Superconductive hot-electron mixers for terahertz heterodyne receiver applications

William McGrath, Anders Skalare, Boris Karasik, Michael Gaidis, Bruce Bumble, et al.

William R. McGrath, Anders J. Skalare, Boris S. Karasik, Michael C. Gaidis, Bruce Bumble, Henry G. LeDuc, P. J. Burke, R. Schoelkopf, D. E. Prober, "Superconductive hot-electron mixers for terahertz heterodyne receiver applications," Proc. SPIE 3357, Advanced Technology MMW, Radio, and Terahertz Telescopes, (31 July 1998); doi: 10.1117/12.317341

Event: Astronomical Telescopes and Instrumentation, 1998, Kona, HI, United States

Superconductive Hot Electron Mixers for THz Heterodyne Receiver Applications

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

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

ABSTRACT

We report on the development of quasioptical Nb hot-electron bolometer mixers for heterodyne receivers operating at 1 THz - 3 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. The measured (DSB) receiver noise temperatures are 1670 K at 1.1 THz, with an estimated mixer noise temperature of ≈ 1060 K, and 2750 K at 2.5 THz, with an estimated mixer noise temperature of ≈ 900 K. The IF bandwidth is found to scale as the length-squared, and bandwidths as high as 8 GHz have been measured. These results demonstrate the low-noise, broadband operation of the diffusion-cooled bolometer mixer over a wide range of far-infrared wavelengths.

Keywords: submillimeter, heterodyne, mixer, hot electron bolometer, terahertz, superconductor, far infrared

Low noise heterodyne receivers are needed for astrophysical and earth remote-sensing observations at frequencies between about 100 GHz and 3000 GHz (3000 μm to 100 μm wavelength). Niobium (Nb) SIS quasiparticle mixers provide excellent performance up to about the bulk superconductive energy gap frequency f_g of 750 GHz, but are unlikely to work well much above 1 THz (see fig. 1) [1]. A unique superconducting transition-edge hot-electron bolometer (HEB) mixer has been proposed[2,3] as an alternative to address the THz-regime applications. 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. The rf impedance of a superconducting microbridge is expected to be real and independent of frequency from about f_g up to a frequency corresponding to the inverse electron-electron elastic scattering time (about 10^{-15} sec in thin Nb films) which is approximately 160 THz ($\lambda \approx 3$ μm)[3]. Theory[4] predicts the HEB mixer noise temperature due to the intrinsic thermal-fluctuation 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 is independent of frequency and can be made very low (less than 100 nW for Nb *diffusion-cooled* devices) for appropriate choice of transition temperature T_c and film sheet resistance. Two different approaches have been pursued to develop a practical HEB mixer. The first device approach employs an ultrathin (≤ 30 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 $f_{3db} = 1/(2\pi\tau_{ep}) \approx 3\text{-}5$ GHz[5]. The other major approach utilizes thicker (≈ 100 Å) low-resistivity, 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].

We have successfully developed and tested quasioptical *diffusion-cooled* HEB mixers at 1.1 THz and 2.5 THz in heterodyne receivers. Record sensitivity and IF bandwidth were obtained demonstrating the advantages of diffusion-cooled HEB mixers at THz frequencies. These results are described here (see recent publications[7,8,9] for additional details).

Further author information:
WRM(correspondence): Email: rob@rob-mac.jpl.nasa.gov; Tel: 818-354-8542; FAX: 818-393-4683

Part of the SPIE Conference on Advanced Technology MMW, Radio, and Terahertz Telescopes
Kona, Hawaii • March 1998 SPIE Vol. 3357 • 0277-786X/98/$10.00

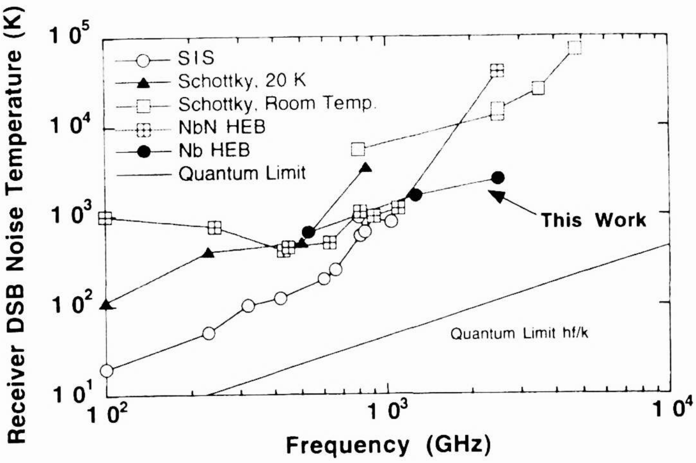

Fig. 1 Diffusion-cooled HEB receiver performance compared to state-of-the-art heterodyne receiver performance at submillimeter wavelengths.

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. This fabrication process produced excellent device parameters: critical temperatures T_c in the range 4.5 K to 6.5 K (for these films, the thickness ≈ 12 nm is smaller than the coherence length $\zeta \geq 40$ nm, and thus T_c is suppressed compared to the bulk value of ≈ 9 K); transition width ≤ 0.3 K; and sheet resistance 10-80 Ω/sq. The critical current density at 4.2 K was as high as 1.5×10^7 A/cm^2.

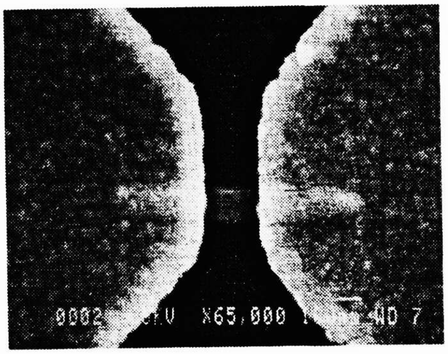

Fig. 2 SEM photo of a submicron Nb microbridge bolometer.

Two different quasioptical mixer designs were developed. For 1.1 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 either a backward wave oscillator operating at 1105 GHz as a local oscillator (LO) source, or a CO_2-pumped FIR laser to generate LO power at 2522 GHz using methanol vapor. 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 1 THz. Thus accurate measurements of receiver noise are possible without any corrections applied. The 1.1 THz receiver used a cooled HEMP IF amplifier centered at 1.5 GHz, and the 2.5 THz receiver used an amplifier centered at 2.1 GHz.

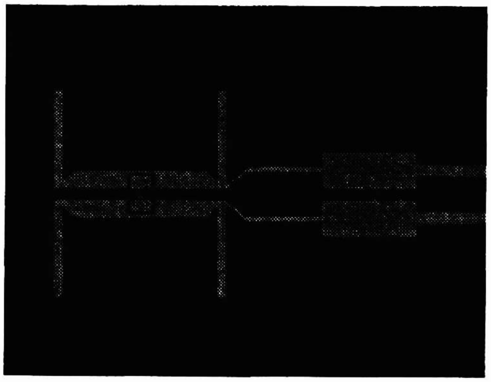

Fig. 3. Double-dipole antenna and coplanar strip line (CPS) embedding circuit and rf bandstop filter used at 1.1 THz. The Nb microbolometer is located in the center of the CPS embedding circuit.

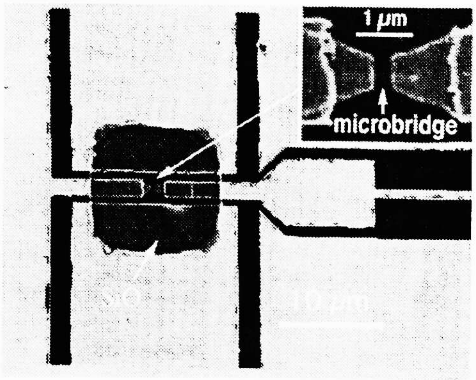

Fig. 4. 2.5 THz Planar mixer circuit consisting of the twin-slot antenna and coplanar waveguide transmission line. To the right are the IF and dc lines with an integrated rf choke filter.

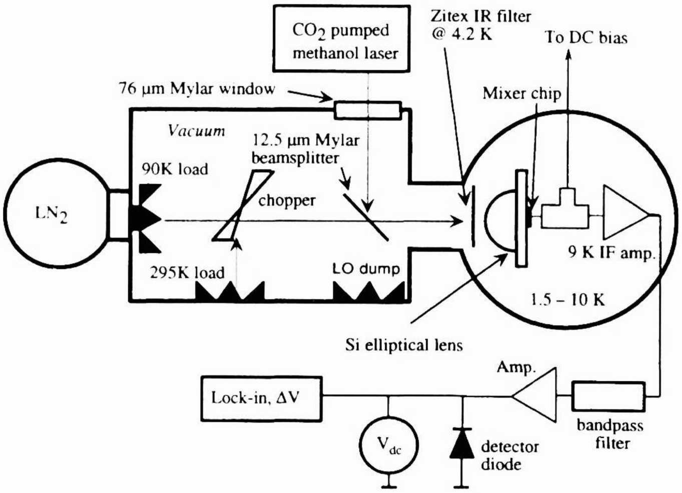

Fig. 5 Block diagram of 2.5 THz receiver test system.

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 microbridge length, for devices shorter than about 0.5 μm[7]. The thermal response time can be calculated from the expression: $\tau_{th} = L^2 / \pi^2 \bullet D$, where D is the thermal diffusivity of the film. This expression results from solving for the transient solution of the differential equation for a time-dependent heat flow in the microbridge[11]. 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[7]. As shown in Fig. 6, the bandwidth did indeed vary as L^{-2}, with the largest bandwidth greater than 7 GHz for a device 0.08μm long. The mixer noise bandwidth however is generally greater than the signal bandwidth[4,12], and recent measurements on the 0.08 μm device indicate a noise bandwidth of greater than 8 GHz. This is the highest bandwidth ever measured for a low-noise bolometer mixer.

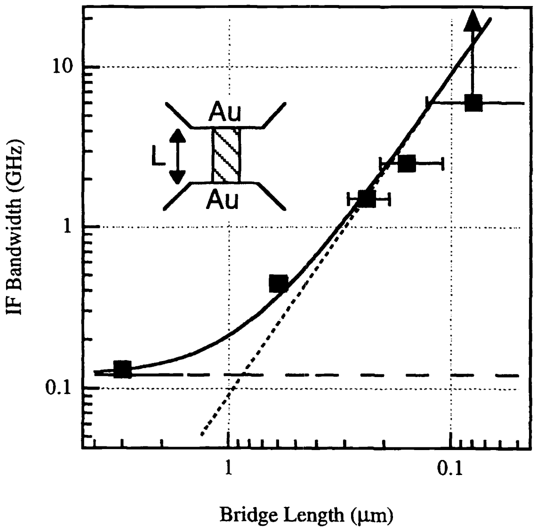

Fig. 6. Bandwidth vs length for devices with lengths: 3μm; 0.6μm; 0.24μm; 0.16μm; 0.08μm. Squares are the experimental data. Lines are the theoretical predictions showing the expected L^{-2} dependence for the diffusion cooled case (dotted line), the phonon-cooled case (dashed line), and the sum of both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

We have also recently confirmed that the IF signal bandwidth of the diffusion-cooled HEB mixer agrees with the frequency dependence of the IF impedance [13]. Measurements of the IF impedance were made within a 0.05-4 GHz frequency range. It has been demonstrated experimentally for phonon-cooled Nb[14,15] and NbN[16] devices that the HEB impedance changes from a high differential resistance value at low frequencies to a lower ohmic resistance R at high frequencies. The crossover occurs at the frequencies related to the intrinsic electron temperature relaxation time, τ_T. Thus, a measurement of the HEB impedance versus frequency allows τ_T to be determined. The mixer bandwidth, f_{3dB}, is then given by:

$$f_{3dB}^{-1} = \frac{\tau_T}{1 + C\frac{R - R_L}{R + R_L}}, \qquad (1)$$

where R_L is the IF load (50 Ω), and C is the self-heating parameter.

For these measurements, a 0.3 μm long device with small contact pads was mounted in a gap in the center conductor of a microstrip transmission line fabricated on 0.5 mm thick Duroid with dielectric constant 10.2. The transmission line test fixture was placed in a LHe dewar and connected through semirigid cables to an HP8510 network analyzer to measure the S_{21} parameter (This approach does not have the shortcomings of S_{11} measurements. See ref. 13 for details of this novel technique). The rf power level for testing was greatly attenuated to avoid any influence of the test signal on the device resistive state. Calibrations were done with the HEB device in the superconductive state ($Z \approx 0$) and normal state ($Z = R_n$). This allowed the HEB IF impedance to be de-imbedded from the microstrip test fixture[13]. According to theory[4] the HEB impedance is given by

$$Z(\omega) = R\frac{1 + C}{1 - C}\,\frac{1 + j\omega\frac{\tau_T}{1 + C}}{1 + j\omega\frac{\tau_T}{1 - C}}. \qquad (2)$$

Large values of the parameter C are required in order to observe a pronounced frequency dependence of the impedance. Equivalently, the device has to be biased to the operating point with a large differential resistance. In the experiment this was accomplished by heating the device to a temperature above 4.2 K. Figure 7 shows the Z(f) dependence (both real and imaginary parts) along with the fitted curves from the equation (2) above. The associated mixer bandwidth is found to be $f_{3dB} = 1.4$ GHz. This quantity is in good agreement with the bandwidth measurements[7] discussed above.

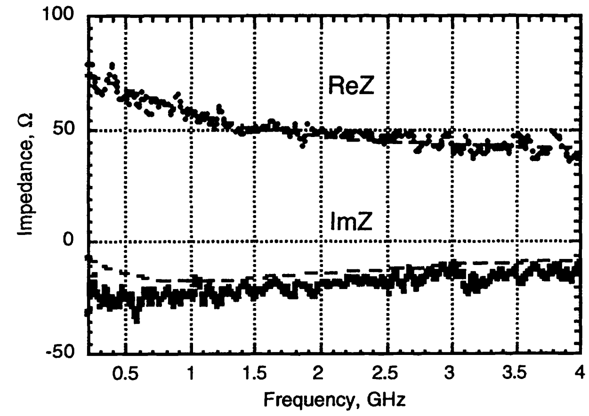

Fig. 7. HEB IF impedance for a 0.3 μm long microbridge. The dashed lines are the fit with C = 0.3

The mixer antenna frequency response was measured using a Fourier Transform Spectrometer (FTS). For this measurement, the HEB device operating temperature was set to a value near T_c, and the bias voltage was adjusted to obtain a large direct-detection response in the bolometer. 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 980 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 (see fig. 8). These results agree with the expected performance for double-dipoles[17] and twin-slots[18] and demonstrate that these antennas still function well up to 2.5 THz.

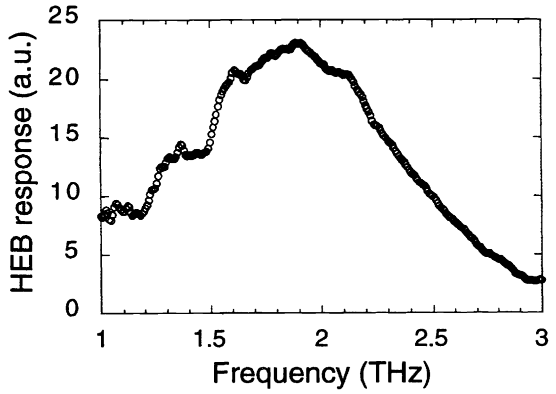

Fig. 8. FTS spectrum measured for the 23 Ω HEB, corrected for the calculated 23 μm FTS beamsplitter efficiency. The HEB was operated as a direct detector.

Y-factor measurements give a noise temperature of 1670 K DSB for the 1.1 THz receiver[8]. 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 ≈ 1230 K; and if the small off-resonant antenna loss of ≈ 0.63 dB is taken into account (the antenna center frequency is 980 GHz, while the LO was set to 1104 GHz), an upper limit of 1060 K is arrived at for the mixer noise (this "mixer noise" includes the beamsplitter loss which contributes at least another 0.5 dB. Removing this loss would imply a mixer noise of ≤ 950 K). 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 LO power absorbed in the device was about 80 nW, and the total *mixer* LO requirement is estimated to be 420 nW (this accounts for the ≈ 7.2 dB of optical and embedding circuit losses, estimated from the FTS measurements[9]). These results at 2.5 THz are 5-times lower noise and 10^4-times lower LO power than competing technologies. Figure 9 summarizes these results along with our previous measurements at 530 GHz[6] and demonstrates that the HEB mixer noise is nearly <u>independent</u> of frequency over a range of at least 2 THz.

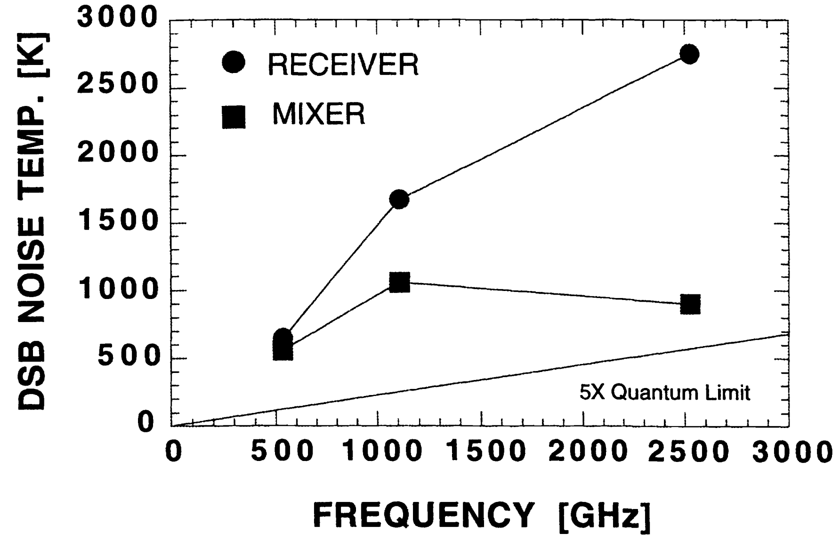

Fig. 9. HEB receiver (circles) and mixer (squares) noise temperature versus frequency for 3 different receivers. The mixer noise is essentially flat over a 2 THz frequency range.

Straightforward 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. Thus receiver noise temperature less than about 1000 K should be readily possible up to 3 THz using Nb devices. In addition, since the mixer noise temperature and LO power are both proportional to T_c (for an optimized mixer), even lower noise temperatures are possible using lower T_c materials. Aluminum films have a $T_c \approx 1.7$ K; and the sheet resistance (10 - 50 Ω/sq) and diffusion constant ($D \geq 10$) make it a suitable candidate for a diffusion-cooled HEB mixer. A factor 4 reduction in noise temperature and LO power over a Nb HEB may be possible. We are currently investigating this material.

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 (using spiral antennas, mixer bandwidths of several octaves should be possible. However, saturation by background radiation will become important in such broadband detectors). To take advantage of such large instantaneous rf bandwidths, a broadband tunable LO source is needed. A *photomixer* LO is a promising candidate technology[19,20,21], and would allow for the possibility of an ultra-broadband heterodyne receiver.

SUMMARY

Excellent performance of diffusion-cooled Nb HEB receivers has been demonstrated at 1.1 THz and 2.5 THz with noise temperatures of 1670K and 2750K respectively. The mixer noise performance is shown to be independent of frequency from 0.5 THz 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 if combined with a broadband photomixer LO would allow for the first time the possibility of a single-channel heterodyne receiver with 700 to 1000 GHz of easily-tunable frequency range.

ACKNOWLEDGEMENT

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

REFERENCES

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.
2. E.M. Gershenzon, G.N. Gol'tsman, I.G. Gogidze, Y.P. Gusev, A.I. Elant'ev, B.S. Karasik, and A.D. Semenov, "Millimeter and submillimeter range mixer based on electronic heating of superconducting films in the resistive state," *Sverhprovodimost' (KIAE),* vol. 3(10), pp. 2143-2160, October 1990 [*Sov.Phys. Superconductivity*, vol. 3(10), pp. 1582-1597, 1990].
3. D.E. Prober, "Superconducting terahertz mixer using a transition-edge microbolometer," *Appl. Phys. Lett.* vol. 62(17), pp. 2119-2121, 26 April 1993.
4. B.S. Karasik and A.I. Elantiev, "Noise temperature limit of a superconducting hot-electron bolometer mixer," *Appl. Phys. Lett.*, vol. 68, pp. 853-855, February 1996; "Analysis of the noise performance of a hot-electron superconducting bolometer mixer," *Proc. of the 6th Int. Symp. on Space Terahertz Technology*, 21-23 March 1995, Caltech, Pasadena, pp. 229-246.
5. H. Ekström, E. Kollberg, P. Yagubov, G. Gol'tsman, E. Gershenzon, S. Yngvesson, "Gain and noise bandwidth of NbN hot-electron bolometric mixers," *Appl. Phys. Lett.* vol. 70, pp. 3296-3298 (1997).
6. A. Skalare, W. R. McGrath, B. Bumble, H. G. LeDuc, P. J. Burke, A. A. Verheijen, R. J. Schoelkopf, and D.E. Prober, "Large bandwidth and low noise in a diffusion-cooled hot-electron bolometer mixer," *Appl. Phys. Lett.*, vol. 68, pp. 1558-1560, March 1996.
7. P.J. Burke, R.J. Schoelkopf, D.E. Prober, A. Skalare, W.R. McGrath, B. Bumble, and H.G. LeDuc, "Length scaling of bandwidth and noise in hot-electron superconducting mixer," *Appl. Phys. Lett.*, vol. 68, pp. 3344-3346, June 1996.
8. A. Skalare, W.R. McGrath, B. Bumble, H.G. LeDuc, "Heterodyne hot electron mixers at 1.1 THz", to be submitted to Applied Physics Letters, 1998; Also see the following for details of HEB mixer measurements at 1.2 THz, including details of the mixer and receiver design. These measurements were made with a high resistance device which showed some effects due to loading by background radiation: A. Skalare, W.R. McGrath, B. Bumble, H.G. LeDuc, "Receiver measurements at 1267 GHz using a diffusion-cooled superconducting transition-edge bolometer" *IEEE Trans. Applied Superconductivity* 7, no. 2, pp. 3568-3571 (1997).
9. B.S. Karasik, M.C. Gaidis, W.R. McGrath, B. Bumble, H.G. LeDuc, " Low noise in a diffusion-cooled hot-electron mixer at 2.5 THz", *Applied Physics Letters* 71, 1567 (1997).
10. B. Bumble and H.G. LeDuc, "Fabrication of a diffusion cooled superconducting hot electron bolometer for THz mixing applications", *IEEE Trans. Applied Superconductivity*, 7, no. 2, pp. 3560-3563 (1997).
11. F.B. Hildebrand, *Advanced Calculus for Applications*, pp.449-454, Prentice-Hall, Inc., Englewood Cliffs, New Jersey (1962).

12. R.J. Schoelkopf, P.J. Burke, D.E. Prober, B. Karasik, A. Skalare, W.R. McGrath, M.C. Gaidis, B. Bumble, H.G. LeDuc, "Noise bandwidth of diffusion-cooled hot-electron bolometers", *IEEE Trans. Applied Superconductivity*, 7, no. 2, pp. 3576-3579 (1997).
13. B.S. Karasik, W.R. McGrath, "Microwave transmission technique for accurate impedance characterization of superconductive bolometric mixers", submitted to IEEE Trans. on Applied Superconductivity, Sept. 1997.
14. A.I. Elantev and B.S. Karasik, "Effect of high frequency current on Nb superconductive film in the resistive state," *Fiz.Nizk.Temp.*, vol. 15, pp. 675-683 (1989) [Sov. J.Low Temp. Phys. vol. 15, pp. 379-383 (1989)].
15. H. Ekström, B.S. Karasik, E. Kollberg, K.S Yngvesson, "Superconducting bolometric mixers," *IEEE Trans. Microwave and Guided Wave Letters* vol. 4, pp. 253-255 (1994).
16. H. Ekström, B.S. Karasik, E. Kollberg, G.N. Gol'tsman, and E.M. Gershenzon, "350 GHz hot electron bolometer mixer," *Proc. of the 6th Int. Symp. on Space Terahertz Technology*, 21-23 March 1995, Caltech, Pasadena, pp. 269-283.
17. A. Skalare, Th. de Graauw, H. van de Stadt, "A planar dipole array antenna with an elliptical lens", Microwave and Optical Tech. Lett., vol. 4, no. 1 (1991).
18. D.F. Fillipovic, S.S. Gearhart, G.M. Rebeiz, "Double-slot antennas on extended hemispherical and elliptical silicon dielectric lenses," *IEEE Trans. on Microwave Theory and Technique,* vol. 41, pp. 1738-1749, October 1993.
19. K.A. McIntosh, E.R. Brown, K.B. Nichols, O.B. McMahon, W.F. DiNatale, T.M. Lyszczarz, Appl. Phys. Lett. 67, 3844 (1995).
20. S. Verghese, K. A. McIntosh, E. R. Brown, "Highly tunable fiber-coupled photomixers with coherent THz output power," IEEE Trans. on Microwave Theory and Techniques, special issue on "Microwave and Millimeter Wave Photonics II", vol. 45, no. 8. pp. 1301 - 1309 (1997).
21. S. Verghese, K. A. McIntosh, E. R. Brown, "Optical and terahertz power limits in the low-temperature-grown GaAs photomixers", Appl. Phys. Lett. vol.71, pp. 2743-2745 (1997).