

# Hot-Electron Bolometer Mixers on Silicon-On-Insulator Substrates for Terahertz Frequencies

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**Abstract**— A terahertz Hot-Electron Bolometer (HEB) mixer design using device substrates based on Silicon-On-Insulator (SOI) technology is described. This substrate technology allows very thin chips (6  $\mu\text{m}$ ) with almost arbitrary shape to be manufactured, so that they can be tightly fitted into a waveguide structure and operated at very high frequencies with only low risk for power leakages and resonance modes. The NbTiN-based bolometers are contacted by gold beam-leads, while other beam-leads are used to hold the chip in place in the waveguide test fixture. The initial tests yielded an equivalent receiver noise temperature of 3460 K double-sideband at a local oscillator frequency of 1.462 THz and an intermediate frequency of 1.4 GHz.

**Index Terms**— Hot-Electron Bolometer, HEB, Superconductor, Heterodyne, Mixer, Terahertz, Submillimeter, Spectrometer

## I. INTRODUCTION

The terahertz regime is of significant interest for the study of the interstellar medium and the life cycle of stars due to a large number of spectroscopic lines from species such as ionized carbon and nitrogen, carbon monoxide and water. The low atmospheric transmission requires that such studies be made from space, balloons, aircraft or one of a few high-altitude ground sites. The best concept for high-sensitivity, high-resolution spectrometers from about 1.4 THz up to several THz is the Hot-Electron Bolometer (HEB) Mixer, [1-4] which can provide low-noise operation with local oscillator (LO) power requirements below 1  $\mu\text{W}$ . In order to increase the data gathering speed, future terahertz heterodyne spectrometers will likely use some form of multi-pixel focal plane array. This is especially important for space-borne

applications, where the cost of observational platforms is very high.

We are investigating the use of waveguide-based mixers for such arrays, using brass mixer blocks for the prototyping and HEB's on very thin (6  $\mu\text{m}$ ) silicon chips that are fabricated from commercial Silicon-On-Insulator (SOI) wafers. The thin silicon chips should allow operation to many THz without the occurrence of substrate modes and resonances that could be expected from thicker substrates. One existing technique uses lapped-down quartz substrates [5], but due to the fragility of these the method is unlikely to work well over about 2 THz. With the SOI approach, the device chips can be shaped almost arbitrarily so that they fit into the waveguide circuit, so that it is not necessary to use larger membranes supported by a frame, which would complicate the microwave design.

The use of a waveguide circuit instead of an open structure (quasioptical) antenna, such as a twin-slot antenna has some advantages. For example, waveguide horn antennas are used, which have better antenna patterns and (in the case of corrugated horns) have better polarization properties than most planar antennas, and which eliminate the risk of cross-talk on the intermediate-frequency side of the mixer. Another advantage, and a main reason for our interest, is that more complex circuits can be constructed to for example allow the LO power to be injected separately from the signal into the mixer block. One of the simplest such configurations is the cross-bar balanced mixer, where a probe on the same chip as the mixer would couple the LO power from a separate waveguide. Since the Signal/LO separation is achieved by use of symmetry and antisymmetry, it should be possible to achieve a broadband mixer circuit that will not require interferometers or beamsplitters in the signal path. Also, a cross-bar mixer does not require moving parts when the local oscillator frequency is tuned, which is an advantage compared to for example a Martin-Puplett interferometer. The mentioned properties would be significant for future space-borne single-pixel mixers, but even more so for a multi-pixel array instrument. We are currently investigating such cross-bar mixers, and will report on produced results in future publications.

Other issues with the SOI chip / waveguide approach that need to be resolved include the difficulties in machining the very small waveguide structures that will be needed at several

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THz. It is likely that silicon micromachining in some form will be required, for example using laser etching [6] or the Bosch-process Deep Reactive-Ion Etching (DRIE) technique [7]. The purpose of this paper is to report experiments with a 1.5 THz mixer based on the SOI chip / HEB concept, using NbTiN bolometer devices and a diagonal horn waveguide block machined from brass.

## II. DEVICES

The mixer chips are produced in-house at JPL and the fabrication has been described in detail in a previous publication [8]. The SOI technology applied is also similar to that described in [9,10]. Commercial Silicon-On-Insulator (SOI) wafers are used, which have a 6  $\mu\text{m}$  thick Si layer bonded to a 400  $\mu\text{m}$  thick oxidized “handle” wafer. In our wafer “front side” process the NbTiN HEB devices and circuits, including gold beam leads, are fabricated on this SOI wafer. In the “back side” process the wafer is attached with wax to a separate thick Si wafer, and the handle wafer is removed from the Si membrane by Deep Reactive-Ion Etching (DRIE). The bared oxide layer is wet-etched, after which the 6  $\mu\text{m}$  thick silicon is patterned and etched by DRIE to define the outline of the silicon chip. The DRIE does not affect the gold beam leads significantly, so that these can extend outside the edges of the silicon. The finished chips are released from the wax using a solvent and then strained out with a filter paper. Fig.1 shows a finished device chip for 1.5 THz. The NbTiN device films produced have a superconducting transition temperature ( $T_c$ ) of about 9.5 K and a film resistance of about 1250 ohms/square, with slightly lower  $T_c$  (8.5 to 9 K) for fully processed devices. The -3dB intermediate frequency bandwidth achieved at a signal frequency of 19 GHz is about 1.4 GHz (Fig. 2), see [8] for more details.

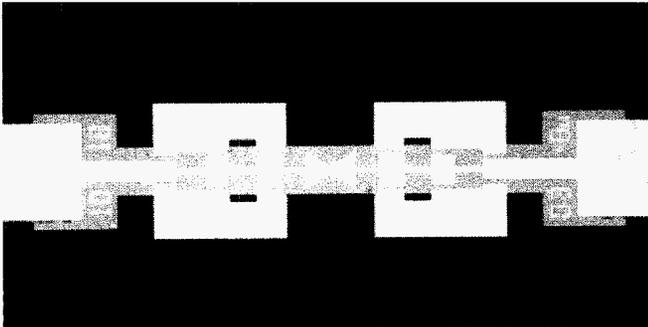


Fig. 1. An HEB/SOI chip. The I-shaped silicon substrate has a thickness of 6  $\mu\text{m}$ , and a width at the bow-tie shaped waveguide probe of 50  $\mu\text{m}$ . Gold beam leads are used to contact the chip and to hold in place in the waveguide circuit. The HEB is at the geometric center.

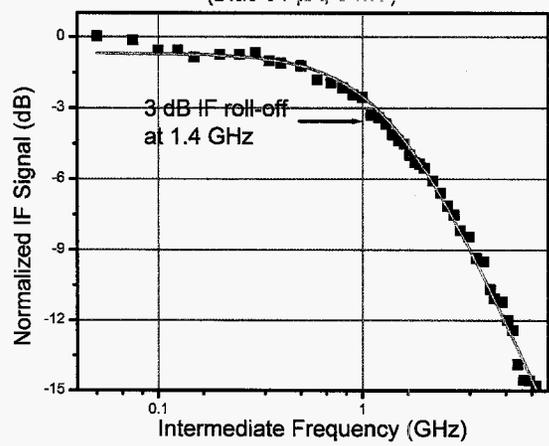


Fig. 2. Bandwidth measurement with a NbTiN HEB, made as an upper sideband measurement by sweeping the LO frequency while keeping the signal fixed at 19 GHz. The LO power level was adjusted to maintain a constant LO pump level.

## III. WAVEGUIDE CIRCUIT

The general approach is to fabricate superconducting HEB's on shaped thin silicon substrates and to install these into a waveguide mixer block, taking advantage of the low losses and the high beam-quality of waveguide horn antennas as well as giving scalability to higher frequencies (waveguide blocks with horns have already been successfully machined at JPL for other applications up to 2.8 THz). The SOI substrate is shaped in such way that it can be installed into a reduced-height waveguide mixer block, and be held in place by clamping the protruding gold beam-leads between different parts of the machined mixer block. The device is mounted with the flat side of the chip against the end of the waveguide, rather in the waveguide E-plane. The primary reason is that the design serves as a prototype for a future cross-bar balanced mixer, where this configuration will allow local oscillator power to be coupled to the devices from a separate waveguide with high coupling efficiencies for both the detection signal and local oscillator without use of an external interferometer. The present (non-balanced) mixer uses a bow-tie shaped capacitively coupled waveguide probe, which is RF-decoupled from the DC/IF lines by a quarter-wavelength section filter. Practically all of the circuit design was made using Ansoft's High-Frequency Structure Simulator (HFSS) software. The goal was to find a prototype design with reasonable coupling in the 1-2 THz band without significant dropouts at any frequency. Initially such dropouts did occur, apparently due to differences between the field generated by the probe and the desired TE<sub>10</sub> waveguide mode that lead to excitation of evanescent modes. It was found that this could be overcome by introducing notches in the waveguide probe close to the HEB device, as shown in Fig.3. The notches in that figure are 2.1  $\mu\text{m}$  long 0.8  $\mu\text{m}$  wide. As further seen in the figure, the near edge of the quarter-lambda section bandstop filter was given a curved shape to agree better with the field that was spreading radially into the substrate channel. The substrate channel had a

depth of  $10\ \mu\text{m}$  on the chip side (towards the horn antenna) and  $8\ \mu\text{m}$  on the other side (towards the waveguide backshort). The waveguide backshort distance was  $65\ \mu\text{m}$ . Figure 4 shows the reflection coefficient vs. frequency for a  $25\ \text{ohm}$  device from the HFSS simulations, which included the entire waveguide circuit except for the horn antenna but which neglected conductor losses. As can be seen, the simulated reflection at  $1.5\ \text{THz}$  is about  $-5\ \text{dB}$ , with optimal coupling occurring at  $1.9\ \text{THz}$ . A simulation shows that the location of the optimum can be shifted to  $1.5\ \text{THz}$  by slightly widening the part of the substrate that is inside the waveguide, but this was not implemented in the mask set used for devices in these experiments. Figure 5 shows a device chip such as the one in Fig. 1 installed into the substrate channel of the mixer block. The waveguide is the dark rectangular hole behind the bow-tie shaped waveguide probe at the center of the picture.

The quality of the machining of the mixer block (Fig.6) is a crucial factor to the feasibility the waveguide approach at this frequency ( $1.5\ \text{THz}$ ) and higher. There are several difficulties that must be overcome: 1) Tool breakage and “wobbling” sets a practical lower limit for the end-mill tool diameter of about  $10\text{-}15\ \mu\text{m}$  (a  $15\ \mu\text{m}$  tool has been successfully used at JPL for cutting a narrow channel in brass). 2) The cutting depths for these small tools are limited to just a couple to a few times the tool diameter. 3) Mating surfaces need to be polished to very high flatness and finish to prevent power leakages and resonances in the circuit. 4) Alignment of different component parts in the block is critical, and is usually achieved either by machining the components together in the same run on the numerically controlled milling machine, or by visual inspection and alignment under a stereo microscope. The parts are usually pinned together with cylindrical steel pins. 5) Some structures cannot be implemented with just two pieces, but require several parts that need to be machined separately and then be aligned to each other, which increases complexity. 6) Installation of the HEB device into the block, which is done with micromanipulators, is difficult but doable. In the circuit described in this paper, the block is split in 3 pieces (2 parts that allow the diagonal horn antenna to be cut and a third part that holds the waveguide backshort and that allows the beam-leads on the chip to be clamped). In our case the most difficult issue above is number 4, the alignment of parts. The described mixer block required a visual alignment step where the backshort component was lined up and pinned using microscope observations through the horn antenna, eventually resulting in an alignment error of less than  $2\ \mu\text{m}$ . The conclusion from the successful production of this  $1.5\ \text{THz}$  block was that the techniques involved can likely be extended in frequency up to about  $3\ \text{THz}$ , but probably not much higher. It is clear that a different technique such as silicon micromachining will eventually be required.

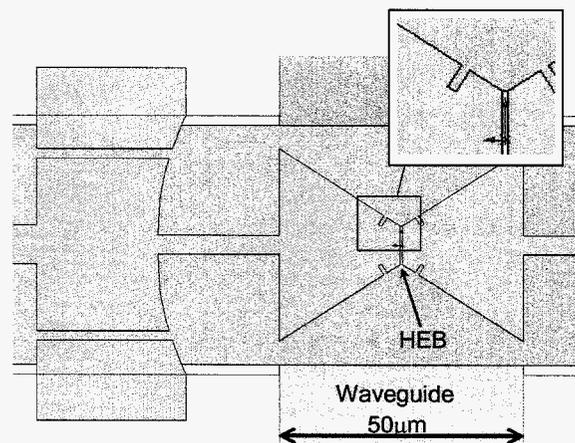


Fig. 3. Close-up schematic of the probe (true to scale).

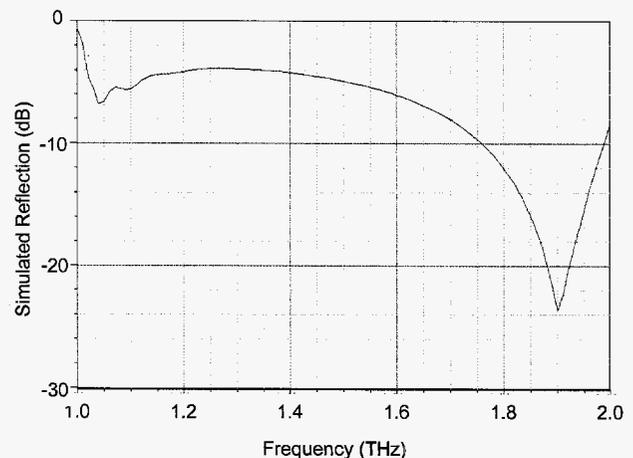


Fig. 4. Simulated reflection coefficient (mismatch) between the waveguide and a  $25\ \text{ohm}$  detector in the  $1\text{-}2\ \text{THz}$  band. The waveguide cut-off frequency ( $\text{TE}_{10}$ ) is  $1\ \text{THz}$ . HFSS was used for the calculation.

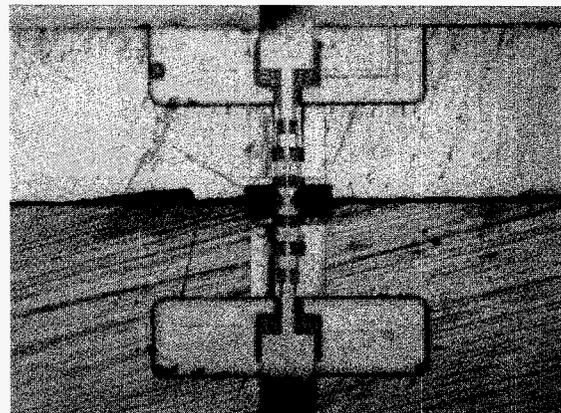


Fig. 5. A  $1.5\ \text{THz}$  HEB/SOI chip aligned to the waveguide. The waveguide cross-section is  $150$  by  $50\ \mu\text{m}$ .

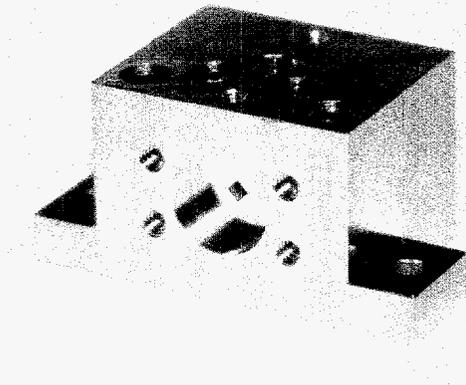


Fig. 6. 1.5 THz mixer test block. The aperture of the diagonal horn antenna is the diamond-shaped hole in the cylindrical cutout on the front side. The entire block is about 1 inch wide.

#### IV. EXPERIMENTS

The mixer testing was done in a setup using a 4.2 K vacuum cryostat with two different solid-state Schottky diode multipliers as local oscillator sources. The purpose was to show that the coupling efficiency of the structure is high enough to pump the HEB device with such sources, and to do a receiver noise calibration measurement. The device used was a 0.3  $\mu\text{m}$  long and 6  $\mu\text{m}$  wide NbTiN HEB with a room temperature resistance of 58 ohms. A pumping experiment was made with a Gunn diode / power amplifier driven multiplier chain at 1.52 THz. The source output was measured to be about 2-3  $\mu\text{W}$  with a calorimeter. The divergent beam from the source was collimated and refocused onto the mixer horn by two 1-inch diameter off-axis paraboloid mirrors. As can be seen in Fig.7, the device could clearly be pumped by this source, although in this case the power was coupled directly to the mixer block without a beamsplitter or interferometer, which is required for a mixer measurement in the present unbalanced configuration. A different, more powerful multiplier [11] source that produced 11 $\mu\text{W}$  (by calorimeter) was used in a subsequent measurement to allow the use of a 50  $\mu\text{m}$  thick Mylar beamsplitter (at 45 degrees angle to the beams with the polarization perpendicular to the plane of reflection). The measurement was made at an LO frequency of 1.462 THz, and with an L-band HEMT amplifier at 1.4 GHz that had an equivalent input noise temperature of 2.3 K. A separate Anritsu bias tee was used to DC bias the device. The highest Y-factor that was measured was 1.061 with calibration target temperatures of 77 K and 293 K, which gives an equivalent noise temperature of 3460 K double-sideband (DSB), see Fig.8 . We believe that this initial number can be improved by improvements in the optical setup such as using an interferometer in place of the beamsplitter, and by using lower-impedance devices that are better matched to the circuit. Also, a modest redesign of the circuit to shift the frequency of best (theoretical) coupling from 1.9 THz to 1.5 THz should contribute to lower input noise.

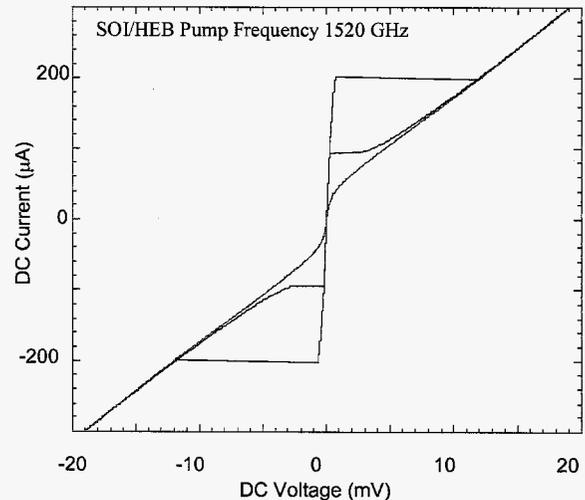


Fig. 7. An unpumped DC IV curve at together with one pumped at 1.5 THz by a JPL solid-state multiplier source. The temperature is 4.2 K.

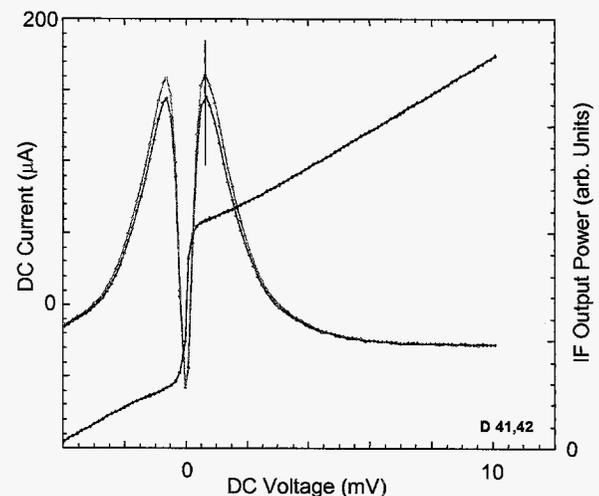


Fig. 8. An LO-pumped IV curve (1.462 THz) together with the detected IF output power at 1.4 GHz. The two power curves were measured with calibration loads at 293 K and 77 K, respectively. The vertical line marks the largest Y-factor response, corresponding to an equivalent noise temperature of 3460 K DSB.

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