Scalable Terahertz-Frequency HEB Mixers

F. Boussaha, J. Kawamura, J. Stern, A. Skalare, V. White

***Abstract*— We are developing low noise waveguide-based heterodyne mixer employing a superconducting NbN hot electron bolometer (HEB) operating around 2.7 THz. The mixer is an NbN nano-bridge integrated with a gold bowtie planar antenna on an ultra-thin silicon substrate of 3 μm thickness. To produce the waveguide embedding circuit for use at such a high frequency, we adopted an original approach combining UV-lithography and micro-plating techniques. The concept was successfully tested at a lower frequency (1.46 THz) where a low noise temperature is achieved. At 2.74 THz, we measured a minimum uncorrected DSB receiver noise temperature of 965 K.**

***Index Terms*—Hot Electron Bolometer, waveguide, gold microplating, heterodyne receiver.**

I. Introduction

JPL is developing waveguide mixers for operation at 1.5 THz [1] for the Stratospheric Terahertz Observatory (STO), a balloon-borne telescope to map a portion of our Galaxy in two key spectroscopic lines [2]. STO will have four spatial pixels per band, representing an incremental improvement from Herschel HIFI [3], which has two in orthogonal polarizations. Future instruments for missions like SOFIA [4] will require an order of magnitude more pixel elements to produce the required science data. Looking ahead to the future, we thus require scalability in terms of both pixel count and frequency. In increasing pixel count, an approach is to produce a filled focal plane array, for example, like a high-frequency version of Supercam, a 64-pixel 0.35 THz camera being built by the University of Arizona. Waveguide mixers offer a compact arrangement as well as the possibilities to implement more sophisticated mixer topology and integration with a local-oscillator source. However, simultaneously increasing the design frequency and pixel count we push conventional machining techniques beyond their practical limits.

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Recognizing this, we are investigating a lithographic microplating technique, pioneered for this application, for example, by Chalmers [5]. By utilizing microplating approach, we can mass-produce waveguide circuits with micron-level precision and nanometer wall smoothness. We compare a mixer produced entirely by conventional machining and a duplicate unit whose critical waveguide structures were fabricated using the microplating technique. At 1.5 THz the mixer performance is indistinguishable; both mixers gave a lowest uncorrected DSB receiver noise temperatures of 850 K were measured at around 1.45 THz (more details are presented elsewhere [1]). In this paper, we adopt the microplating technique for a higher frequency operation around 2.7 THz. This allows us to produce numerous waveguide circuits at low cost with excellent reproducibility.

II. Concept and design

Figure 1 depicts the basic mixer circuit utilized in this work. It consists of the mixer chip placed in a channel crossed by a waveguide which couples the RF signal from the feed antenna to the mixer. For producing the mixer chips, we use high-resistive silicon on insulator (SOI) substrate, which is compatible with nitride growth for NbN films [6]. The metallization and the HEB nanobridge are suspended at a distance corresponding to the substrate thickness t_{sub} plus an air-cavity depth $t_{cavity1}$ from the bottom. To realize the mixer block, we use a split-block configuration [7-8] consisting of a section with a feedhorn input ending with a rectangular waveguide (not shown) and a back section with the mixer chip in a waveguide circuit. In Fig. 1, the two pieces are shown to be separated by the XY plane.

The main challenge in manufacturing of the mixer block lies in the producing the channel with the small dimensions that holds the mixer. This can be regarded as the stack of 3 cavities whose dimensions are summarized in table 1. To address this issue, the channel is not machined directly on the back metal piece, but micro-plated onto a silicon wafer using deep-UV photolithography to define the structures. The dimensions of the silicon back-piece are also defined using lithography and deep-trench reactive ion etching. This backpiece is then inserted into a pocket precisely machined in the metal back piece. This approach allows accurate definition of smaller patterns since it is limited by lithography and not the machining technique. A key requirement of this approach is to ensure good alignment between the two pieces of the mixer. This is accomplished by utilizing high precision conventional machining where metrology of several microns can be readily achieved. Another important simplifying aspect of our approach is that, unlike several previous authors [9-14], we do not use a frame around the mixer chip or beam leads for handling and contacting. This greatly simplifies the fabrication thus increasing yield and reducing fabrication time. Also the use of a frame can make it difficult to thermally heat sink the mixer chip.

A. *HEB mixer device*

The mixer in fig. 1 is optimized using HFSS 3D electromagnetic simulator. The mixer chip is made up of a superconducting HEB nanobridge of ~ 4 nm-thick integrated along with a bowtie antenna which converts the waveguide TE_{10} EM field to RF currents and couples them to the HEB mixer. The antenna is connected to choke filters contacted by IF and DC bias leads. The optimization was carried out with a HEB resistance set to 80Ω. The silicon substrate is 22µm wide and 3µm thick. The channel into which is inserted the chip is crossed by a half height waveguide (HHWG) of 78x19 µm. The mixers are fabricated on 3-inch diameter SOI wafers. The top Si layer is high resistivity silicon nominally 3.0 µm thick, although the actual wafers were 2.5 µm on a 2 micron oxide layer and a 0.4 mm handle wafer. The NbN films have a sheet resistance of 1000 Ω and a critical transition temperature of T_c >9 K with a transition width of 0.5 K. Typical mixer chips were 1.5 by 0.2 µm with a resistance of 80-100 Ω. The fabrication process is described in [15].

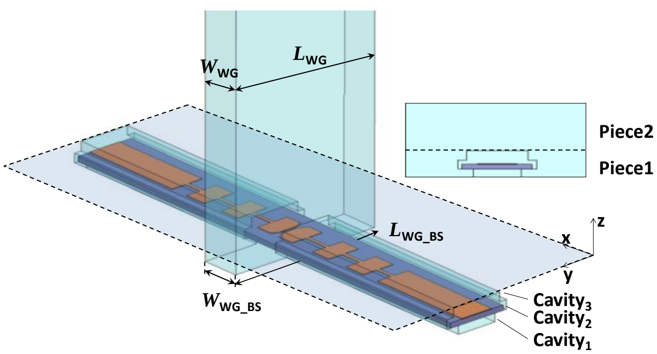

Figure 1: HEB Mixer structure designed at 1.46 THz then scaled up 2.7 THz. The plane XY materializes the mixer split-block concept which consists of a horn piece followed by the waveguide (L_{WG}, W_{WG}) and a back piece in which is defined a channel crossed by the waveguide backshort (L_{WG_BS}, W_{WG_BS}). The chip is inserted into the channel.

TABLE 1
2.7 THz channel dimensions

Cavity	t(µm)	*w*(µm)
1	5	26
2	3.5	40
3	5	26

B. *Mixer block*

The 2.7 THz mixer is essentially a scaled version of the 1.46 THz mixer. With the critical dimensions being reduced to nearly half-size (see Table 1), the critical element of the mixer circuit design cannot be readily produced by conventional machining. The mixer block consists of 3 pieces. A metal horn piece, realized by RPG Company [16], has a Pickett Potter horn ending a section of waveguide, a 2-mm-square silicon chip on which the mixer circuitry is printed and mixer mounted, and a metal back piece with a pocket to receive the silicon ship and an SMA connector on the back side. Figure 2 shows the electron microscope image of the micro-plated channel structure. This part consists of three layers of gold each with a nominal thickness shown in Table 1, crossed by a back short waveguide, with a lateral dimension of 78 x 19 µm. Each layer is defined by photolithography using GKR 4400 resist followed by a plating step (further fabrication process details are in [17]).

C. *Assembly*

The assembly process goes as follows: The chip is slid into the channel so that the center of the antenna is properly aligned in the middle of the waveguide, as shown in Fig. 3-a. Figure 3-b displays a close-up view of an electron micrograph showing how the mixer is precisely aligned in the waveguide. The electrical contact pads are contacted by means of ultrasonic wire bonding.

The silicon piece is inserted into the square pocket and the horn piece is clamped in place. The two sections are aligned to each using steel dowel pins, and the Si piece is aligned mechanically to the back piece by the perimeter of the pocket.

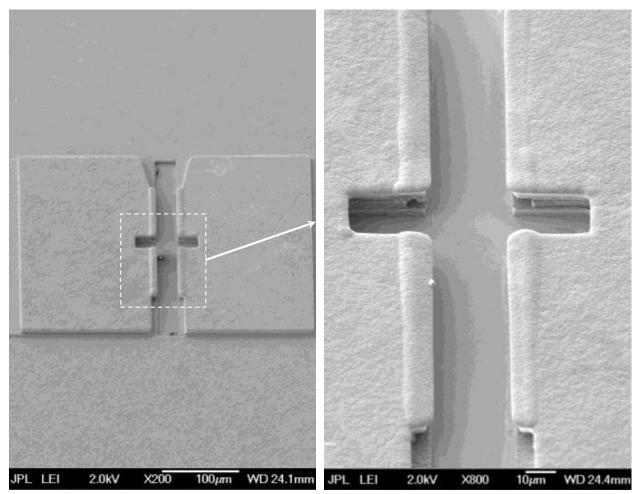

Figure 2: Electron microscope image of the channel structure consisted of stack of 3 gold layers of 5, 4 and 5 µm-thick, respectively and realized by means of the UV-photolithography and the micro-plating technique.

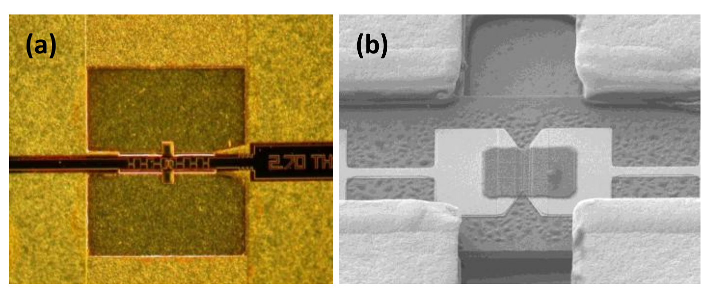

Figure 3: Optical microscope image (a) and electron microscope image (b) of the 2.7 THz mixer chip inserted in the channel. The HEB integrated along with the bowtie antenna is properly aligned in

the waveguide. An SiO_2 passivation layer covers the superconducting HEB nanobridge. The ultra-thin substrate (t≈2.3μm) is kept flat by the substrate channel.

The alignment may be verified on an assembled mixer by looking down the feed with a microscope. A circular spring is placed behind the silicon chip to ensure that it maintains physical contact to the horn section during deep cryogenic cooling (see fig. 3).

III. Experiment and Measurements

The mixer block is fixed on a 4.2 K cold plate of a liquid helium cryostat. The RF radiation passes the cryostat window, a 1 mm-thick sheet of high-density polyethylene, and the infrared filter, a layer of porous Teflon material on the liquid nitrogen-cooled radiation shield. The output signal at the intermediate frequency is amplified by a cryogenic low noise amplifier with an input noise temperature of 5 K, followed by a room-temperature amplifier and filtered for a final IF bandwidth centered at 1.5 GHz with a detection bandwidth of 500 MHz. The NbN nanobridge mixer device has a width of 2.5 and a length of 0.25 µm, with a normal state resistance of 84 Ω with a critical current of 120 µA. The current-voltage curves are plotted in Fig. 5.

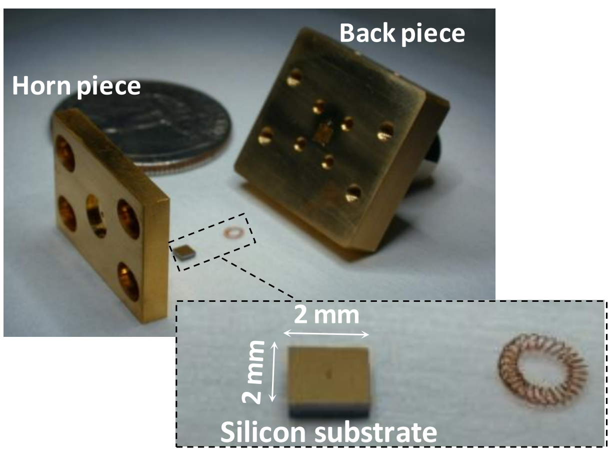

Figure 4: Picture of the mixer split-block consisting of a metal horn piece, a 2-mm square silicon chip holding the mixer, and a metal back piece with an SMA connector on its back side. The spring is placed behind the substrate to exert a force to push the chip against the horn piece.

The sensitivity of mixer is measured by terminating the input of the receiver with room temperature (T_{hot}=295 K) and liquid-nitrogen (T_{cold}=77 K) temperature loads. A molecular gas laser tuned at a frequency of 2.74 THz was used. The receiver noise temperature is computed using the expression $T_{rec}=(T_{eff,hot}-YT_{eff,cold})/Y-1$, where, according to the Callen-Welton formula [18], T_{hot} and T_{cold} become $T_{eff,hot}$ = 300 K and $T_{eff,cold}$ = 95 K, respectively, at 2.74 THz. There is so much LO power margin using the laser that the grid beam splitter angle was set to provide minimum LO port coupling (< 1%). In this set-up we measured a DSB receiver noise temperature of 965 ± 30 K (Y-factor of 1.19 ± 0.005).

These results are comparable to those measured based on quasi-optical mixer block employing a dielectric lens around 2.7 THz [19-21]. Yet we do not consider these values representing the ultimate sensitivity since it is done without any correction of optical losses. Therefore, we expect an improved noise temperature receiver using a vacuum receiver calibration setup.

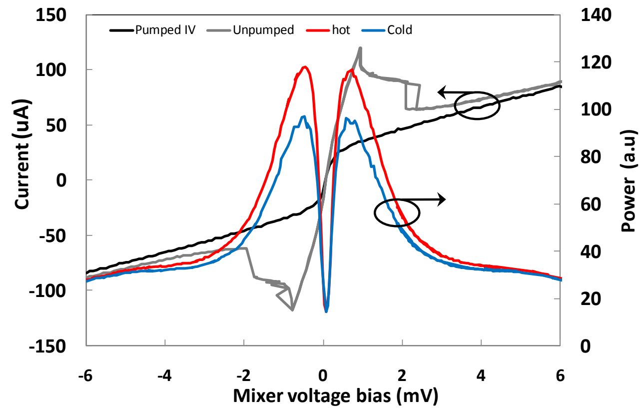

Figure 5: Unpumped and pumped *I-V* curves as well as output powers at intermediate frequency (IF) at hot (295K) and cold (77K) load temperatures at 2.74 THz.

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