Micro-Machined Integrated Waveguide Transformers in THz Pickett-Potter Feedhorn Blocks

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Abstract— We present laboratory measurements of a circular-to-rectangular waveguide transformer integrated into a 1.9 THz Pickett-Potter feedhorn detector block. This design is applicable for instruments where circularly symmetric feedhorns are required to mate with rectangular waveguide fed receiver devices. Compared to previous transformer segments machined into separate blocks or machined into split-block segments, we ensure axial alignment along the waveguide segments at the cost of rounding the edges of the rectangular waveguide. This architecture was fabricated by direct metal micro-machining, which offers significant advantages over competing techniques in complexity, timescale, and cost of manufacturing. All machining passes during manufacture can be made from the front of the block including the final **waveguide** segment. We compared **simulations of the waveguide circuit performance using multiple electromagnetic software packages to finalize the dimensions of the optimized transformer module. A single pixel feedhorn-transformer module was manufactured on a 3-axis CNC milling machine. We tested integrated feedhorn-transformer modules using waveguide-fed hot electron bolometer mixers designed and fabricated at the Jet Propulsion Laboratory using a liquid helium-cooled cryostat. Beam patterns of the Pickett-Potter modules were measured using a high-power 1.9 THz multiplication chain as the source. We find good agreement between the simulated and laboratory beam pattern.**

INTRODUCTION

Recent work in terahertz (THz) heterodyne instruments for astronomical research have utilized rectangular waveguide-fed receiver devices [1], [2], [3]. For single-polarization receivers, it is generally desirable to use a feedhorn type that maximizes coupling to the detector and minimizes cross-polarization. Several feedhorn profiles offer ease in fabrication and have low cross-polarization [4], [5] [6], but have circular exit waveguides requiring a waveguide transformer to integrate them with existing rectangular waveguide-fed devices.

Circular-to-rectangular (CTR) waveguide transformers (WGT) have been demonstrated in a laboratory setting using direct-metal micromachining techniques [5] [6]. In both cases, the transformer segment was machined into separate pieces of the receiver modules. These transformer segments become increasingly difficult to manufacture at short wavelengths (high frequencies). With multiple receiver segments, the mated system is more susceptible to misalignment between the transformer, the detector housing, and feedhorn blocks. One solution is to integrate the transformer into the feedhorn block using a split-horn fabrication technique, though this decreases the alignment advantage of using circularly symmetric feedhorns because there can be misalignment between the two halves of the split-block upon mating.

We offer the solution of integrating the CTR WGT directly into the feedhorn block. Considering future design and fabrication of large focal plane arrays, decreasing the number of individual components saves valuable machining time and has the additional benefit that misalignment errors do not tend to propagate between pixels in the array.

TRANSFORMER DESIGN

The motivation for this work is based on instrument development to survey large regions of the galaxy in the astrophysically important [CII] cooling line of the interstellar medium at 158 μm (1.9 THz). Pickett-Potter horns have highly symmetric E and H planes, <-28 dB side lobe levels, and cross-polarization coupling less than -25dB relative to the main beam [4]. The fractional bandwidth is 10-20%, which is suitable for emission line surveys. Pickett-Potter horns have a flat-topped conic profile, allowing them to be machined with custom-ground tools without requiring electroforming, adhesives, or etching methods.

The design of the CTR WGT is based on [7], with the dimensions of the cross section scaled in frequency for operation at 158 μm. The feedhorn choice defined the input CWG dimensions at the input of the CTR WGT. Fig. 1 shows a diagram of the transformer module profile, and the dimensions for this particular module at 1.9 THz are givin in Table I.

MANUFACTURING TECHNIQUES

It is possible to machine all waveguide circuitry from the aperture of the Pickett-Potter horn with just three tools; one custom tapered tool with a flat end for the feedhorn, and two additional modified endmills. To achieve the proper dimensions at 1.9 THz, the horn tool was ground at a 6.5-degree half angle and the tip was flattened to match the diameter of the step between the horn and the CWG. The first endmill is slightly smaller in diameter than the CWG (here 150 μm) at the exit of the feedhorn, and the second endmill has a diameter less than that of the short dimension of the output RWG (here 40 μm). The diameter of these endmills is standard but both were recessed an the tool neck in order to fit in the horn aperture. The recessing was done at the Jet Propulsion Laboratory by grinding the tool at the appropriate clearance angle.

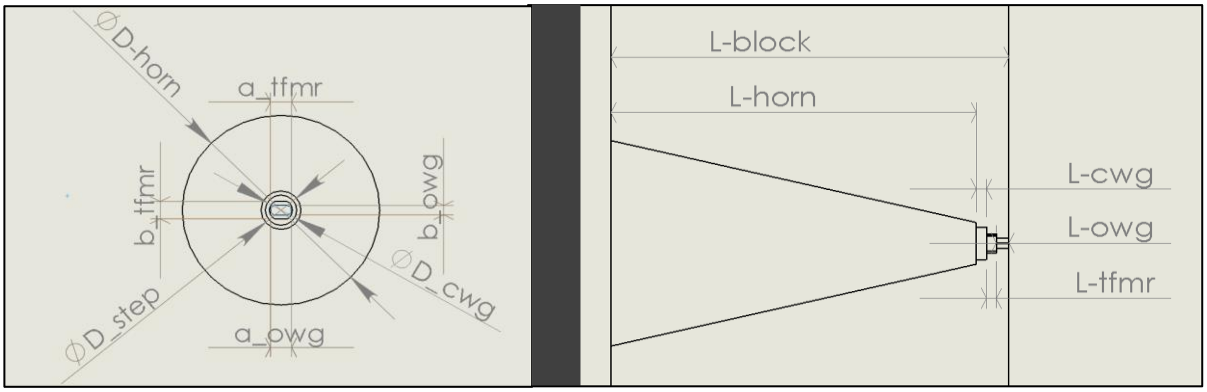

Fig. 1. Critical dimensions of the design model of the waveguide circuitry of the horn-transformer module as seen looking down the aperture (a) and a cut across the profile (b). Dimensions of these features are listed in Table I. The horn is located in the middle of a 20 mm square block of 145 copper (ultra-high purity) copper alloy. A set of four guide pins spaced on the flange outside the frame of this model image ensured precise alignment to the mixer backend.

TABLE I
MODULE DIMENSIONS

Dimension	Design (mm)	Machined (mm)
D_{horn}	1.011	1.015
D_{step}	0.205	0.208
D_{CWG}	0.161	0.159
a_{tfmr}	0.117	0.114
w_{OWG}	0.100	0.108
b_{tfmr}	0.093	0.098
h_{OWG}	0.050	0.053
ℓ_{tfmr}	0.046	0.035

The designed and as-machined dimensions of the feedhorn-transformer module. The as-machined dimensions were verified using a microscope with sub-micrometer precision. The tested unit was measured without cutting it open, so there is $^{+}/.0.008$ mm uncertainty in the measurements due to diffraction of optical light within the horn.

TABLE II
BEAMWAIST

z (mm)	ω_o measured (mm)
480	0.287
600	0.296
800	0.310
Average	0.298
Theory	0.281

The calculated beamwasit for all three measurement scans is slightly larger than the theoretical value calculated in [4]. This is an expected phenomenon since we do not correct for the beam size of the source probe.

RESULTS

We measured the radiation pattern of Picket-Potter feedhorn-transformer module to ensure there were no distortion effects produced by the integration of the WGT into the feedhorn module, and the results are presented in Table II. The beam angle of the receiver is determined by the feedhorn design, but deviation between the expected and measured radiation patterns can be used to verify the transformer performance and diagnose alignment errors. All three measurements show close agreement to the theoretical beamwaist of 0.281 mm.

CONCLUSIONS

We have modeled, fabricated, and tested a CTR WGT, which can be easily machined directly into a feedhorn block with a circularly symmetric feedhorn profile. Pickett-Potter feedhorns are more desirable than the traditional diagonal feedhorns for their lower cross-polarization properties, so these modules provide an attractive alternative in both performance and machining simplicity. The advantages of an integrated architecture are in the more precise alignment of waveguide circuitry features, reduction in the number of independently machined segments, and minimization of the mismatch risk. The performance of the integrated transformer is well matched to physical optics simulations, confirming both simulation and fabrication techniques. These new technological advances can serve as a pathway toward the implementation of large monolithic focal plane array units.

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