**Invited Paper**

# Low-noise and wideband hot-electron superconductive mixer for THz frequencies

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## ABSTRACT

Superconductive hot-electron bolometer (HEB) mixers have been built and tested in the frequency range from 1.1 THz to 2.5 THz. The mixer device is a 0.15-0.3 μm microbridge made from a 10 nm thick Nb film. This device employs diffusion as a cooling mechanism for hot electrons. The double sideband noise temperature was measured to be ≤3000 K at 2.5 THz and the mixer IF bandwidth is expected to be at least 10 GHz for a 0.1 μm long device. The local oscillator (LO) power dissipated in the HEB microbridge was 20-100 nW. Further improvement of the mixer characteristics can be potentially achieved by using Al microbridges. The advantages and parameters of such devices are evaluated. The HEB mixer is a primary candidate for ground based, airborne and spaceborne heterodyne instruments at THz frequencies. HEB receivers are planned for use on the NASA Stratospheric Observatory for Infrared Astronomy (SOFIA) and the ESA Far Infrared and Submillimeter Space Telescope (FIRST). The prospects of a submicron-size $YBa_2Cu_3O_{7-\delta}$ (YBCO) HEB are discussed. The expected LO power of 1-10 μW and SSB noise temperature of ≈2000 K may make this mixer attractive for various remote sensing applications.

**Keywords:** submillimeter, heterodyne, mixer, hot electron bolometer, terahertz, superconductor, far infrared, high-$T_c$

## 1. INTRODUCTION

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 frequencies of visible light. Theory[4] predicts the HEB mixer noise temperature due to the intrinsic thermal-fluctuation noise mechanisms to be very low, so it would be most likely quantum limited 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

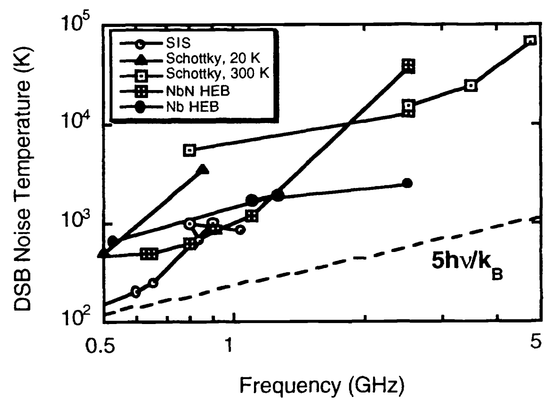


Fig. 1. Diffusion-cooled HEB receiver performance compared to state-of-the-art heterodyne receiver performance at submillimeter wavelengths.

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Part of the 4th International Conference on Millimeter and Submillimeter Waves and Applications • San Diego • July 1998
SPIE Vol. 3465 • 0277-786X/98/$10.00

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 combination of the intrinsic electron-phonon interaction time, $\tau_{ep}$, and the phonon escape time, $\tau_{es}$, to be $f_{3db} \approx$3-5 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].

## 2. NOISE PERFORMANCE OF Nb HEB MIXERS AT THz FREQUENCIES

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).

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. Fig. 2 shows an SEM photo 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, transition width ≤ 0.3 K; and sheet resistance 10-80 Ω/sq. The critical current density at 4.2 K was as high as $1.5\times10^7$ A/cm$^2$.

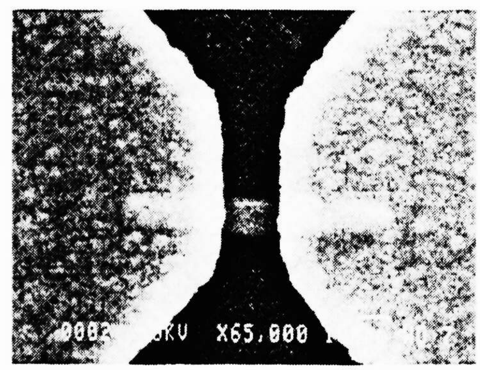


Fig. 2. SEM photo of a submicron Nb microbridge bolometer.

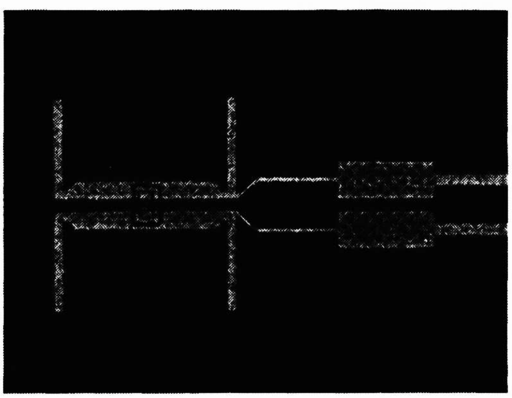

Fig. 3. Double-dipole antenna and coplanar strip line (CPS) embedding circuit and rf bandstop filter used at 1.1 THz. The Nb microbolometer is located in the center of the CPS embedding circuit.

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 HEMT IF amplifier centered at 1.5 GHz, and the 2.5 THz receiver used a similar amplifier centered at 2.1 GHz.

## 3. IF BANDWIDTH IN Nb HEB DIFFUSION-COOLED MIXERS

Since these bolometer mixers use outdiffusion of hot electrons as the cooling mechanism, the thermal relaxation $\tau_T$ 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: $\tau_T = L^2/(\pi^2 D)$, where D is the thermal diffusivity of the film. Thus the 3-dB IF bandwidth $f_{3dB} = 1/(2\pi\tau_T)$ should vary as $L^{-2}$.

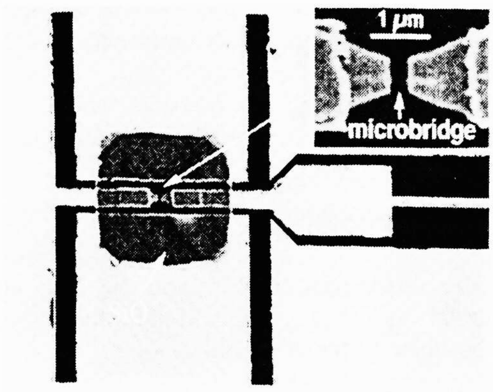


Fig. 4. 2.5 THz Planar mixer circuit consisting of the twin-slot antenna and coplanar waveguide transmission line. To the right are the IF and dc lines with an integrated rf choke filter.

The IF bandwidth of several devices varying in length between 3 µm and 0.08 µm 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 0.08 µm long. The mixer noise bandwidth however is generally greater than the signal bandwidth [4,11], 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.

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 [12]. Measurements of the IF impedance were made within a 0.05-4 GHz frequency range. It has been demonstrated experimentally for phonon-cooled Nb [13,14] and NbN [15] 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, $\tau_T$. Thus, a measurement of the HEB impedance versus frequency allows $\tau_T$ to be determined. The mixer bandwidth, $f_{3dB}$, is then given by:

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

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 references 9 & 12 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 [12]. According to theory [4] the HEB impedance is given by

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

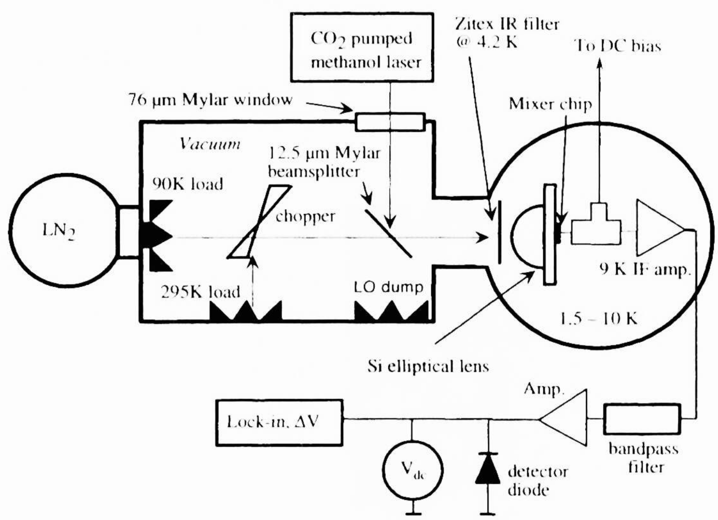


Fig. 5 Block diagram of 2.5 THz receiver test system.

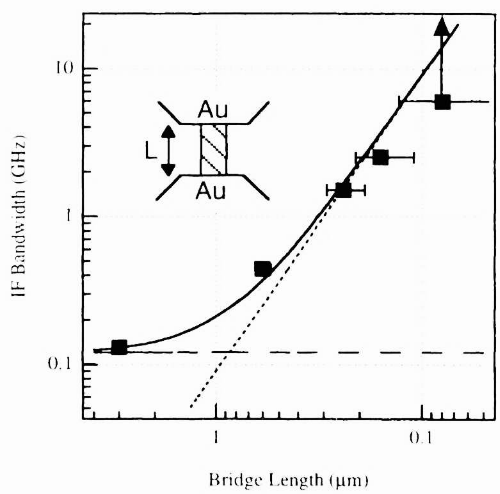


Fig. 6. Bandwidth vs length for devices with lengths: 3 µm; 0.6 µm; 0.24 µm; 0.16 µm; 0.08 µm. Squares are the experimental data. Lines are the theoretical predictions showing the expected $L^{-2}$ dependence for the diffusion cooled case (dotted line), the phonon-cooled case (dashed line), and the sum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

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. Fig. 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.

## 4. RF COUPLING AND LOSSES IN THE MIXERS

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 [16] and twin-slots [17] and demonstrate that these antennas still function well up to 2.5 THz.

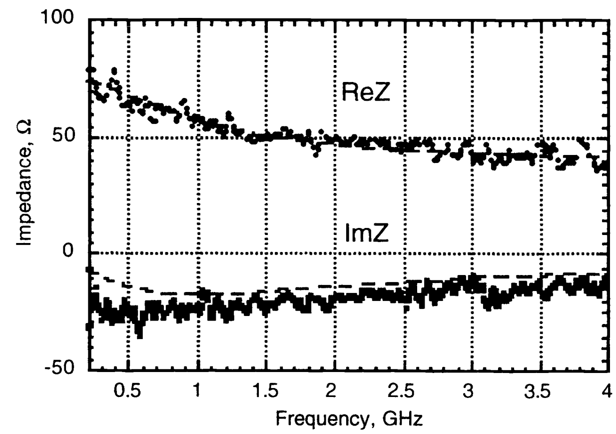


Fig. 7. HEB IF impedance for a 0.3 μm long microbridge. The dashed lines are the fit with C = 0.3

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. Fig. 9 summarizes these results along with our previous measurements at 530 GHz [6] and demonstrates that the HEB mixer noise is nearly independent of frequency over a range of at least 2 THz.

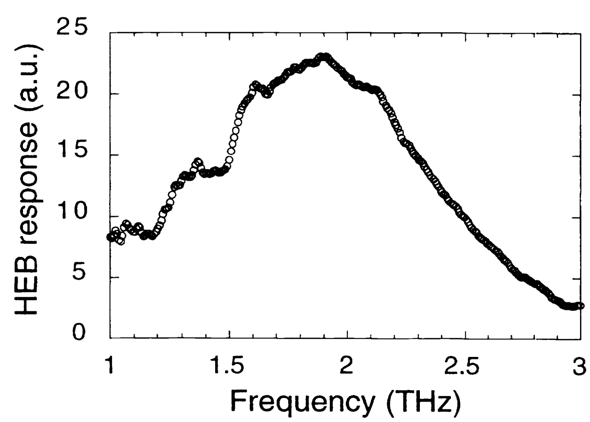


Fig. 8. FTS spectrum measured for the 23 Ω HEB, corrected for the calculated 23 μm FTS beamsplitter efficiency. The HEB was operated as a direct detector.

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.

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 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 [18,19,20] and would allow for the possibility of an ultra-broadband heterodyne receiver.

## 5. ADVANTAGES OF MATERIALS WITH LOWER CRITICAL TEMPERATURE FOR HEB MIXERS

Although the LO requirement for HEB mixers is lower than any competing device technology, there are nonetheless no tunable solid state sources available to pump HEB mixers at frequencies above 1.5 THz. An instant bandwidth of ~4 GHz is sufficient for many practical spectroscopy applications, however the unavailability of tunable THz LO sources may require much larger bandwidth for an HEB mixer. This is because a $CO_2$-pumped FIR laser may be the only option for an LO, and most often the available laser emission lines are many GHz separated from the particular spectral line of interest.

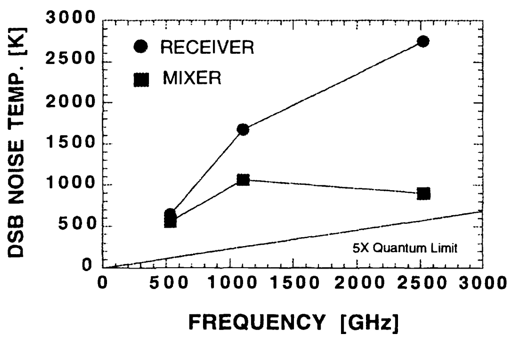


Fig. 9. HEB receiver (circles) and mixer (squares) noise temperature versus frequency for 3 different receivers. The mixer noise is essentially flat over a 2 THz frequency range.

Currently LO source technology is not as well developed as mixer technology and this puts further demands for improvement of HEB mixers in terms of decreasing the LO power requirements and increasing the IF bandwidth. Also, since theoretically the HEB mixers can achieve quantum limited noise performance, it is of practical interest to find a way to achieve this limiting performance. In general, there is always a tradeoff between mixer characteristics when one attempts to optimize a *particular* characteristic of the mixer. The relationships between the mixer characteristics depend on the cooling mechanism dominant in the HEB device. A proper choice of the device material can create a more optimal combination of mixer parameters. In this section, we evaluate several superconducting materials with the goal of achieving optimal mixer performance and show what limitations are set by the cooling mechanism.

The diffusion cooling regime can be achieved in most materials as long as the device is made sufficiently short. It is simpler to observe however when the diffusion constant $D \geq 1$ cm$^2$/s. For smaller diffusivities, the device length needs to be less than 0.1 µm in order to provide a practical (ie: > 1 GHz) bandwidth. Such short device sizes are difficult to achieve. Fortunately, there is a variety of materials where large diffusivities can be easily obtained. As seen in Fig. 10, Nb, NbC, and Al all have $D \geq 1$ cm$^2$/s.

For $D = 10$ cm$^2$/s (a typical value for aluminum) and $L = 0.1$ µm, the calculated diffusion time is ≈ 1 ps which corresponds to an effective mixer bandwidth of 160 GHz. Even taking into account the difference between the theory and experiment, a bandwidth of several tens GHz seems to be quite possible.

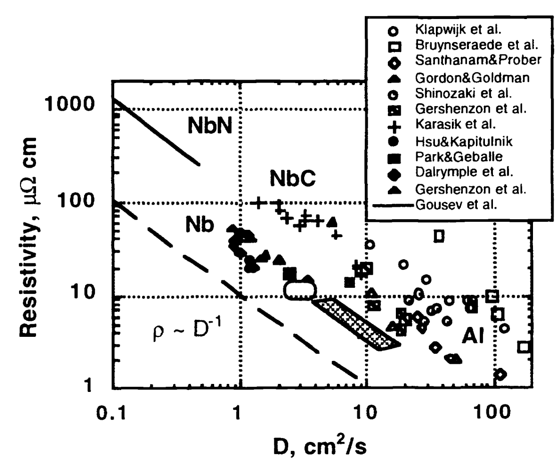


Fig. 10. The resistivity vs diffusivity data for different superconducting films. The shaded tetragonal is an extrapolation for some low-resistive Nb film (diffusivity was not measured), the oval represents the range for Nb films used at JPL.

A large range of diffusion constants gives flexibility in adjusting the mixer resistance to a desirable value. Indeed, if one tries to increase the bandwidth by using a very clean film, it may happen that the resistivity will be so low that the mixer device will be mismatched with the planar antenna impedance. Such a situation is more likely in Nb which has a higher density of electron states $N_\varepsilon$ ($\rho^{-1} = N_\varepsilon e^2 D$) than Al and NbC where the density of states is three times lower than in Nb (see Fig. 10) Therefore one can use cleaner films (= larger bandwidth) of these materials, while maintaining at the same time a suitable resistance for matching to rf embedding circuits.

Niobium nitride is the only material which has a short enough electron-phonon time and, therefore, is useful for fabrication of phonon-cooled HEB mixers. There is indirect evidence that the intrinsic bandwidth set by the electron-phonon relaxation time at the critical temperature of 8-9 K is ~ 10 GHz [21]. The corresponding relaxation time $\tau_{ep} \approx 13$ ps [22] is very short. However, even for the thinnest NbN films used in the recent experiments [22,23] the phonon escape time was 40 ps, i.e. phonons do not remove the thermal energy from the film instantly but rather exchange it with electrons. As a result, the relaxation slows down and the apparent bandwidth is smaller than that implied by $\tau_{ep}$, i.e. 4 GHz instead of 10 GHz (see more details in [24]. This situation can be adequately described by introduction of both electron and phonon temperatures different from the temperature of substrate. Any further increase of bandwidth in NbN seems to be problematic because: (a) it is hardly possible to fabricate even thinner (<3 nm) high quality NbN films; and (b) electron diffusion still does not play a role in the relaxation since $D \approx 0.2$ cm$^2$/s.

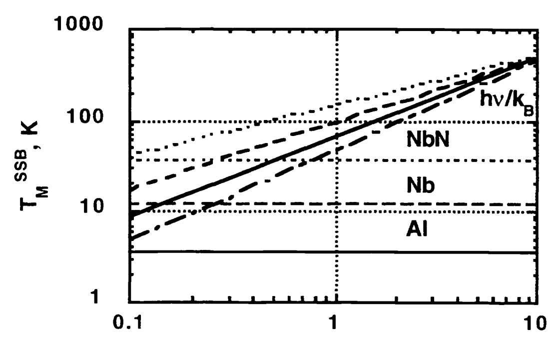


Fig. 11. Theoretical noise temperature limits for different mixer materials. The dash-and-dot line is the quantum limit.

According to theory [4] the best HEB mixer performance takes place when the thermal fluctuation noise dominates over the Johnson noise. This is a case of a strong self-heating in the mixer device which is possible if the device has a sharp superconducting transition and large critical current density. Under these circumstances assuming that the device operates at temperature $T << T_c$, the SSB mixer noise temperature, $T_M$, is given by the following expression:

$$T_M = (n+2)T_c, \quad (3)$$

where n is the exponent in the temperature dependence of the electron temperature relaxation time. For phonon-cooled devices it is an electron-phonon time: n = 1.6 for NbN, n = 2 for Nb, n = 3 for NbC. For diffusion cooled devices n = 0. The limits given by Eq. 3 are shown in Fig. 11 (horizontal lines). One can see that the theoretical limit for Al is many times lower than that for NbN. The theory [4] does not consider any quantum phenomena though the quantum noise limit will be important at THz frequencies. A simplistic empirical correction can be made by adding one quantum contribution, $h\nu/k_B$, to the limit of Eq. 3. As a result the difference in $T_M$ between Al and NbN HEB mixer becomes smaller but is still significant.

The theoretical values of required LO power [24] are given in Fig. 12. A further reduction of the local oscillator power might be achieved in a phonon-cooled mixer by reduction of the volume. However, in the case of NbN, the large resistivity of the material requires the use of ~0.1 square size devices to ensure a reasonable match of the device resistance to a planar antenna impedance. Therefore, the NbN device of Fig. 12 with the sizes 0.15 (length) × 1.5 (width) × 0.003 (thickness) μm$^3$ is close to the optimum. In the case of diffusion-cooled mixers one has a choice of materials with lower values of critical temperature. For $T^2 << T_c^2$, $P_{LO} \propto T_c^2$, and one can see that Al with its low $T_c$ (≈ 1.6 K) requires very low LO power compared to other materials. The bandwidth does not suffer however since it is temperature independent, in contrast to that in phonon-cooled devices.

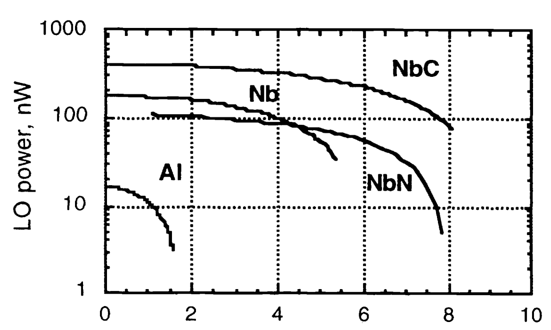


Fig. 12. Local oscillator power for optimized diffusion-cooled (Nb, NbC and Al with R = 20 Ω) and phonon-cooled (NbN) HEB mixers.

As can been seen from the above considerations, for a phonon-cooled HEB mixer, the IF bandwidth depends on the electron-phonon interaction time which is temperature dependent. Since a material with a relatively high $T_c$ such as NbN is required, a wide bandwidth means higher noise temperature and higher LO power. Thus these mixer characteristics must be traded against each other to optimize the performance for this type of mixer. For a diffusion cooled HEB mixer, the IF bandwidth is independent of temperature. Relatively lower $T_c$ materials, such as Al, can be chosen to reduce mixer noise and LO power requirements without sacrificing IF bandwidth. This type of mixer thus provides more flexibility in optimization for a particular application.

## 6. HIGH-$T_c$ HEB MIXER

Sensitive and tunable terahertz heterodyne receivers are required for several important remote-sensing and in-situ applications, including spectroscopic mapping of the earth's atmosphere, other planetary atmospheres, as well as the gases and chemical composition of comets. Today the only heterodyne instrument available for such long-duration space missions is based on a Schottky-diode mixer. This mixer typically provides a high noise temperature of 3000 K at 500 GHz rising to ~10,000 K at 2.5 THz and to ~70,000 K at 5 THz. The fixed-tuned RF bandwidth is less than 20%, and the required LO power is 1-3 mW which can be provided only by a bulky and power consuming FIR laser at terahertz frequencies.

We are proposing a new detector technology based on a high-$T_c$ bolometer mixer which due to its lower noise and wider RF bandwidth will replace Schottky receivers in most space-based earth and planetary spectroscopic applications.

During the last few years preliminary heterodyne mixing experiments have been performed with large area devices ($\approx 20\times10\ \mu m^2$) made from a 50-60 nm thick YBCO film [25,26] These experiments demonstrated that (a) the mixing mechanism is bolometric (b) the mixing performance does not depend on the radiation frequency (the measurements were done between 30 THz and 300 THz), and (c) the conversion efficiency bandwidth can be as wide as ~100 GHz and is determined by the intrinsic electron-phonon relaxation time in the material. These were basic device physics experiments and no attempt was made to provide a suitable mixer embedding circuit, therefore the RF losses were very large and evaluation of the conversion efficiency and the noise temperature was difficult.

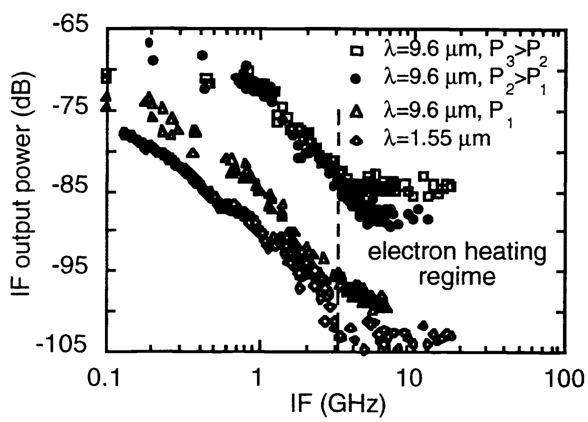


Fig. 13. Data on optical mixing in YBCO films (Ref's. 25, 26). The three curves for $\lambda = 9.6\ \mu m$ correspond to different levels of LO power P.

Our theoretical calculations [27] show that $YBa_2Cu_3O_{7-\delta}$ (YBCO) HEB mixers operating at 66–77 K can perform better than Schottky-diode mixers in terms of both noise temperature and LO power requirements. This HEB mixer can be especially useful in space-borne applications, e.g. for atmospheric and planetary research, where low-power mechanical cryocoolers are readily available, and where requirements for low LO power are critical. For such an application, an HEB device made from a thin YBCO film can be used. The fabrication technology for such films has been significantly improved since the discovery of high-$T_c$ superconductivity. Now, ultrathin films having a thickness d down to a few unit cells have been successfully fabricated. A critical temperature $T_c > 85$ K and superconducting transition width $\delta T_c = 1$–$2$ K are typical for films with $d \geq 10$ nm, and a critical current density $j_c = 8\times10^6\ A/cm^2$ was observed in 10 nm thick films at 77 K. Fabrication of superconducting structures made from YBCO with in-plane sizes 100–500 nm has also been demonstrated. A variety of materials (e.g. MgO, $LaAlO_3$, $NdGaO_3$, YSZ) have been found to provide a moderate dielectric constant and epitaxial YBCO film growth. Also, the use of buffer layers allows growth of YBCO films on silicon and sapphire (YSZ or $CeO_2$ buffer layer for Si and $CeO_2$ for sapphire).

In contrast to slow bulk bolometric detectors, an HEB mixer can operate with a high intermediate frequency (IF) of the order of several gigahertz. Mixer optimization, however, is quite different from direct-detector bolometer optimization. Our analysis includes the equations for temperature of both the electrons and phonons, expressions for mixer conversion efficiency and IF impedance and is valid for a wide range of IF. The contributions of both electron temperature fluctuations and Johnson noise in the mixer noise temperature have been investigated as functions of dc and LO power. Also, the requirements for the substrate thermal conductivity with respect to the device in-plane size have been determined. A distinguishing feature of the present theory is a consideration of the phonon diffusion from the device in to the normal metal contacts. This mechanisms significantly increases the thermal conductance between the electron and phonons, allowing for larger amount of the LO power and lower noise temperature of the mixer. The phonon diffusion mechanism becomes especially effective when the device length is made very short (L~0.1 μm). Fig. 14 shows the size dependence of the noise temperature and the required LO power for an optimized high-$T_c$ mixer device at 66 K. An intermediate frequency was chosen to be $f_{IF}$ = 2.5 GHz, which is a practical frequency for remote sensing applications in astrophysics and atmospheric science. One can see that the noise temperature as low as ≈2000 K along with the LO power of a few μW might be possible for a 0.1 μm long device fabricated from a 10 nm thick YBCO film.

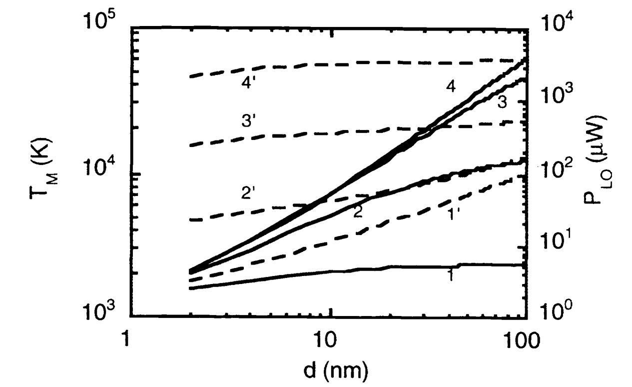


Fig. 14. Size dependence of the mixer noise temperature (solid lines) and optimal LO power (dashes). 1 and 1', L = 0.1 μm; 2 and 2', L = 0.3 μm; 3 and 3', L = 1.0 μm; 4 and 4', L = 3.0 μm.

During our preliminary study, relatively large, 1×1 $\mu m^2$, devices were fabricated from a 20 nm thick YBCO film on an $YAlO_3$ substrate. The fabrication was done at the JPL Microdevices Laboratory, and is briefly discussed here. Very thin films, ≤ 20 nm, are required to minimized the phonon escape time from the film and hence improve the thermal conductance which improves the mixer performance. These ultra-thin films must also retain their near-bulk superconducting properties. Such films were produced by laser ablation on an $YAlO_3$ substrate with a 20 nm $PrBa_2Cu_3O_{7-\delta}$ (PBCO) buffer layer. Next a 100 nm Au layer was deposited *in situ* by DC magnetron sputtering. Typical transition temperatures for these trilayers, as determined by AC susceptibility, are 83-86 K with a transition width of less than 2 K. The patterning of the PBCO/YBCO/Au trilayer into the antenna, RF filter, IF/DC contacts and bolometer microbridge was performed using optical contact lithography and ion etching techniques. The final antenna-coupled device looked very similar to that of Fig. 4. The superconducting transition in our devices occurs at ≈85 K and the transition width is less than 2 K. These parameters are excellent for such thin films, except the sheet resistance was too low indicating that the etching did not remove all the gold from the microbridge area. A more detailed description of the whole process is given in [28].

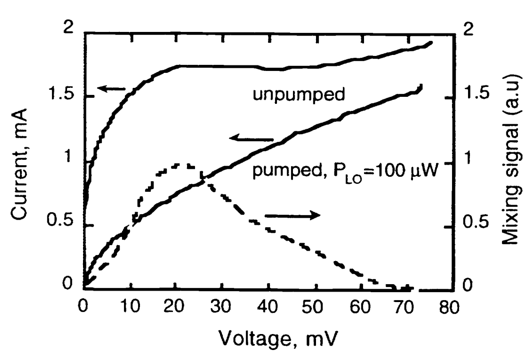


Fig. 15. Pumped and unpumped IV characteristics of a high-$T_c$ HEB mixer and the output mixing signal.

Using a $CO_2$-pumped far-infrared laser, we performed RF tests of the high-$T_c$ devices at 77 K. Fig. 15 shows the pumped and unpumped IV-characteristics of a device and also an output IF signal at 2.2 GHz due to the mixing of a 1.6 THz LO with a blackbody source. The amount of LO power needed to maximize the mixing signal as well as the position of the optimal operating point were close to those predicted by theory [27]. However the overall RF coupling to the device was poor due the presence of the gold film shunting the microbridge. A reasonable (but large) correction could be made to the measured noise temperature knowing the resistance of the gold shunt. The result of ≈ 40,000K was close to the value predicted for such as large area device (as discussed above, much lower noise is expected for submicron-sized devices). While the results of our initial study are encouraging, it is clear that tests of unshunted devices and submicron-sized devices must be performed to provide a fully convincing "proof of concept" test of this new technology.

## 7. 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.

The further development of HEB mixers is seen to go both to lower and to higher temperatures. At subkelvin temperatures HEB devices for radioastronomy applications made from low-$T_c$ materials, such as Al, can demonstrate a quantum limited performance with $\approx 10\ \mu W$ of required LO power dissipated in the device. At $\approx 70$ K submicron size YBCO devices can outperform Schottky-diode mixers since they would require only a few $\mu W$ of LO power. The natural niche for such mixers would be long duration atmospheric and planetary missions aimed at spectral surveys and mapping of chemical species in atmospheres.

## 8. ACKNOWLEDGMENTS

The valuable contribution to this work made by M. Gaidis and M. Burns is greatly appreciated.

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

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