Terahertz waveguide mixer development with micromachining and DRIE

P. Pütz, T. Tils, K. Jacobs and C. E. Honingh

***Abstract*—Simple waveguide mixers have been fabricated up to 1.9 THz in traditional technology. Advanced mixer concepts such as sideband separation or balancing demand more complicated and precise waveguide technology. Mixer development at KOSMA is based on a dual fabrication technology approach. On the one hand we have extended our traditional, CNC lathe based, metal micro machining capabilities. We will present micro milling results of 490 GHz waveguide couplers with ±5 µm precision. On the other hand deep reactive-ion etching (DRIE) of silicon for fabricating waveguides as a new, very powerful technology is explored. This will be demonstrated with successfully fabricated 1.9 THz waveguide structures. Feature reproducibility, given by the photolithography based processes, is ±1 µm, which is sufficiently precise up to frequencies of 10 THz. Features with two different etch depths, such as a waveguide with substrate channel, have been successfully fabricated by using a dual masking scheme.**

***Index Terms*— DRIE, feedhorn, heterodyne receivers, micromachining, mixers, terahertz, waveguide**

I. Introduction

KOSMA has developed a THz waveguide mixer with proven performance up to 1.9 THz [1]. This mixer is a rather straightforward modification of the standard KOSMA SIS mixer design that has demonstrated its good performance in numerous occasions up to 880 GHz in the past [2], [3]. The hardware of the standard design is composed of three main components. First is a solid copper block with a stamped fixed backshort waveguide cavity and a cut substrate channel feature on its face side, which is all machined at the KOSMA workshop. Second is a Pickett or Potter type electroformed feedhorn with integrated waveguide transition manufactured by RPG [4], which is mounted perpendicularly onto the block's face. Third is a lapped Si frame on which the only 2 µm thin Si_3N_4 membrane is flip-chip bounded and enables careful alignment of the device into the waveguide cavity without risking breakage of the fragile membranes (see Fig. 1 for a close-up of the modified mixer block with mounted device) [5], [6].

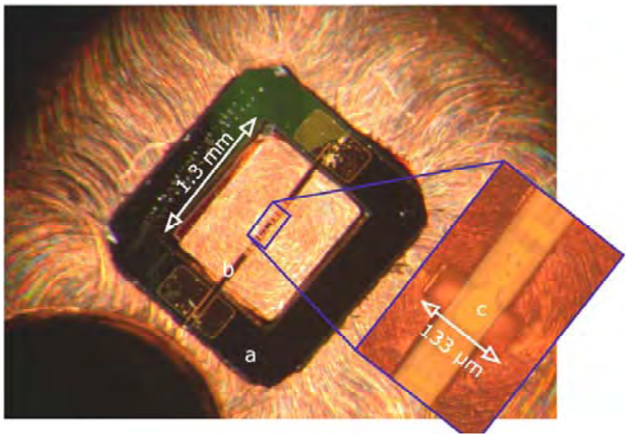

Fig. 1. Close-up of the center of a KOSMA 1.9 THz waveguide mixer block (feedhorn removed). Depicted are (a) the Si frame centering (b) the Si_3N_4 membrane based superconducting HEB device in the substrate channel and (c) a close-up of the waveguide probe in the waveguide.

As a mixing device for THz application we use a phonon-cooled superconducting Hot-Electron Bolometer also completely fabricated in-house.

Although this design works, it is necessary to completely rethink mixer design, in particular when THz array applications, e.g. STAR on SOFIA, are targeted. First the frame mount approach works for a single-pixel application but is too critical and time-consuming for an observatory array receiver. Second the metal machining of the waveguide and substrate channel features is lacking sufficient precision, speed and yield for reproducible volume fabrication of array mixer units.

II. Future KOSMA THz waveguide mixers

A. More mature designs

Our goal is a mixer design mature enough to include features like balancing and high IF output for array applications up to an operating frequency of several THz. The general approach is to use the newly available plasma based deep-reactive ion etch (DRIE) of Si wafers for the small, high frequency structures, which is novel to submillimeter and THz waveguide mixer fabrication. This is made possible by the latest addition to KOSMA cleanroom processing equipment, an inductively coupled plasma (ICP) etcher [7].

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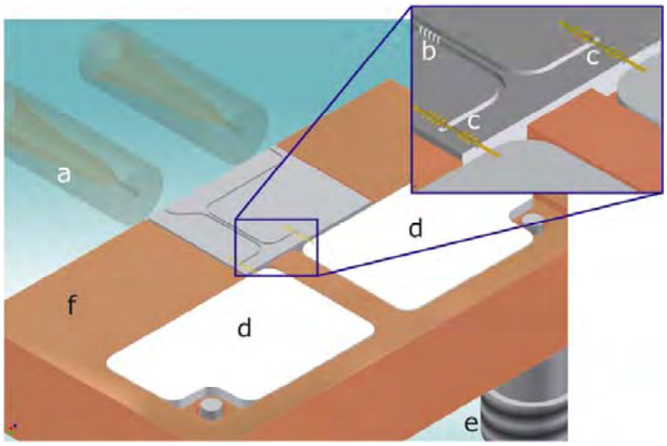

Fig. 2. Conceptual 3D rendering of the hybrid test mixer for 1.4 THz. The individual components are (a) the smooth-walled feedhorn, (b) the DRIE micromachined silicon insert with branchline coupler and mixer waveguide, (c) the devices on membranes with beamleads, (e) the SMP type output connector and (f) the copper support block.

Larger scale, lower frequency structures will be machined with refined metal milling on a CNC lathe. For THz frequencies this leads to a hybrid mixer design, which has a DRIE structured Si wafer insert with the waveguide and substrate channel features and a metal support block to accommodate the insert, the IF board and the dc and IF connectors (Fig. 2). The mixer will be of an E-plane split-block type.

A 1.4 THz balanced mixer is being constructed to demonstrate this hybrid design approach, and in parallel the metal micromilling processes is being improved while manufacturing branchline couplers for new 490 GHz mixers.

For maximum performance and ease of mounting in later array mixer units the mixing elements will be beamlead supported Si or Si_3N_4 membrane devices [8], [9]. The beamleads will also deliver RF and IF ground to the device.

B. *Improved feedhorn performance*

Feedhorn reproducibility is an additional issue for THz frequencies. Currently, the highest performance feedhorns are typically of the corrugated type, as e.g. for Band 1–4 of the HIFI instrument of the Herschel Space Observatory, and are fabricated through an electroforming process at RPG. The corrugations of the feedhorn become mechanically unreliable for THz frequencies and, more importantly, pose a significant additional effort during feedhorn fabrication. Feedhorn alignment onto the waveguide cavity has to be precise to a few micrometers at 1.9 THz, which is difficult to achieve with a typical dowel pin type interface. A simpler more precise and reproducible alignment scheme is required for the feedhorns and, at least for the high frequencies, should favor a split-block type approach with the feedhorn directly machined into the mixer block. In this case the alignment accuracy between feedhorn and waveguide features is determined by the precision of the machining process. Then only the split-block half alignment itself remains critical.

Hence we are investigating two new routes for THz compatible feedhorns, again with reproducibility and ease of volume production for array mixer units in mind.

First we have investigated the performance of smooth-walled type feedhorns fabricated with the same electroforming technique as the corrugated ones [10]. The performance of these horns is excellent even though of the vastly simplified fabrication [11]. The alignment concept for these horns remains the conventional at first.

Second, avoiding the horn / waveguide alignment for the high frequency range, is the laser micromachining (LMM) process of split-block corrugated feedhorn features into Si [12], [13]. This process uses a powerful laser in combination with a chlorine environment to write 3D features directly into a Si wafer with a few micrometer precision by means of scanning optics. As this micromachining process is only available for the THz mixer community at the Steward Observatory Radio Laboratory (SORAL), U. of Arizona, a close collaboration between KOSMA and SORAL has been set up. In combination with the DRIE process it seems possible to fabricate all critical mixer features in Si and enabling sufficiently precise waveguide features up to 10 THz.

III. Fabrication

Several areas need to be investigated for the hybrid mixer fabrication.

A. *Metal micromilling*

We are currently improving our CNC lathe milling process. The goal is to mill features down to 50 µm to ±3 µm precision. This would enable a very precise fit of the silicon inserts in the mixer block and additionally permit the use of metal milled branchline waveguide couplers up to 800 GHz.

B. *Silicon micromachining of planar structures*

We have started developing the Si DRIE process for waveguide fabrication and have principally demonstrated its ability to precisely reproduce structures defined by the photolithographic masking process to better than two micrometers for very high aspect ratio features. One principal limitation of the DRIE process is that it can only yield planar features normal to the wafer surface and only on one depth level per DRIE process step. A one level structure could e.g. be a hybrid coupler for a balancing or sideband separating mixer.

Because a waveguide environment composed of a waveguide cavity and substrate channel is a two-level structure, a two step DRIE process is required with two masking layers.

C. *Silicon micromachining of tapered and stepped structures*

Stepped and tapered Si structures are micromachined with the LMM system at SORAL. As this process is rather slow when compared to DRIE, large area planar structures should be avoided. The current LMM systems can write structures with 3 µm resolution within a 2 mm × 2 mm scanning field, and a new, higher resolution system is being finalized which will provide a 10× higher resolution but with equally reduced scanning field.

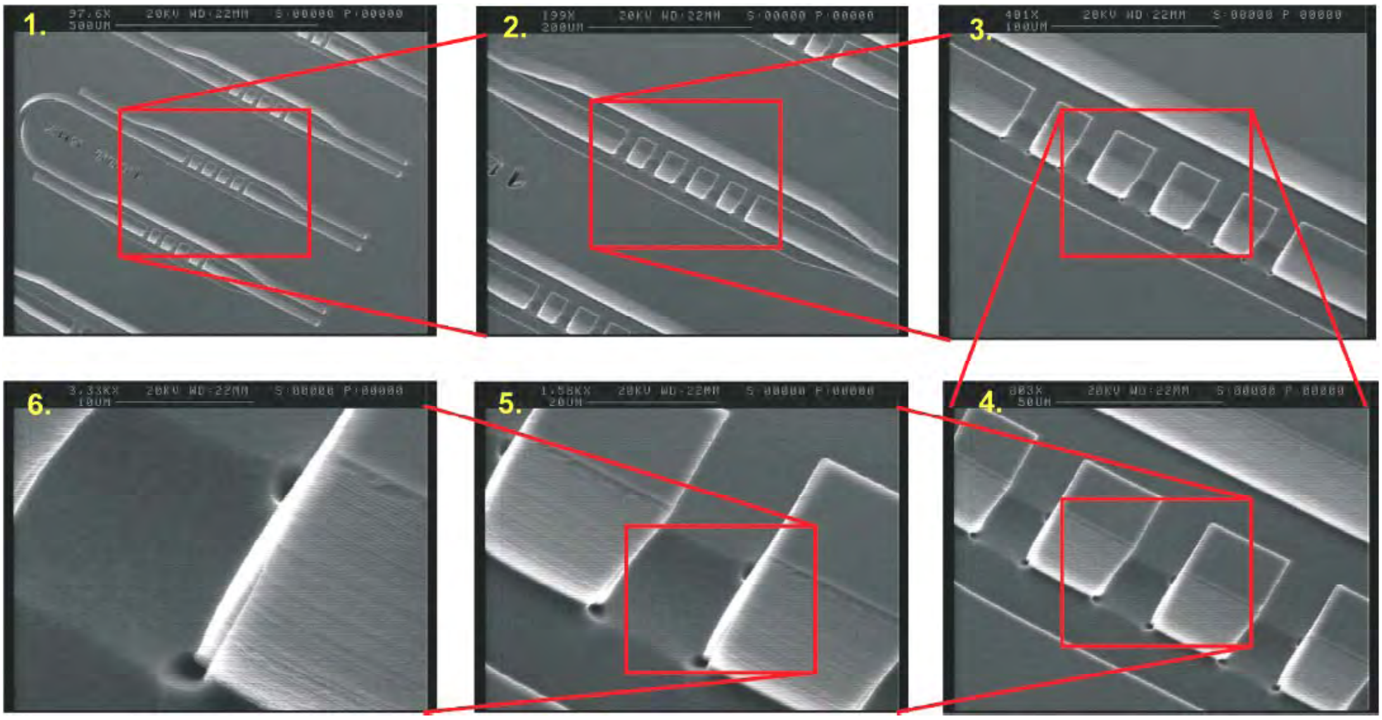

Fig. 3. SEM micrograph zoom in sequence onto a Si DRIE 1.9 THz branchline coupler. The scale bar on the last micrograph measures 10 µm. Etch depth is 55 µm. Note the low sidewall roughness of the Bosch process. The view is inclined by approx. 45°.

D. Additional considerations

The Si features need to be plated with Au. For typical high-aspect ratio waveguide features sidewall coverage needs to be investigated as well as the cryo compatibility. Resulting from our experience gained from constructing the HIFI Band 2 mixer we opted for 200 nm sputter-deposited Au on top of 50 nm sputter-deposited Al. DRIE structured Si wafers were cycled 10× in LN2 and then several times to LHe temperature in vacuum, according to HIFI specifications. Microscopic inspection of the Au surface revealed no noticeable change such as peeling or discoloring and tape pull tests showed no difference in adhesion strength before and after the cooling cycles.

Dependent on the mixer block design a concept for precise feedhorn alignment needs to be developed. For the silicon insert split-block alignment could be achieved through self-aligning the Si pieces by means of additional DRIE structures.

IV. Silicon Micromachining of THz structures

DRIE is executed with a time-multiplexed process, also known as the Bosch process, in our inductively coupled reactive-ion etcher [14]. The process switches between an etch and a deposition (passivation) cycle every few seconds which results to near-perfect vertical etching, i.e. high aspect ratio structures for several hundred micrometers. The resulting scalloping of the sidewalls is so small that is not of concern, as can be seen on the last SEM micrograph of the zoom in sequence onto a 1.9 THz branchline coupler in Fig. 3. Remarkably the process leaves no residue. Time averaged etch rate is typically 5 µm/min.

The lateral feature size reproducibility of this process therefore is determined by the photolithography process used for defining the etch mask and is ±1 µm. The etch depth is computer controlled in-situ during the DRIE with means of a dual beam interferometer to < 1 µm.

For two-level structures we have developed a dual masking scheme process with uses two DRIE steps. The process has been optimized to prevent formation of a burr at the step between the two levels (Fig. 4).

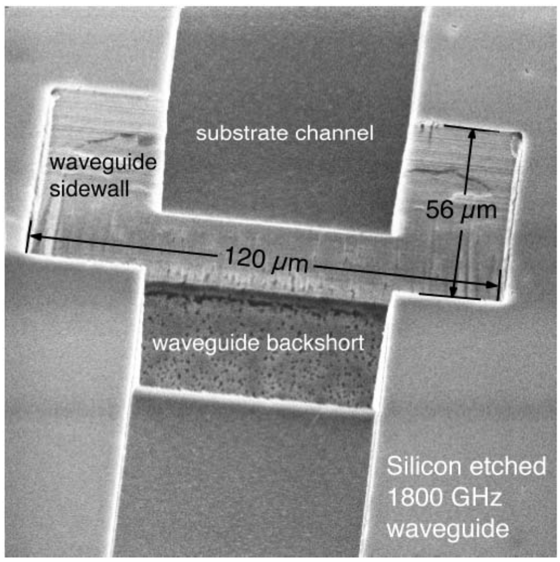

Fig. 4. SEM micrograph of a 1.9 THz two-level Si DRIE waveguide-substrate channel structure. Note that the dual masking process has been optimized to prevent formation of a burr between the waveguide and the substrate channel.

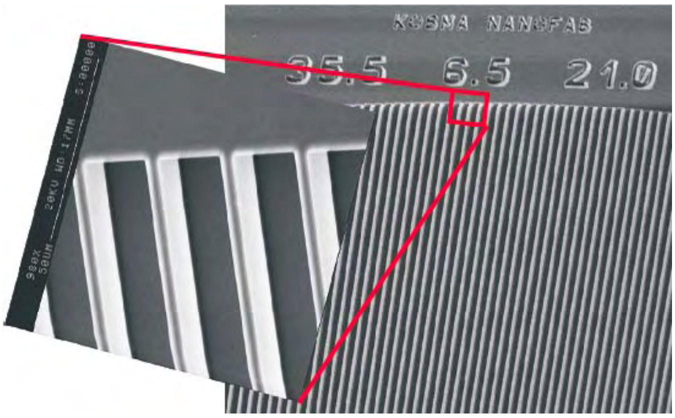

Fig. 5. SEM micrographs of DRIE etched antireflection structures on a Si window. The large numbers give the target values for period, bar width and etch depth. Note the absence of any residue from the DRIE process.

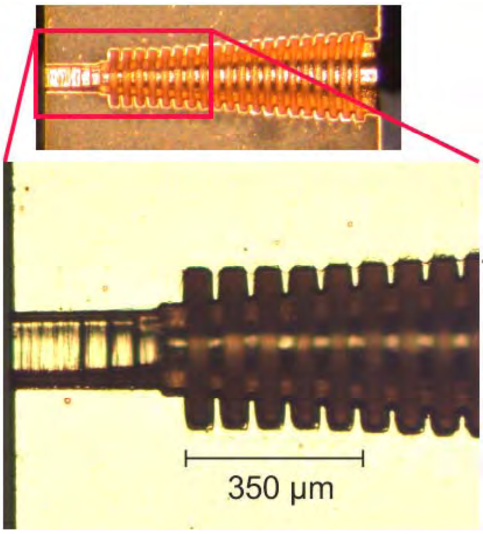

Fig. 6. Microscopic view of a LMM 1.9 THz feedhorn half. The feedhorn is gold plated. The lower image shows a close-up of the neck area with the waveguide transformer section.

Fig. 5 depicts another application for Si DRIE. Si is one of the materials with the lowest losses in the 1–2 THz range and therefore very interesting as e.g. the dewar window material. Due to its high dielectric constant some kind of antireflection coating is required. Structuring precise periodic structures into the Si can serve this purpose [15].

What we have learned up to now is that the DRIE process is extremely powerful. It is a very fast structuring method and due to its precision and reliability most suitable for volume production of array mixer units.

LMM feedhorns are now available from SORAL. Fig. 6 shows a microscopic view onto a 1.9 THz feedhorn half that already has been Au plated. Judging from the microscopic inspection feature size reproducibility and precision of this sample horn is good enough for this frequency, even though this feedhorn was machined with the lower resolution LMM system.

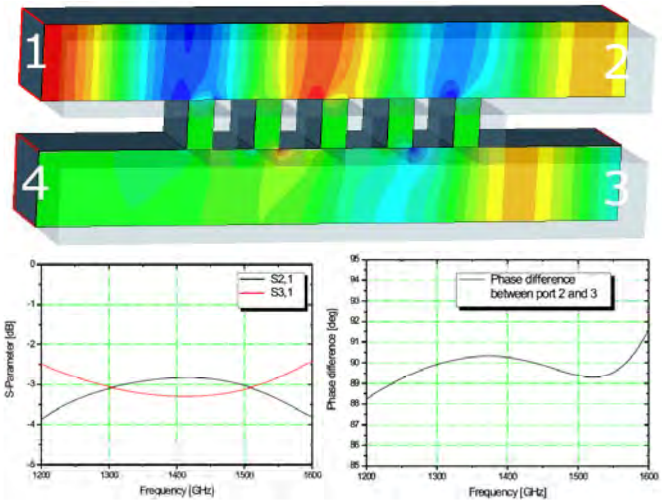

Fig. 7. Simulation of an optimized 1.4 THz branchline coupler. Port 1: input; Port 2: -3 dB output; Port 3: -3 dB output with 90 degree phase difference to Port 2; Port 4 is terminated by a load. Top depicts the field distribution in the coupler structure and plots below show the results for S21 and S31 as well as phase difference.

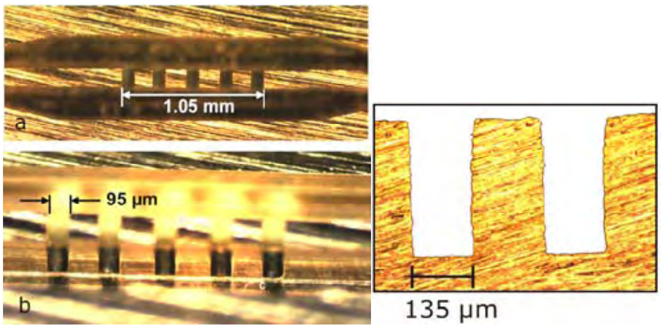

Fig. 8. Microscopic view of CNC lathe machined metal branchline couplers. Right: (a) depicts a top and (b) a tilted side view of the 490 GHz structures. Right: Microscopic cross-section of the same branchline coupler. (Milling tool diameter: 100 µm, milling tool rotation speed: 70000 rpm)

V. Design of Waveguide Structures

Waveguide structures such are designed and optimized with CST Microwave Studio 3D EM simulation software [16]. Fig. 7 shows the simulation results of the optimized 3 dB 90 degree branchline waveguide coupler for the 1.4 THz balanced mixer [17], [18]. The top part of the figure depicts the field intensity distribution through the coupler structure, whereas the plots below show that S21 and S31 are 3±0.5 dB and the phase balance between ports 2 and 3 is within ±1.7 degrees for the simulated frequency range 1.2–1.6 THz.

VI. Prototyping at 490 GHz

As an intermediate step we are currently optimizing the machining process for 490 GHz branchline couplers for a single-sideband mixer project. Currently we can machine the couplers to ±5 µm precision which is sufficient for this frequency (Fig. 8).

VII. Conclusion

We believe that our dual technology approach for the mixer hardware should make reproducible fabrication of wideband waveguide based mixers possible to 10 THz. The use of metal micromilling techniques for fabrication of mixer housings, as well as for (lower frequency) less critical waveguide features, in combination with silicon micromachined waveguide inserts is powerful enough for volume production of THz array mixer hardware.

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