SUPERCONDUCTIVE HOT ELECTRON MIXERS WITH ULTRA-WIDE RF BANDWIDTH FOR HETERODYNE RECEIVER APPLICATIONS UP TO 3 THz

W. R. McGrath*, A. Skalare, B. Karasik, M. Gaidis, B. Bumble, H.G. LeDuc
Center for Space Microelectronics Technology, Jet Propulsion Laboratory, California Institute of Technology, Mail Stop 168-314, 4800 Oak Grove Drive, Pasadena, California 91109, USA
**Email: rob@rob-mac.jpl.nasa.gov*

P.J. Burke, R.J. Schoelkopf, and D.E. Prober
Department of Applied Physics and Physics, Yale University, 15 Prospect Street, New Haven, Connecticut 06520-8284

S. Verghese, K.A. McIntosh, and E.R. Brown
Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02173-9108

Abstract; We report on the development of quasioptical Nb hot-electron bolometer mixers for heterodyne receivers at 1.2 THz and 2.5 THz. The devices have submicron in-plane sizes, thus exploiting diffusion as the electron cooling mechanism. Quasioptical mixer circuits have been developed with planar double-dipole or twin-slot antennas. Specially designed THz test systems which avoid atmospheric absorption were used in the experiments. The measured (DSB) receiver noise temperatures are 1900K at 1.2 THz, with an estimated mixer noise temperature of 950 K, and 2750 K at 2.5 THz, with an estimated mixer noise temperature of ≈ 900 K. These results demonstrate the low-noise operation of the diffusion-cooled bolometer mixer over a wide range of frequencies up to at least 2.5 THz.

Low noise heterodyne receivers are needed for astrophysical observations at frequencies between about 100 GHz and 3000 GHz. Nb SIS tunnel junction mixers provide excellent performance up to about the bulk superconductive energy gap frequency of 750 GHz, but are unlikely to work well much above 1 THz [1] (see fig. 1). A unique superconducting hot-electron bolometer (HEB) mixer has been proposed [2-3] as an alternative to address these high-frequency needs. The HEB mixer is expected to operate up to at least several 10's of THz, due to the relatively frequency independent absorption of rf radiation in a superconductor above the gap frequency. Theory [4] predicts the HEB mixer noise temperature due to intrinsic noise mechanisms to be as low as ~ 100 K, which is of the order of the quantum limit at THz frequencies. Also the required local oscillator (LO) power can be made very low (less than 100 nW for Nb *diffusion-cooled* devices) if the device size and sheet resistance are appropriately chosen. Two different approaches have been pursued to develop a practical HEB mixer. The first device approach employs an ultrathin (< 40 Å) NbN film where, due to the fast phonon escape, the mixer 3-dB IF signal bandwidth, f_{3db}, is determined by the intrinsic electron-phonon interaction time τ_{ep} to be $f_{3db} = 1/(2\pi\tau_{ep}) \approx$3-4 GHz [5]. The other major approach utilizes thicker (≈ 100 Å) low-resistive high quality Nb films, in which out-diffusion of electrons to normal metal contacts serves as the dominant electron cooling mechanism [3]. For Nb device lengths L less than 0.4 µm, useful IF bandwidths have been demonstrated in the range of 2-6 GHz [6-7].

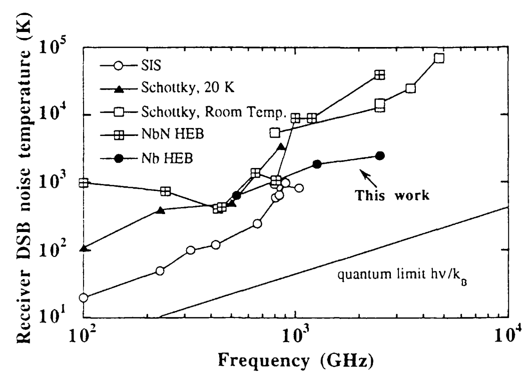

Fig. 1 Diffusion-cooled HEB receiver performance compared to state-of-the-art heterodyne receiver performance at submillimeter wavelengths.

We have developed and tested quasioptical *diffusion-cooled* HEB mixers at 1.2 THz and 2.5 THz in heterodyne receivers. Record sensitivity and IF bandwidth were obtained demonstrating the superiority of diffusion-cooled HEB mixers at THz frequencies. These results are described in detail elsewhere [7,8,9] and will be briefly summarized here.

Proceedings of the ESA Symposium 'The Far Infrared and Submillimetre Universe', 15-17 April 1997, Grenoble, France, ESA SP-401 (August 1997)

The bolometer devices used in these experiments consist of a 0.30 µm long by 0.15 µm wide microbridge made of a 12 nm thick sputtered-deposited Nb film. The length of the bridge was defined by the gap between the 150 nm thick gold contact pads using a unique self-aligned fabrication process [10]. The surrounding mixer embedding circuit and planar antenna are fabricated from 300 nm thick gold. This process gives automatic registration of the Nb under the gold to provide dependable electrical and thermal contact. Figure 2 shows an SEM of a completed device. The critical temperature of the device was about 6.5 K, the transition width was < 0.5 K, and the sheet resistance was 11-15 Ω/sq. The critical current density at 4.2 K was measured to be 1.5×10^7 A/cm^2.

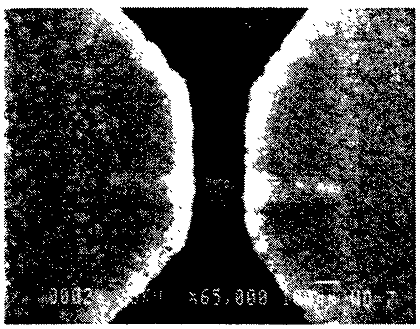

Fig. 2 SEM photo of a submicron Nb Microbridge bolometer.

Two different quasioptical mixer designs were used. For 1.2 THz, the mixer consisted of double-dipole antenna with coplanar strip transmission lines located at the focus of a quartz hyperhemispherical lens [8] (see fig. 3). The mixer embedding circuit for 2.5 THz used a twin-slot antenna and coplanar waveguide transmission line located at the second focus of an elliptical silicon lens [9] (see fig. 4). The receiver test system employed a CO_2-pumped FIR laser as a local oscillator (LO) source to generate power at 1267 GHz using difluorormethane gas, and at 2522 GHz using methanol. A vacuum box containing two blackbody loads with similar emissivities was designed and built for Y-factor measurements of the receiver noise temperature (see fig. 5). The box is connected to the LHe vacuum cryostat, allowing operation without a pressure window in the signal path. The box and cryostat are evacuated to remove the effect of atmospheric absorption which is significant above a THz. Thus accurate measurements of receiver noise are possible without any corrections applied. The 1.2 THz receiver used a 1.5 GHz IF, and the 2.5 THz receiver used 2.1 GHz IF.

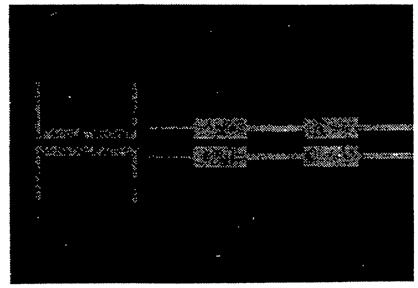

Fig. 3. Double-dipole antenna and coplanar transmission line embedding circuit and rf bandstop filter used at 1.2 THz. The Nb microbolometer is located in the center of the antenna circuit.

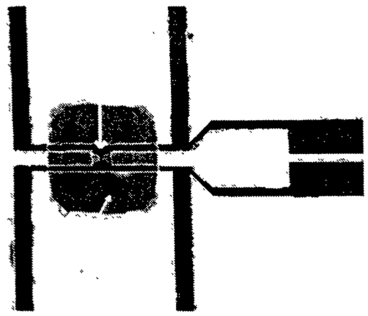

Fig. 4. 2.5 THz Planar mixer circuit consisting of the twin-slot antenna and coplanar waveguide transmission line. To the right are the IF and dc lines with an integrated rf choke filter.

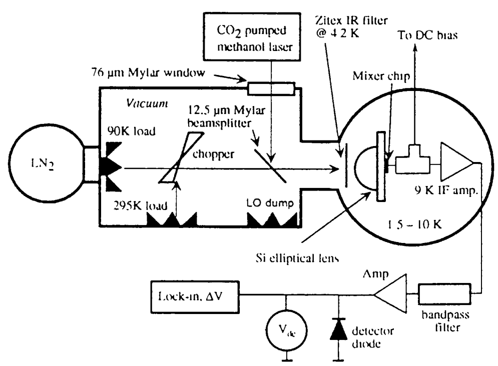

Fig. 5 Block diagram of 2.5 THz receiver test system.

Since these bolometer mixers use outdiffusion of hot electrons as the cooling mechanism, the thermal relaxation τ_{th} time should vary as L^2, where L is the device length, for devices shorter than about 0.5 µm [7]. Thus the 3-dB IF bandwidth $f_{3dB} = 1/(2\pi\tau_{th})$ should vary as L^{-2}. The IF bandwidth of several devices varying in length between 3µm and 0.08µm was measured in mixing experiments at frequencies between 4 to 20 GHz. As shown in Fig. 6, the bandwidth did vary as L^{-2}, with the largest bandwidth greater than 6 GHz for a device 0.08μm long. The mixer noise bandwidth however is generally greater than the signal bandwidth [4, 11], and recent measurements on the 0.08μm device indicate a noise bandwidth of greater than 8 GHz. This is the highest bandwidth ever measured for a bolometer mixer.

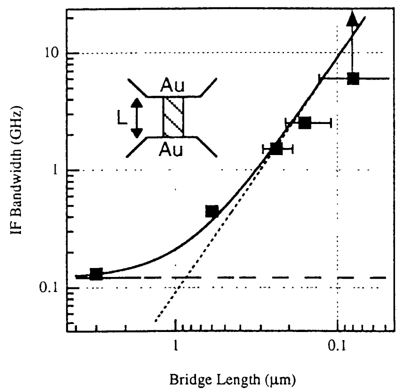

Fig. 6(b) Bandwidth vs length for devices with lengths: 3μm; 0.6μm; 0.24μm; 0.16μm; 0.08μm. Squares are the experimental data. Lines are the theoretical predictions showing the expected L-2 dependence for the diffusion cooled case (dotted line), the phonon-cooled case (dashed line), and the sum of both mechanisms (solid line).

The antenna frequency response was measured using a fourier transform spectrometer with the HEB operated as a direct detector. The detector response was corrected for the calculated frequency dependence of the beamsplitter in the spectrometer. The remaining frequency dependence is dominated by the antenna response. For the double-dipole antenna the center frequency is about 1100 GHz and the rf bandwidth is 730 GHz. For the twin slot antenna, the center frequency is about 1900 GHz and the 3-dB bandwidth is approximately 1.1 THz. These results conform with the expected performance for double-dipoles [12] twin-slots [13] and demonstrate that these antennas function well at THz frequencies.

Y-factor measurements give a noise temperature of 1880 K DSB for the 1.2 THz receiver [8]. The LO power absorbed in the HEB mixer was 6 nW (which is consistent with the relatively high impedance ≈ 140Ω of the device tested). To calculate the mixer noise, only the simplest and best measured corrections were made. If the IF amplifier noise of 6.3 K is eliminated, the remaining noise temperature is ≈ 1370 K, and if the small off-resonant antenna loss of ≈ 1.6 dB is taken into account (the antenna center frequency is 1100 GHz, while the LO was set to 1267 GHz), an upper limit of 950 K is arrived at for the mixer noise. For the 2.5 THz receiver, a best noise temperature of 2500-3000 K was obtained for an IF near 1.4 GHz. Again, if we remove the IF system noise and correct for the off-resonant antenna (center frequency is 1900 GHz as mentioned above) of 1.5 dB, an upper limit of about 900 K is obtained for the mixer at 2522 GHz. The absorbed LO power was about 80 nW. These results are the best reported for heterodyne receivers operated above 1 THz. Figure 7 shows these results along with our previous measurements at 530 GHz [6] and indicate that the mixer noise is independent of frequency over a range of 2 THz.

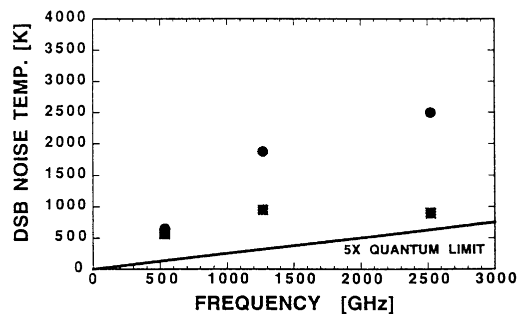

Fig. 7 HEB receiver (circles) and mixer (squares) noise temperature versus frequency for 3 different receivers. The mixer noise is essentially flat over a 2 THz frequency range. Simple improvements in antenna design, device impedance match, and use of anti-reflection coatings should result in at least a factor 2 improvement in receiver noise.

The HEB mixer fixed-tuned rf bandwidths of ≈ 50%, discussed above, are many times larger than SIS mixers since the rf impedance of the HEB device is almost purely resistive up to frequencies corresponding to electron-electron elastic scattering times (over 100 THz [3]). The HEB thus provides a broadband resistive match to the broadband planar antennas. To take advantage of such large rf bandwidths, a broadband LO source is needed. An LO using tunable diode lasers operating at 850 nm to drive a low-temperature-grown (LTG) GaAs photomixer is capable of generating microwatts of power, with 700 GHz of tunable range at frequencies up to about 3 THz [14,15]. The optical power P_0 from the lasers is focussed onto an inter-digitated "finger" structure approximately 8x8 μm^2 on the LTG-GaAs. The THz output power is radiated from a planar antenna connected to the fingers. However, the output power above 1 THz rolls off at about 12 dB per octive: 6 dB/octive from the carrier lifetime, and another 6 dB/octive from the parasitic capacitance of the fingers. One way to increase the THz output power is to increase the total optical power since the output power is proportional to P_0^2. Above $P_0 \approx 60$mW the photomixer fails due to thermal effects. Recent measurements on photomixers cooled to 77 K show that P_0 can be raised to 90 mW, achieving an output power of 0.2 µW at 2.5 THz [16]. We are currently working on integrating a photomixer LO with an HEB mixer to demonstrate the feasibility of an ultra-broadband heterodyne receiver.

In summary: Excellent performance of diffusion-cooled Nb HEB receivers has been demonstrated at 1.2 THz and 2.5 THz with noise temperatures of 1880K and 2750K respectively. The mixer noise performance is shown to be independent of frequency from 0.5 to 2.5 THz. The absorbed LO power is 80 nW or less. The ultra-wide rf bandwidths (up to 1 THz) of these HEB mixers when combined with a broadband photomixer LO allow for the first time the possibility of a single-channel heterodyne receiver with 700 to 1000 GHz of easily-tunable frequency range.

This research was performed by the Center for Space Microelectronics Technology, Jet Propulsion Lab, California Institute of Technology in collaboration with Yale University and Lincoln Laboratory with funding from NASA Office of Space Science, and the National Science Foundation.

[1] These data are borrowed from different sources: Schottky diode data are taken from the Proc. 7th Int. Symp. on Space Terahertz Technology (STT-7), University of Virginia, Charlottesville, VA, March 1996; most recent SIS data are from STT-7 and Ref. 11; NbN HEB data are from STT-6, STT-7, Ref. 5, J. Kawamura et al., J. Appl. Phys., vol. 80, pp. 4232-4234, October 1996; Appl. Phys. Lett., vol. 70, March 1997, and A.D. Semenov et al. Appl. Phys. Lett., vol.69, pp. 260-262, July 1996; Nb HEB data are from Ref's. 6, 8, & 9.

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