequent facets at the two stigmatic frequencies. The Rowland circle has a radius of 13.3 cm, and the input position and stigmatic frequency output positions are selected on this circle. The focal curve on the Rowland circle is approximated by six facets. After 16 spectrometers are stacked, six focal planes are formed on which the 2-D TES arrays are mounted. The spectrometer assembly and grating are shown in Fig. 3. Each spectrometer has 60 TES detectors corresponding to R ~ 100. There are 1920 TES detectors in total in the 32 spectrometers.

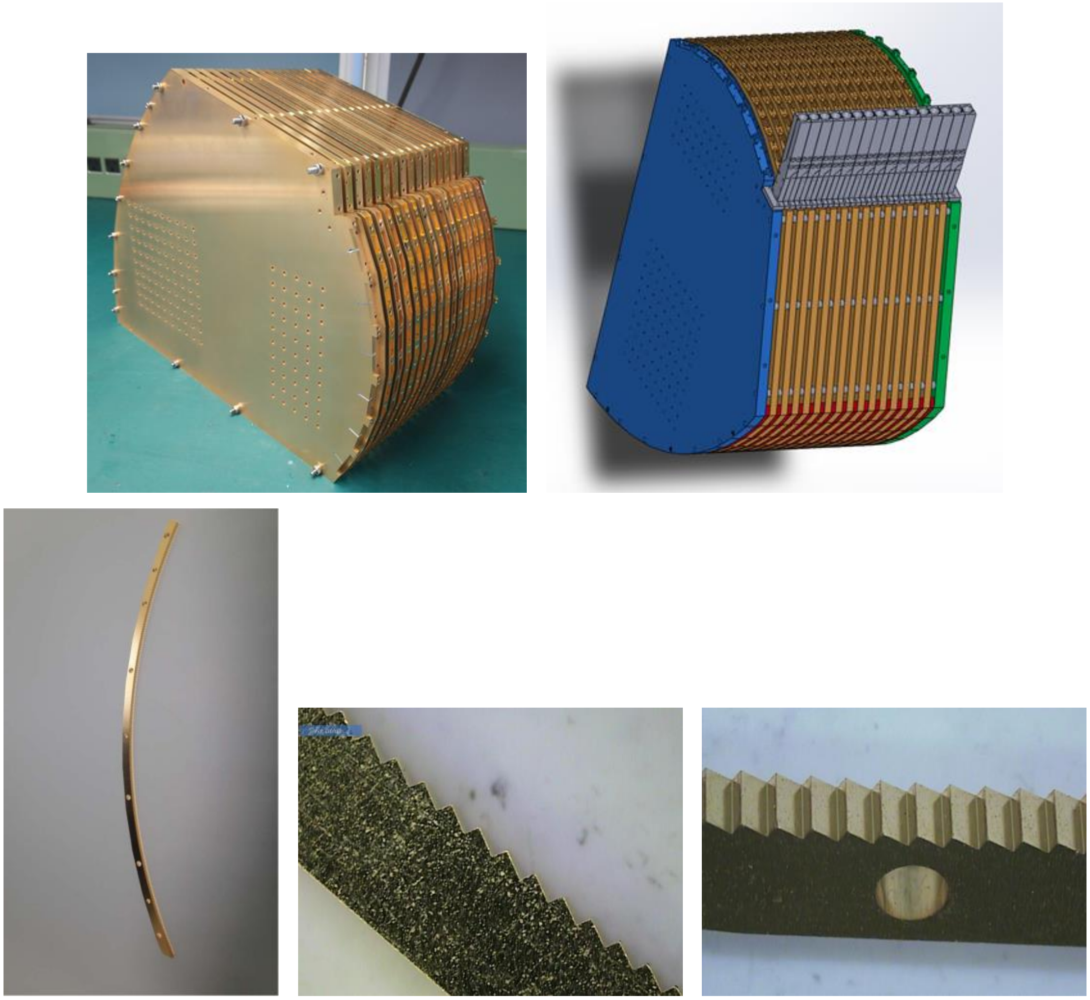
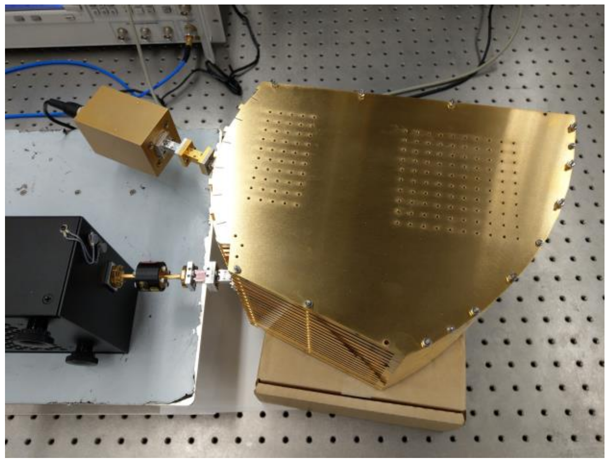


Fig. 3. [Top] TIME spectrometer assembly. The longest dimension in the structure is 32 cm. The mechanical model of the spectrometer and feed assembly is shown on the right. [Bottom] Views of the grating. Zoomed views of the grating are shown on the right.

The parallel plates and gratings utilized in the spectrometer were machined of aluminum. All parts were coated with a 3-μm copper layer and a flash of gold after machining. Copper, rather than nickel, was plated between the gold and aluminum because nickel is ferromagnetic and the SQUID readout is susceptible to magnetic fields. Machining tolerance was specified to be within 10 μm. From analysis, grating performances start degrading when facet position errors are larger than 20 μm. For parallel plate waveguides, spacing must be maintained across the entire region to hold the same dispersion relation. The tolerance is of the order of 80 μm, corresponding to a change in wavelength less than 1 part in 500. To minimize conductivity loss, the surface roughness of waveguides was specified to be Ra 0.2, which corresponded to approximately one skin depth of aluminum at room temperature in our frequency range. Ra 0.2 enhances the attenuation by a factor of about 1.7 [5]. To avoid deformation once cooled, each part was thermal stress relieved prior to and after machining.

B. Warm testing

The spectrometers were tested at room temperature with a sweep-able millimeter-wave source and a power meter. Signals were coupled to the parallel plate waveguide through an input waveguide. The input waveguide tapers from a WR 4.3 or WR 3.4 waveguide to a single model rectangular waveguide to illuminate the grating with a Fraunhofer diffraction pattern, from which the illumination efficiency can be estimated. The incoming signal propagates within the parallel plate waveguide until diffracted by the grating. Various frequency components are focused at different locations on the focal curve, received with another rectangular waveguide, and coupled to a power meter for detection. Frequency responses of the spectrometer were measured when the output waveguide was mounted at different locations on the focal curve, as presented in Fig. 4. The ray tracing response and Gaussian fit are also plotted in the figure.



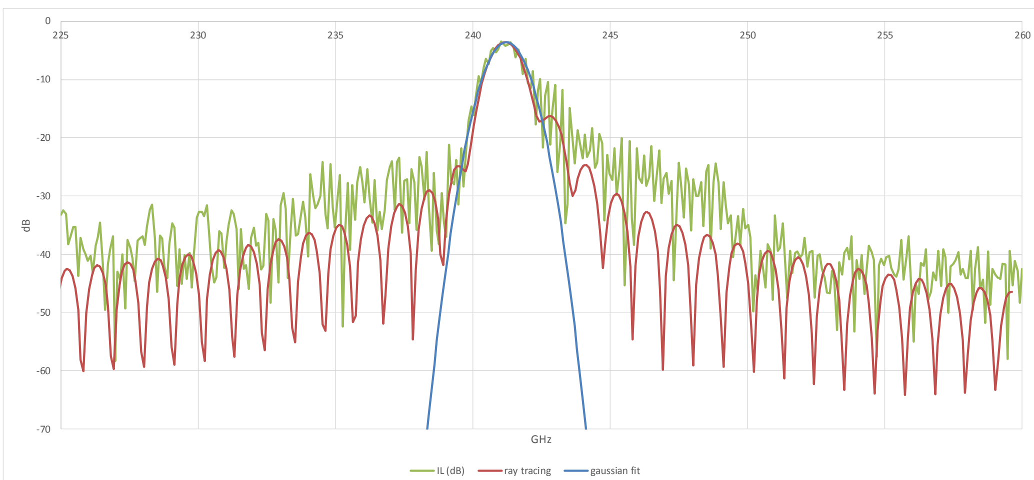


Fig. 4. [Top] A spectrometer assembly was tested using a sweep-able coherent source and a power meter with the input and output waveguides. [Bottom] The test results (green), ray tracing response (red), and Gaussian fit (blue) around 240 GHz.

The warm single-mode measurements suffer from standing waves and multi-reflections. Mis-matching along the signal path caused standing waves that can be seen as oscillations from the spectral response. Some high sidelobes were due to multi-reflections within the parallel plate waveguide. The measured FWHM was slightly wider than that calculated using ray tracing because the beam was convolved with the finite width of the output waveguide. The spectra show approximately 40% transmission, depending on the width of the output waveguide. Based on few known sources of loss, the measurements were within ±15% of the expected values, as listed in Table I. The S polarization blaze efficiencies were simulated using a software toolkit (PCGrate). The coupling between the diffracted beam and the output waveguide was derived from the coupling between a 1D Gaussian beam and the TE_{10} waveguide mode. The propagation loss within the parallel plate waveguide was estimated by considering the surface resistance and roughness. The losses of the input and output waveguides were measured directly.

TABLE I

SPECTROMETER TRANSMISSION ESTIMATES AND RESOLVING POWER

Frequency (GHz)	**203**	**241**	**303**
Grating illumination	0.84	0.88	0.90
Blaze efficiency	0.93	0.99	0.86
Parallel plate waveguide propagation loss	0.97	0.98	0.98
Input/output waveguide loss	0.86	0.85	0.83
Output coupling	0.58	0.62	0.72
Product	**0.38**	**0.45**	**0.45**
Measure	0.33	0.44	0.49
Measure/expected	**0.87**	**0.98**	**1.08**
Measured *R*	244	196	175
De-convolved *R*	**258**	**209**	**193**

III. COUPLING STRUCTURES

TIME spectrometers use feed horns to couple signals from the telescope to spectrometers. These input feeds are stacked to form a 1-D array with a 2.2 $f\lambda$ spacing for *f/3* optics. We utilized the multi-flare-angle (MFA) feed design [6] because it can be directly machined and thus suitable for use in large format arrays. The MFA feeds were designed with 3 sections. By varying the length and flare angle of each section, the design was optimized to match the beam width to an *f/3* beam while suppressing sidelobes across the frequency band of interest. The simulations were carried out using a commercial 3-D EM simulator (HFSS). Parameters of the prototype design are listed in Table II, and the simulated far-field radiation patterns are presented in Fig. 5. The prototype feed was fabricated and tested with a coherent source and a power meter mounted on a rotary stage. Far-field radiation patterns were measured and plotted along with simulations (Fig. 6).

Waveguide gratings are single polarization devices. The incident signals are S polarized for the TIME spectrometers. Therefore, feeds for one spectrometer stack include 90° twists to rotate the E field after the polarizing grid, as displayed in Fig. 7. Waveguide twists were fabricated, and the transmission and reflection were measured (Fig. 8). Because the parallel plate waveguides were over-moded, a section of waveguide choke was included in the revised feed design to cut off low frequency signals, as displayed in Fig. 9. Following the MFA section, the waveguide twist, and choke, the feed tapers to a rectangular waveguide to illuminate the grating. To machine these coupling components, the split block design was employed.

TABLE II

GEOMETRICAL PARAMETERS FOR THE THREE-SECTION MFA FEED PROTOTYPE

Parameter	**Length (mm)**
R_0	0.56
R_1	1.16
R_2	1.33
R_3	3.8
L_1	1.71
L_2	1.18
L_3	24

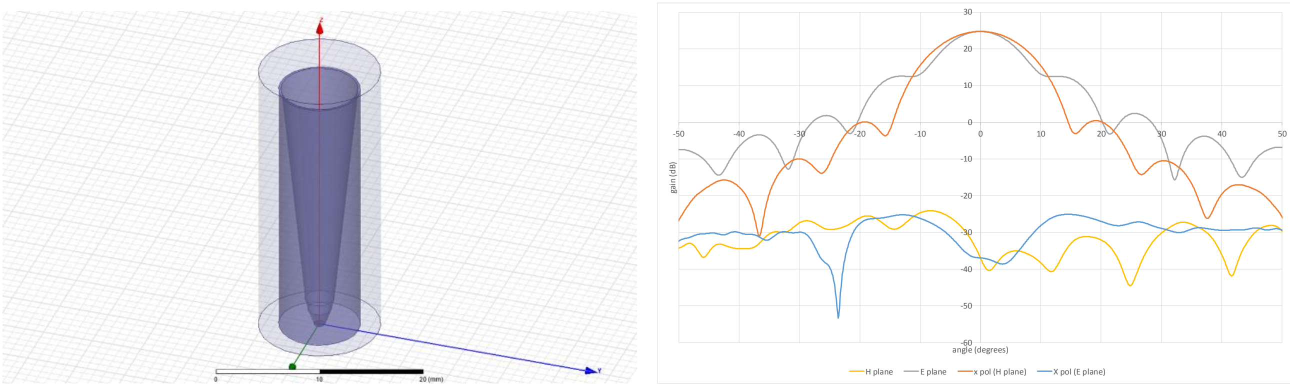


Fig. 5. [Left] EM model of the three-section MFA feed. [Right] Radiation patterns (H plane, E plane, and cross polarizations) of the prototype MFA feed design simulated using HFSS at 245 GHz.

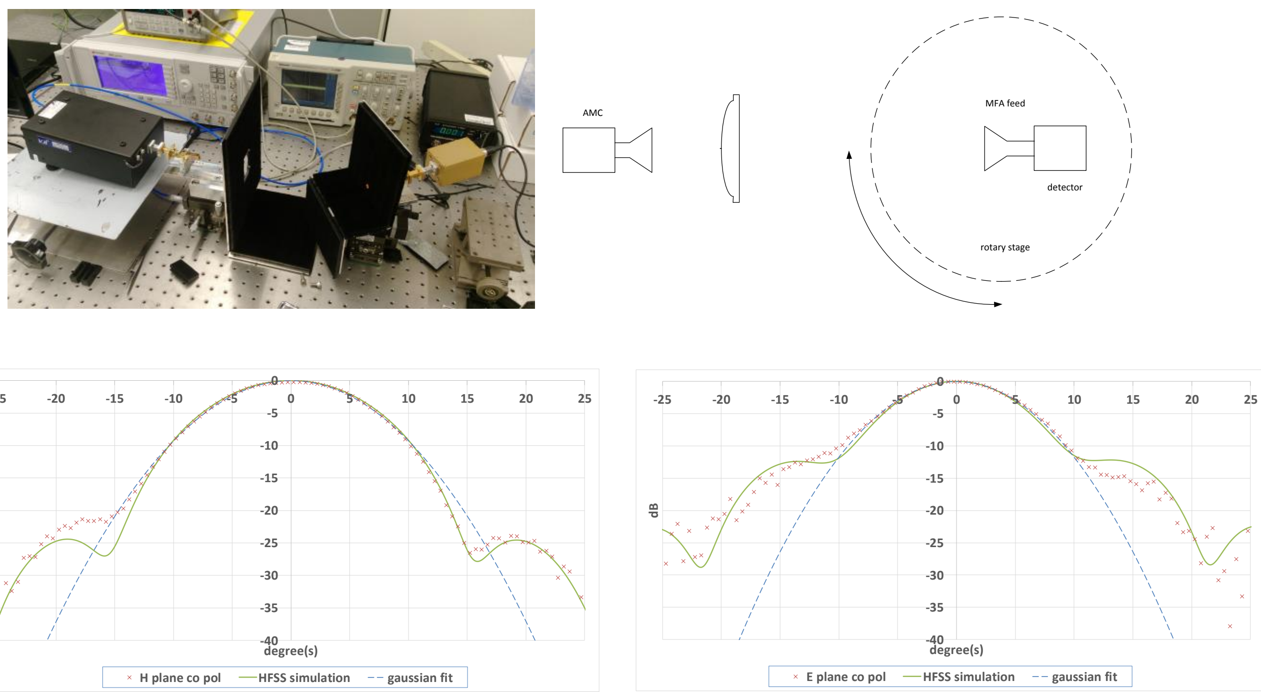


Fig. 6. Radiation patterns of the MFA feed horn were measured using a coherent source and a power meter mounted on a rotary stage. The co-polarization measurements on the H and E planes at 245 GHz, along with simulation results and Gaussian fits are plotted.

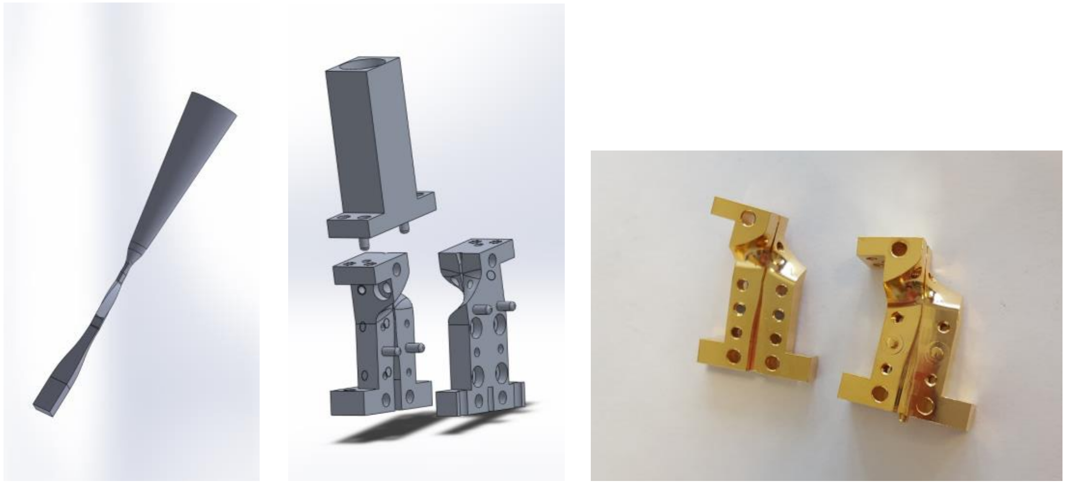


Fig. 7. [Left] Prototype coupling component with a twist. The MFA feed horn for coupling to the telescope, followed by the waveguide twist, taper, and the input feed that illuminates the grating. [Center] Split block design for fabrication. [Right] Waveguide twist split block.

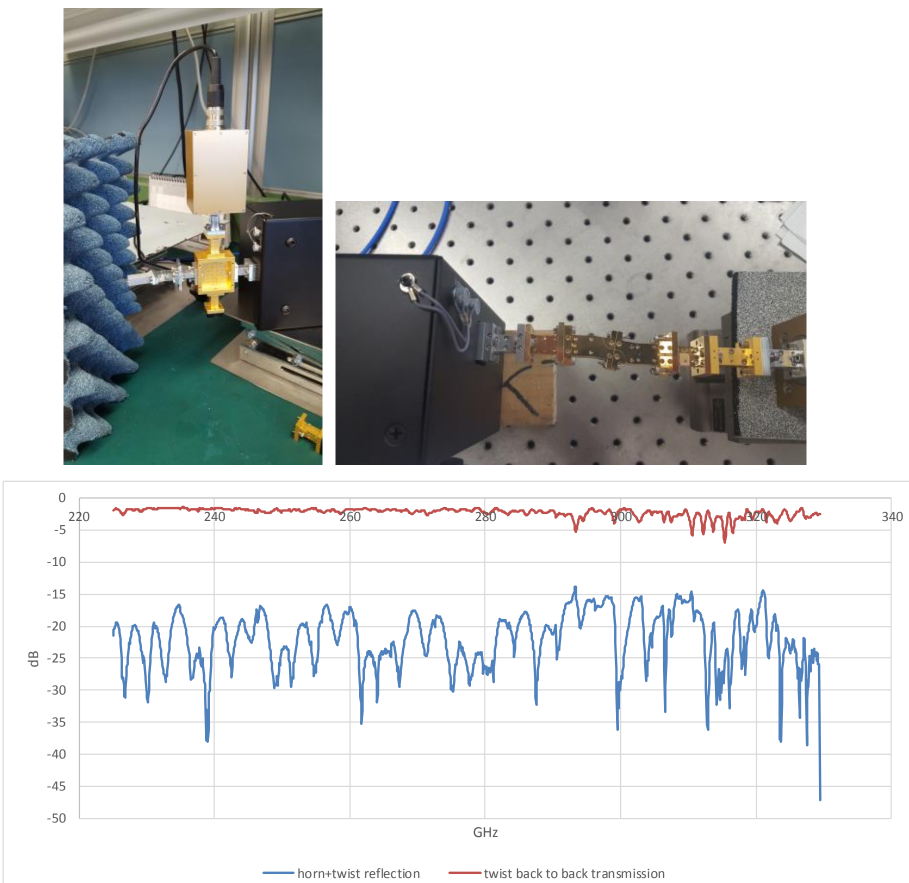


Fig. 8. Reflection and transmission measurements of the waveguide twist.

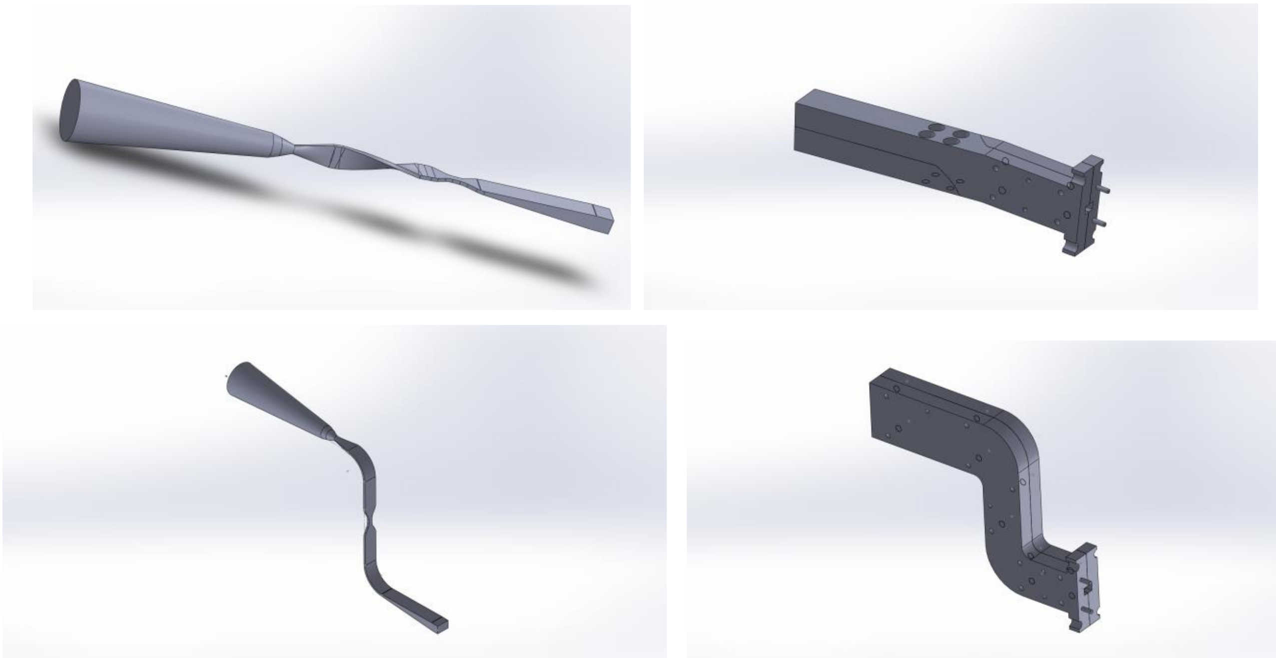


Fig. 9. [Top] Revised design of the coupling component with a twist. The MFA feed horn followed by the waveguide twist, choke, taper and input feed. The split block design is shown on the right. [Bottom] Design of the coupling component without a twist. The MFA feed horn followed by the waveguide bend, choke, taper, and input feed.

IV. CONCLUSION

We designed and fabricated the grating spectrometer array and input feed horns for TIME. The throughput measurements at room temperature are within ±15% of the expected values, and the resolving power varies between 150 and 250 across the band of 186–324 GHz. The spectrometers will soon be integrated with the TES detectors, and cryogenic testing will be conducted.

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