Low-noise Terahertz Waveguide Hot-Electron Bolometer Heterodyne Receiver

C.-Y. Edward Tong, Jonathan Kawamura, Raymond Blundell,

Gregory Gol'tsman, and Eugene Gershenzon

Abstract—We have developed a terahertz frequency fixed-tuned waveguide heterodyne receiver employing an NbN superconductive hot-electron bolometer mixer. Measurement with a Fourier transform spectrometer shows that the response is centered near 1.1 THz with a bandwidth of about 400 GHz. Since the required local oscillator (LO) drive is very low, we operate the receiver with all solid-state LO units, comprising of a Gunn oscillator followed by 2 stages of varactor multipliers. The mixer is operated at 4.2 K bath temperature. Noise measurements were performed using the standard Y-factor method with hot (295 K) and cold (77 K) loads at an intermediate frequency of 1.4 GHz. At 872 GHz, we measured a Y-factor of 1.36. At 1.035 THz and 1.26 THz, the Y-factors are 1.26 and 1.185 respectively.

Index Terms— Superconducting receiver, Hot-Electron Bolometer mixer, Terahertz techniques.

I. INTRODUCTION

In recent years, the superconductive hot-electron bolometer (HEB) mixer has emerged as the mixer of choice for the development of low-noise terahertz receivers. Many groups have reported very good noise performance at THz frequencies using superconductive HEB integrated with planar antennas [1-3]. At frequencies below 1 THz, however, the majority of high performance receivers operating in the field, e.g., as astronomical receivers, is based on waveguide technology. Although waveguide mounts for submillimeter wavelengths are difficult to produce, they are robust and also couple well to free space. Waveguide mounts have been successfully produced for use up to 2.5 THz [4,5].

Based on our experience developing superconductive HEB waveguide mixers for operation below 1 THz, we have built a version to operate above 1 THz. The THz mixer is essentially a scaled design of our highly successful 800 GHz superconductive HEB receiver that has been used at the 10 m Heinrich Hertz Telescope on Mt. Graham, Arizona, during the past 2 observing seasons [6,7]. This 800 GHz receiver was the first superconductive HEB receiver ever deployed in the field, outside the laboratory environment. It has been used successfully to detect molecular emission lines from a number of astronomical sources at 690 GHz and 810 GHz. It was also used to conduct astronomical observations for a number of projects.

II. INSTRUMENT DESIGN

A. Hot-electron bolometer elements

The mixer elements are made from high purity NbN film deposited on a heated 0.1 mm thick *Z*-cut crystalline quartz substrate. The film is about 4 nm thick. The critical temperature of the film varies between 7 and 9 K, with a transition width of about 0.5 K. The active area of the bolometer, lying between two normal conducting TiAu electrodes, is typically 2 μm wide and 0.2 μm long. The normal-state resistance (R_N) of the devices varies from batch to batch but is fairly uniform over a single wafer. We have recently introduced larger devices into the mask so that the quality of each wafer can be monitored. We have tested devices with R_N between 150 and 600 Ω, and critical current between 35 and 150 μA. The IF bandwidth of these devices is limited by a 3-dB roll-off frequency of about 2 GHz.

The quartz wafer is first diced into small blocks of about 5 mm square before being lapped and polished to a thickness of 23 μm. After final dicing, the mixer chip measures 90 μm wide and 1.4 mm long. Even with these small dimensions the mixer chips are quite robust and are rather easy to handle.

B. Mixer block design

The mixer block is made in two sections. The front section carries the corrugated feed horn, which is electroformed and soldered into a copper mounting block. The corrugations are 46 μm wide and 76 μm deep, and the pitch is 100 μm. This horn produces a 25-degree wide beam at the –10 dB points at 1.26 THz. The back section houses a short section of half-height waveguide, 200 x 50 μm. Two blocks with different waveguide backshort lengths have been built and tested. The quartz chip is suspended across the waveguide and is clamped between the two halves of

---

C.-Y. Edward Tong and Raymond Blundell are with the Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA.

Jonathan Kawamura is with the California Institute of Technology, 320-47, Pasadena, CA 91125, USA.

Gregory Gol'tsman and Eugene Gershenzon are with the Moscow State Pedagogical University, Moscow, 119435 Russia.

the mixer block. It is electrically contacted by two 75 μm diameter wires to the IF connector and the ground.

C. Receiver layout

The layout of the receiver is shown in Fig. 1. The mixer block is housed in a liquid helium-cooled cryostat equipped with a liquid nitrogen-cooled radiation shield. The corrugated feed illuminates a 30-degree off-axis parabolic mirror positioned near the center of the dewar cold plate. The beam reflected off the paraboloid passes through several layers of infrared blocking filters, made from porous Teflon sheets, at 4.2 and 77 K. A 0.5 mm thick TPX sheet is used as the vacuum window.

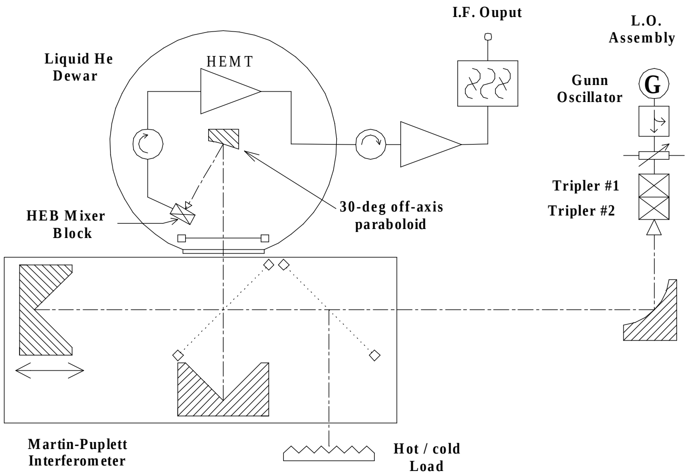

Fig. 1 Layout of the Receiver. The mixer block, isolator, parabolic mirror, and HEMT amplifier are mounted on the 4.2 K cold plate. The MPI is placed in front of the cryostat window, and is at room temperature. The optical path from the vacuum window to the load is approximately 0.5 m.

Radiation from the LO assembly is collimated by a 90 degree off-axis parabolic mirror before combining with the signal beam from the hot/cold load in a Martin-Puplett interferometer (MPI) placed in front of the cryostat vacuum window. The interferometer employs free-standing wire grid polarizers with 10 μm diameter wire at a 40 μm pitch. The polarizer should be highly efficient up to several THz. The insertion loss of the MPI is estimated to be about 1 dB.

The mixer is connected to a 1.5 GHz HEMT amplifier, mounted on the same cold plate, through a bias tee and an isolator. After a second-stage room temperature amplifier, the IF signal is fed through a 200 MHz wide bandpass filter centered at 1.4 GHz. The total power is measured by a calibrated power meter.

D. Local oscillator sources

Because the bolometer elements are small, they require very low LO drives. We estimate that, at the optimal operating point of the mixer, the incident LO power at the LO port of the MPI is less than 1 μW. With some care in the optics design, we were able to provide sufficient LO power using all solid-state LO units, which comprise of a Gunn oscillator followed by 2 stages of varactor multipliers [8]. Table 1 lists the LO units which were available for our measurements. These units allow us to make measurements continously from 780 GHz to 960 GHz, and at point frequencies near 1035 and 1260 GHz. At our highest measurement frequency of 1.26 THz, the available LO power is 2.5 μW. Even with this scarce amount of LO power, we were able to pump the mixer with power to spare.

Frequency Range (GHz)	Gunn Frequency (GHz)	Gunn Power (mW)	Mult. Stages (first, second)	Peak Output Power (μW)
780-840	130-140	25-40	x2, x3	10-50
842-960	107-120	25-40	x2, x4	-
990-1044	110-116	30-50	x3, x3	~10
1260-1278	140-142	25-30	x3, x3	2.5

Table 1. Available solid-state local oscillator sources.

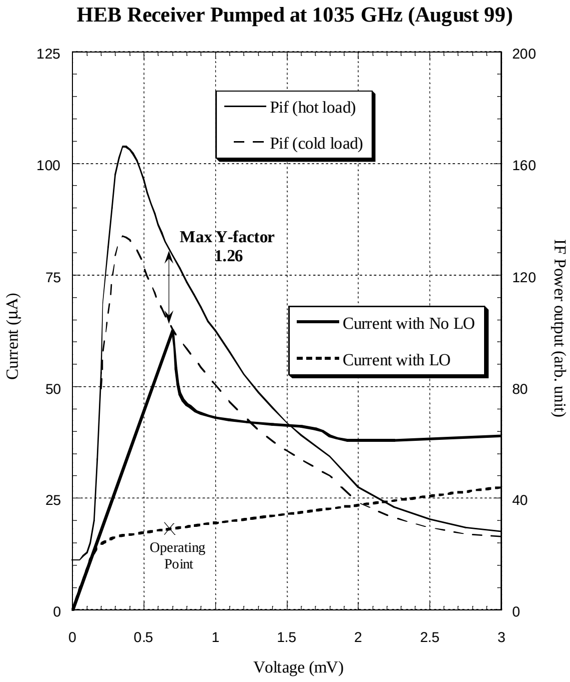

Fig. 2 Current-voltage characteristics of an HEB mixer element, with and without LO drive at 1.035 THz at a bath temperature of 4.2 K. Also shown is the receiver IF power as a function of bias voltage in response to the hot (295 K) and cold (77 K) loads. The normal state resistance of the mixer element is 150 Ω and the critical current is about 60 μA.

III. MEASURED PERFORMANCE

The current-voltage characteristics of a mixer is plotted in Fig. 2. The figure also shows the heterodyne response to the hot and cold loads at an LO frequency of 1.035 THz. At this frequency, a Y-factor of 1.26 was obtained at a bias voltage of 0.7 mV and a bias current of 18 μA. The double-side-band conversion loss at this operating point is estimated to be 12 dB. The Y-factor as a function of LO frequency is plotted in Fig. 3.

The spectral response of this mixer was measured with a Fourier transform spectrometer (FTS), using the mixer element as a direct detector. In this measurement, no LO power is applied, but the mixer is operated at an elevated bath temperature so that the mixer DC bias is set at the same point as that used for optimal heterodyne performance. Though the general shape of the spectral response does not appear to depend too strongly on the bias point, the mixer is most sensitive near this operating point. Fig. 3 shows the spectral response measured with the FTS together with the heterodyne spectral response. Not surprisingly, the heterodyne sensitivity closely traces the spectral response measured with the FTS. The data shows that this mixer has an input bandwidth of about 400 GHz, centered near 1.1 THz. Other mixers tested exhibit similar bandwidths, although the center frequency may shift by 10 – 15 % depending on the length of the backshort and the reactance of the RF filter.

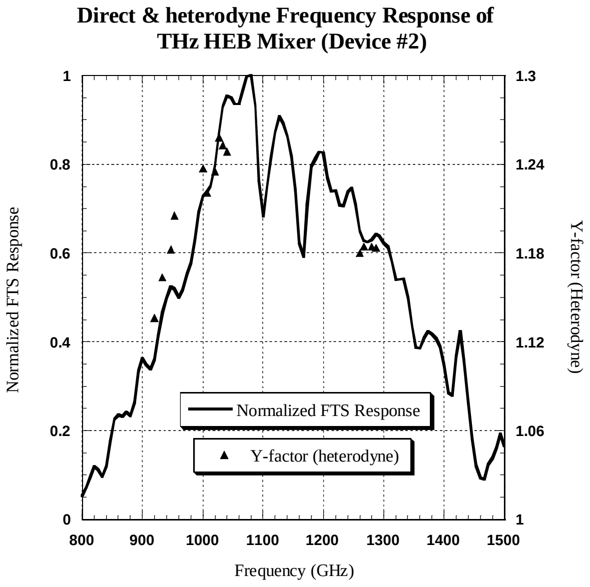

Fig. 3. Spectral response of the HEB mixer as measured by an FTS in direct detection mode and in heterodyne mode using the hot/cold method. Note that the notches at 1.1 and 1.16 THz are produced by saturated water lines over an air path of about 5 cm in the FTS setup.

The receiver is not affected by saturation and direct detection effects. From the total power-voltage curve in Fig. 2 and our estimate for the conversion loss, we estimate that the mixer would require about 10 nW at the input to be driven into output saturation. This value is significantly higher than the power from incident thermal radiation of an ambient load with an IF bandwidth of ~2 GHz. At the same time, the incident radiation from an ambient load with 400 GHz bandwidth is still an order of magnitude smaller than the required LO power. Thus, direct detection effects are also expected to be minimal. At the optimal operating point given in Fig. 2, the bias current changes by 60 nA, or about 0.3 %, when switching between hot and cold loads, when the bias voltage is kept constant. When the MPI is replaced by a beam splitter, the change in bias current is approximately doubled because the MPI admits only half of the bandwidth of the incident thermal radiation from the hot and cold loads. In all our measurements, bias current changes due to direct detection are less than 1%.

The presence of direct detection in general means that the noise temperature deduced from the measured Y-factor will not correspond to the actual heterodyne sensitivity of the receiver. For our receiver, we estimate that the uncertainty in noise temperature introduced by direct detection effect is typically less than 5%.

In Fig. 4, we have plotted the noise temperature calculated from the measured Y-factor as a function of LO frequency for two devices. Mixer 1 is most sensitive around 872 GHz where the noise temperature is 550 K. For mixer 2, the best noise temperature is 760 K at 1.035 THz. The noise temperature rises to 1100 K at 1.26 THz. These noise temperatures approach 10 *h*ν/*k*.

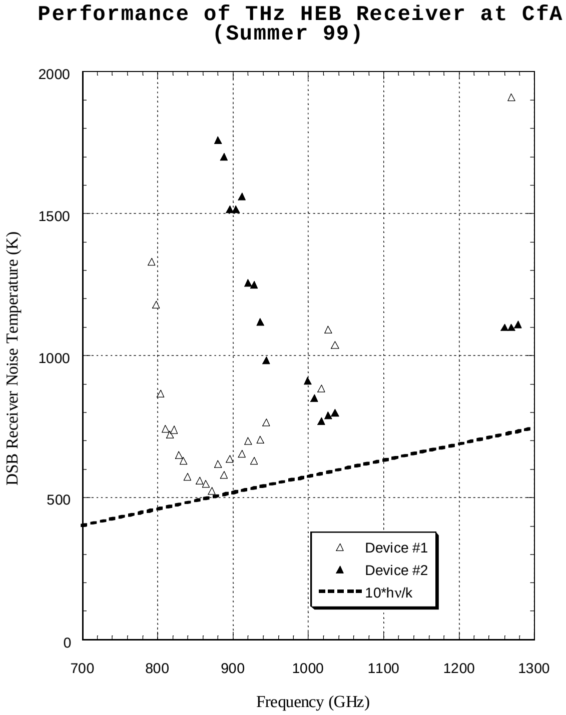

Fig. 4. Double sideband receiver noise temperature for 2 mixers with different mixer elements. For both mixers, the sensitivity closely follows the spectral response measured with an FTS.

IV. SUMMARY

In conclusion we have developed and characterized a terahertz frequency superconductive HEB waveguide receiver. The LO power was supplied by solid state sources. The sensitivity is excellent, and between about 0.85 to 1.05 THz, the performance of this receiver is superior to that of the best Nb-based SIS mixers [9]. We do not anticipate any significant technical difficulty in scaling this technology up to 2.5 THz.

[1] B. S. Karasik, M. C. Gaidis, W. R. McGrath, B. Bumble, and H. G. LeDuc, “Low noise in a diffusion-cooled hot-electron mixer at 2.5 THz,” *Appl. Phys. Lett.*, vol. 71, pp. 1567-1569, 1997.

[2] P. Yagoubov, M. Kroug, H. Merkel, E. Kollberg, G. Gol’tsman, S. Svechnikov, and E. Gershenzon, “Noise temperature and local oscillator power requirement of NbN phonon-cooled hot-electron bolometric mixers at terahertz frequencies,” *Appl. Phys. Lett.*, vol. 73, pp. 2814-2816, 1998.

[3] K. S. Yngvesson, E. Gerecht, C. F. Musante, Y. Zhuang, T. Goyette, J. Dickinson, J. Waldman, P. A. Yagoubov, G. N. Gol’tsman, B. M. Voronov, and E. M. Gershenzon, “Low-noise HEB heterodyne receivers and focal plane arrays for the THz regime using NbN,” to be published in *Proc. SPIE*, vol. 3795 (Terahertz and Gigahertz Photonics), 1999.

[4] B. N. Ellison, B. J. Maddison, C. M. Mann, D. N. Matheson, M. L. Oldfield, S. Marazita, T. W. Crowe, P. Maaskant, and W. M. Kelly, “First results for a 2.5 THz Schottky diode waveguide mixer,” *Proc. Seventh Int. Symp. Space Terahertz Tech*., pp 494-502, 1996

[5] P. H. Siegel, R. P. Smith, M. C. Gaidis, and S. C. Martin, “2.5 THz GaAs monolithic membrane-diode mixer,” *IEEE Trans. MTT*, vol. 47, 596-604, 1999.

[6] J. Kawamura, C.-Y. E. Tong, R. Blundell, D. C. Papa, T. R. Hunter, G. Gol’tsman, S. Cherednichenko, B. Voronov, and E. Gershenzon, “An 800 GHz NbN phonon-cooled hot-electron bolometer mixer receiver,” *IEEE Trans. Appl. Superconductivity*, vol. 9, pp. 3753-3756, 1999.

[7] J. Kawamura, R. Blundell, C.-Y. E. Tong, D. C. Papa, T. R. Hunter, S. N. Paine, F. Patt, G. Gol’tsman, S. Cherednichenko, B. Voronov, and E. Gershenzon, “Superconductive hot-electron bolometer mixer receiver for 800 GHz operation,’’ to appear in *IEEE Trans. MTT*, 1999.

[8] C.-Y. E. Tong, R. Blundell, D. C. Papa, M. Smith, J. Kawamura, G. Gol’tsman, E. Gershenzon, and B. Voronov, “An all solid-state superconducting heterodyne receiver at terahertz frequencies,” *IEEE Microwave and Guided Wave Lett.*, vol. 9, pp. 366-368, 1999.

[9] M. Bin, M.C. Gaidis, J. Zmuidzinas, T. G. Phillips, and H. G. LeDuc, “Low-noise 1 THz niobium superconducting tunnel junction mixer with normal metal tuning circuit,” *Appl. Phys. Lett.*, vol. 68, pp. 1714-1716, 1996.