Waveguide Packaging Technology for THz Components and Systems

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***Abstract-* We present an integrated THz waveguide packaging solution based on the combination of all-metal micro-machined THz waveguide technology and active component chip layouts suitable for the realization of systems from 200 up to 5000 GHz. This packaging solution is compatible with different THz component technologies, for room temperature and cryogenic operations and employs space-qualified wire-bonding for electrical contacting. The THz waveguide packaging provides possibility of making 3-dimensional structures via facilitating of multi-level (layered) designs. The surface roughness of the fabricated THz waveguide structure was demonstrated to be 20 nm, while the alignment accuracy of the active component chip was measured to be about 2 µm. Some of the demonstrators are already in used, at.e.g., APEX telescope in the SHeFI receiver [1].**

I. Introduction And Background

Regardless of the core technology for Terahertz sources and detectors (e.g, Schottky diodes, MMIC, SIS or HEB mixers), the components have to be integrated into THz electromagnetic guiding structures, in order to produce complete THz systems, which in this context is defined as THz packaging.

Waveguides are widely used in the industry and are particularly attractive guiding systems for electromagnetic waves, since they are relatively broadband and low loss transmission lines. Furthermore, waveguides provides complete confinement of the EM field inside a hollow structure and thus have negligible sensitivity to RF interference and limit RFI/EMI in the systems.

The challenges for THz waveguide are the small waveguide dimensions (~100x200 μm^2 and ~20x40 μm^2 at 1 THz and 5 THz, respectively) and the required nanometric surface roughness of the waveguide walls. The small dimensions originate from the scaling of the solutions of Maxwell's equation with the wavelength. The surface roughness limitations are coupled to the submicron size of the skin depth at these frequencies, and directly responsible for the RF losses. In any case, both these constraints are completely out of reach for conventional machining even with the latest CNC technology, even though slightly more tolerant designs of components have been introduced for hybrids [2].

Besides, handling the substrate-based active components and mounting them into a waveguide structure becomes really demanding at THz frequencies when the dimensions of such "substrate" becomes as small as e.g, 1000x70x17µm [3].

In this paper, we present a complete waveguide packaging technology suitable for frequencies up to 5000 GHz, combining all-metal THz waveguide technology [4] based on micromachining, for ultimate waveguide quality and a novel chip layout based on SOI structure [5], forming a Π-frame supporting the active devices on a thin cross beam, for simple, fast and accurate chip positioning.

II. All Metal Waveguide Technology

Multi-level (layered) waveguide structures were fabricated using the GARD process [3] for different SIS and HEB mixers for frequencies ranging from 350 GHz to 2 THz [1],[5-6] (Fig.1 and Fig 2).

The process is based on copper electroforming over sacrificial layered mold made out of SU-8 and pattern by conventional photolithography. As a result, submicron linear accuracy and surface roughness of the waveguide walls down to 20 nm were verified [4] on the fabricated waveguide structures. Furthermore, the fabricated hardware is already in use on the SHeFI receiver of the APEX telescope [1].

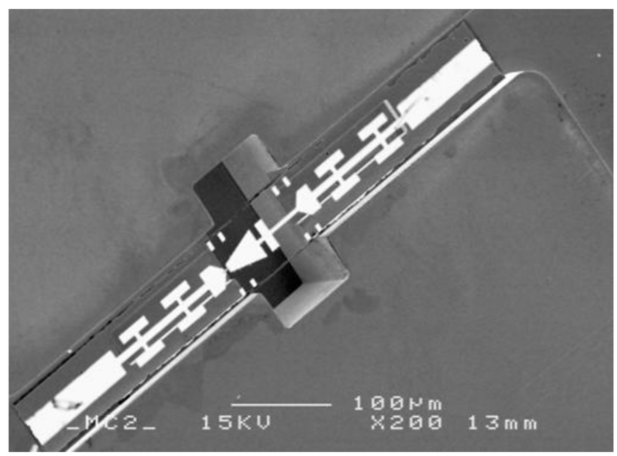

Figure 1. SEM image of the fabricated multi-level structure: a back-piece of the APEX T2 1.3 THz HEB mixer block, with chip schematic overlayed. [4]

Importantly, the photolithographic nature of the GARD process makes this fabrication technique very attractive in for volume production due to its throughput and reproducibility, compared to the competing technologies.

Even though Silicon micromachining [7]-[8] has been used to produce waveguide structures for THz receivers, this technique is largely limited to fabrication of 2 layer structures, with inherent difficulty of making evenly deep grooves of different width, and, generally, the process somewhat cumbersome. Direct laser ablation has also been demonstrated on Silicon [9] but requires extremely long processing time and thus has inherently low throughput.

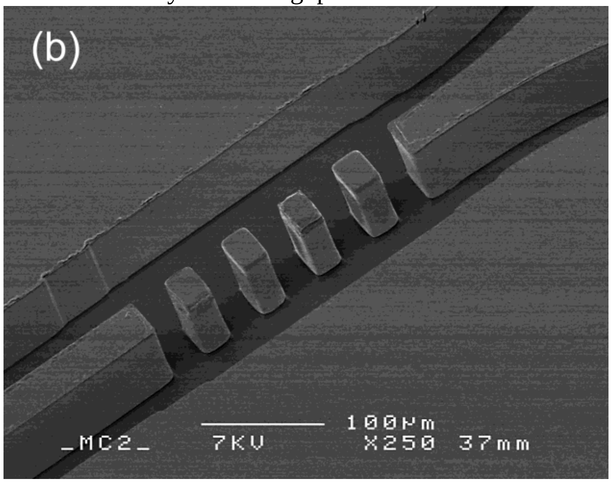

Figure 2. SEM picture of the 1.6-2.0 THz hybrid made as waveguide branch-line coupler in split-block technology (60×60 µm in every split half) [5]

Alternatively, waveguide structures defined and processed exclusively out of thick SU-8 photoresist [10] or combining Si etching and thick photoresist [11] are almost incompatible with cryogenic operation due to the large mismatch between the their thermal expansion coefficients and Copper.

All-metal multilayer structures opens new possibilities for millimeter and THz cryo-receivers both for ground based and space borne observations, since it permits the realization of large mixer block parts and hence simplifies the assembly and eradicate thermal differential contraction problems, unlike other Silicon waveguide micromachining technologies.

Furthermore, the availability of split block technology at THz frequencies naturally, along with achieving extremely high waveguide surface quality and thus low RF loss and possibility of using multi-level designs, the suggested technology opens solid prospects for building complex waveguide circuits (Fig. 3). This would naturally increases the level of integration in THz systems, making them more compact and eventually lighter, which might be very relevant from space borne observatories.

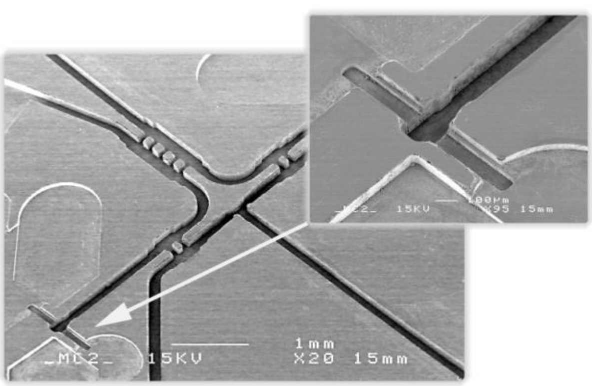

Figure 3. SEM picture of the micro-fabricated 600-750 GHz 2SB SIS Mixer.

Even though the all-metal waveguide technology was largely demonstrated on cryogenic receivers, it is not limited to low temperature hardware. In fact, it is fully compatible with room temperature technologies such as MMICs or Schottky diodes.

The presented micromachining technique faces though different limitations in reproduction of structures' geometry depending on the frequency. For Sub-Millimetre wave components with bigger waveguide dimensions, some specifics of the photolithography process should be taken into account. In particular, the verticality of the SU-8 pattern walls and internal photoresist stress issues could be challenging. During our initial experiments, we have fabricated a waveguide circuit for 2SB SIS mixer with even larger waveguide dimensions. The measured depth of the processed waveguides structure was 350 µm, which suggests that, used in a split-block layout the waveguide circuits down to 200 GHz could be fabricated using the proposed micromachining technique.

Towards higher THz frequencies, the availability of active elements, e.g., Schottky mixers. HEB, SIS and constrains coming from the handling and mounting of these extremely small and fragile components into the waveguide mixer block, would be the limiting factor, rather than the waveguide dimensions, which can easily be pushed down with the use of DUV lithography. Therefore we envisage that this proposed technology could be advantageously used at frequencies up to 6-7 THz.

III. Active Component integration

The all-metal waveguide technology opens solid prospects for building split block complex waveguide circuits by employing a single photo-mask set, e.g., a balanced receiver scheme comprising the hybrid, bends and waveguides providing interfaces to the input horns and to the mixers.

3D FEM electromagnetic simulations for such a split.block waveguide balanced HEB mixer resulted in a mixer chip dimensions of 360 × 50 × 2 µm and clearly would be extremely difficult to manipulate and integrate in the mixer block [4].

Earlier suggested beam-leads and membrane solutions [12-14] partly solve the problem of the electrical interfacing the device but do not provide improved handling by leaving the substrate size as small as it is. Another proposed solution would employ a micro-machined frame supporting the mixer substrate [15-16], providing far more possibilities to handle the mixer chip. However this type of design requires a back-piece configuration making it incompatible with the split-block technique.

In our novel approach, atarting from SOI wafers, a Π-shaped bulk silicon frame is formed, providing alignment reference for the active device fabricated on a cross beam as outlined in Fig. 4. The shape of the HEB mixer chip is defined via micromachining, photolithography and consequent etching, while the thickness of the beam and the supporting frame depends on the SOI substrate. Consequently, in order to integrate the HEB mixer chips having this novel layout into the mixer block does not require any additional lapping and dicing.

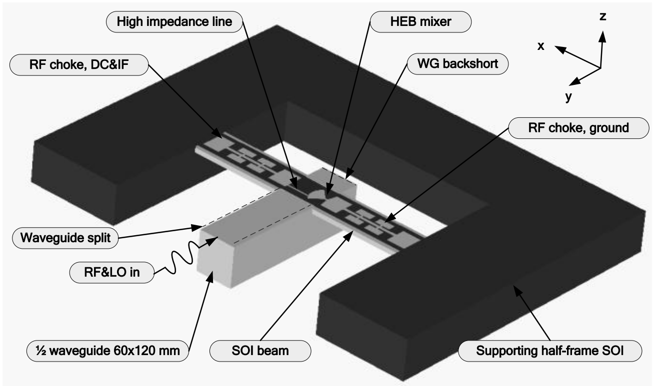

Figure 4. Illustration of the HEB mixer chip with supporting half-frame [5].

This chip layout ease the handling, electrical contacting and mounting of the active device in the waveguide. The shape and the dimensions of the supporting Π-frame are chosen such that it provides alignment reference with respect to the corresponding recess in the mixer housing where it should be integrated. Based on this approach we have fabricated a technology demonstrator for 1.6 – 2.0 THz receiver (Fig 5.), where an alignment accuracy of about 2 micrometers has been confirmed (Fig 6.).

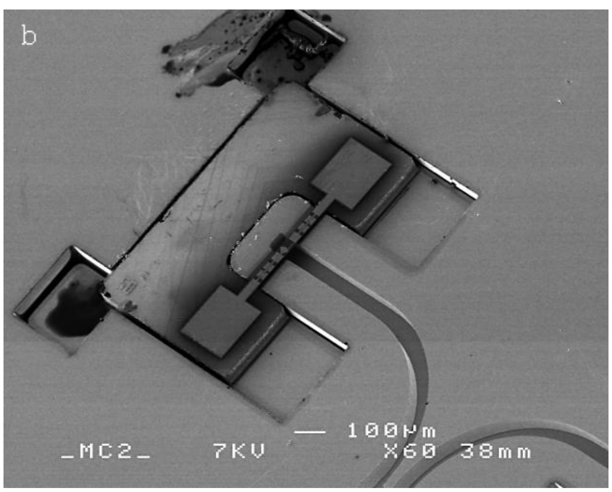

Figure 5. Technology demonstrator for 1.6 – 2.0 THz receiver [5].

IV. CONCLUSIONS

In this paper, we presented a complete waveguide packaging technology, suitable for all millimeter and THz device technology with the considerable advantage of being reliably compatible with cryogenic operating conditions. The presented packaging technology takes full advantages of all-metal waveguide combined with a novel component design. This design uses a novel layout for the HEB mixer employing bulk Si Π-frame, supporting a cross beam accommodating the active devices. We successfully demonstrated all technological steps and final integration of a balanced THz mixer. We believe that the demonstrated approach is suitable for building a single-end deep-terahertz mixer operating at up to 5 THz. The confirmed ease of integration by means of self-aligning of the mixer chip in the mixer housing opens prospective for making moderately large heterodyne terahertz array receivers. The proposed technology does not limit the number of pixels, which is rather constrained by a possibility to generate enough LO power. Even though demonstrated for HEB, the technology is suitable for other active mixer components such as Schottky diode- and SIS mixers or terahertz.

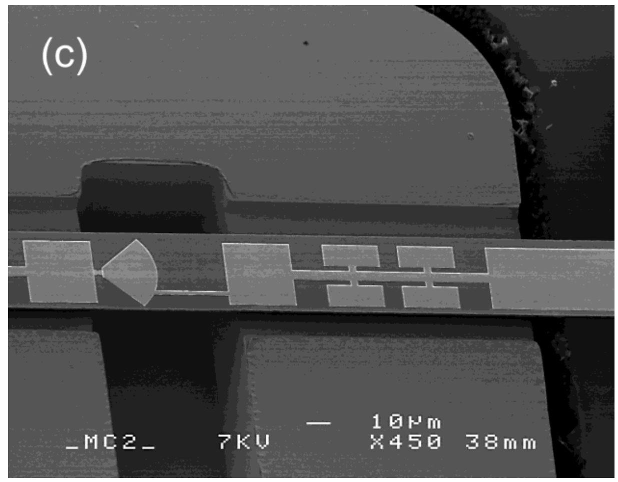

Figure 6. Aligned HEB mixer beam crossing the waveguide [5].

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