NOISE TEMPERATURE AND IF BANDWIDTH OF A 530 GHz DIFFUSION-COOLED HOT-ELECTRON BOLOMETER MIXER

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Superconducting hot-electron bolometers[1-4] are currently of significant interest for use in heterodyne receivers at frequencies above 1 THz for radioastronomy applications. The mixing process in this type of device relies on heating of the electron gas, which means that, unlike an SIS tunnel junction mixer, the bolometer mixer does not have an upper frequency limit related to the superconductive energy gap (in fact, it absorbs rf power more uniformly for frequencies above the gap frequency). Until recently, hot-electron bolometers have not been extensively developed as heterodyne mixers because of the limitation in intermediate frequency (IF) bandwidth imposed by the thermal relaxation time of the heated electrons in bulk devices. For bulk indium antimonide bolometers, for example, the IF roll-off frequency is around 1 MHz [5], while the typical bandwidth requirement for molecular-line spectroscopy is at least 1 GHz. Recently however, novel hot-electron bolometers using very thin superconductive films have been proposed which can achieve practical IF bandwidths of several GHz [1, 2]. Bolometer mixers using thin NbN films and relying on electron-phonon interactions to cool the electrons have recently demonstrated IF bandwidths near 700 MHz [4].

In this paper we present the first receiver noise and IF bandwidth measurements with a *diffusion-cooled* superconducting niobium hot-electron bolometer mixer, that was first proposed by Prober in 1993 [2, 6]. This device is different from earlier superconducting hot-electron bolometers in that the thermal conductance that cools the heated electrons is provided by rapid electron diffusion rather than phonon emission. To achieve the short electron diffusion time required for a high IF bandwidth the device needs to be very short, less than 0.5 μm. The Nb film must also be very thin (~10 nm) to place it in the dirty limit. In this limit the very short (≈ 1-10 nm) mean free path enhances the electron-electron interactions relative to the electron-phonon interaction [1]. Thus when absorbing RF power, the electron gas can thermalize at a higher temperature than the lattice. The small electron specific heat, especially for a submicron size device, and the high thermal conductance provided by diffusion result in a very short thermal response time, ≈ 55 ps[7], and hence a 3 dB IF rolloff around 2-3 GHz. The bolometer is contacted at both ends by normal metal films rather than by superconductors, to prevent the occurrence of Andreev reflections which could potentially increase the device response time. See reference [8] for a more detailed description of the device operation.

A more complete description of our measurements will be given elsewhere [9] so they are only briefly described here. The bolometer used in the measurements consists of a 10 nm thick strip of Nb with an approximate width of 0.14 μm and a length of 0.28 μm [6] that was fabricated on a fused quartz substrate; see Fig. 1. Two 100 nm thick gold films contact the device at both ends, and connect to a waveguide probe and an RF filter circuit patterned from a 110 nm thick niobium layer. The critical temperature T_C of this Nb film is ~4.7 K, with a transition width ΔT_C of ~1.2 K (in these thin dirty films the T_C is suppressed relative to the bulk value of ~9.2 K).

The bolometer chip was mounted into a two-tuner waveguide mixer block designed for 547 GHz [10], which was subsequently placed into a vacuum cryostat and cooled down to 2.2 K by pumping down the pressure in the liquid helium tank. A ×2×3 multiplier chain driven by an 89 GHz Gunn oscillator was used to generate the local oscillator power at 533 GHz, which was coupled into the receiver beam using a folded Fabry-Perot interferometer. A cooled HEMT amplifier[11] together with an isolator was used as the first stage in the intermediate frequency (IF) amplifier chain, which operated at 1.4 GHz and had a total noise temperature of 6 K. A 320 MHz bandpass filter was used to define the IF bandwidth for receiver noise measurements. The receiver sensitivity was determined through Y-factor measurements where 295 K and 77 K blackbody loads were switched into the receiver beam. Fig. 2 shows the best Y-factor response achieved after adjusting the mixer block backshort and E-plane tuner for best coupling of the LO, and optimizing the LO power. As can be seen, the best response is in the resistive branch of the IV curve at a bias voltage just above the "drop-back" voltage. The largest Y-factor was 1.15 dB, corresponding to a double sideband receiver noise temperature of 650 K. The mixer conversion was estimated to -11.4 dB DSB including RF coupling losses. Several tests were made to check for non-heterodyne contributions to the response. Switching between loads with LO power applied and with both loads at 295 K gave no response, which shows that the mixer response is not due to standing waves in the local oscillator path. Switching between 295 K and 77 K loads without LO pump power did not give any output power response. The same switching with LO power applied did not shift the bias voltage of the device measurably (<2 μV) with the bolometer current-biased at DC, indicating that the measured mixer response was not a result of a bias point shift due to heating from the hot and cold loads.

In a separate measurement, an additional Gunn was connected to the multiplier, which thereby generated both power at the local oscillator frequency and a weak signal that could be used as a monochromatic source for mixer experiments. A simple aluminum mirror was used to couple both the local oscillator and signal lines into the receiver, and the intermediate frequency output port was connected to a spectrum analyzer. Measurements were made with the mixer block at 4.3 K and 2.2 K. In both cases the analyzer showed that the mixer output did indeed contain a monochromatic line, which could be tuned over the whole available 1 to 2 GHz IF band by adjusting the frequencies the two Gunn oscillators. A measurement at 2.2 K showed that the difference in IF output power when switching between a hot and a cold blackbody load in the receiver beam showed the same bias voltage dependence as did the output power due to a monochromatic signal source. This fact further supports that the measured Y-factor response is heterodyne. Additionally, a superconducting magnet inside the cryostat was used to apply a magnetic field of approximately 400 Gauss to the bolometer, but was observed to have no effect on the monochromatic IF output power to within the measurement accuracy (0.2 dB).

An important issue for a bolometer mixer is the IF dependence of the conversion efficiency that is set by the thermal response time. Due to significant output power variations with frequency in the multiplier / two-Gunn source, we chose to determine this dependence with a broadband blackbody RF signal source and with a spectrum analyzer used as a tunable 1 MHz filter after the IF amplifier chain. The IF system of the receiver was also reconfigured with a broadband FET amplifier that was cooled to 77 K in place of the HEMT amplifier. A 25 µm thick Kapton beamsplitter was used to couple the LO power into the cryostat. The measurement was done by switching between a 295 K and a 77 K load in the receiver beam, thereby varying the detected IF output power by $\Delta P_{Out} = \Delta f \cdot k_B \cdot \Delta T_{Load} \cdot \eta_{Mx} \cdot G_{IF}$, where Δf is the 1 MHz filter bandwidth of the spectrum analyzer, η_{Mx} is the DSB conversion efficiency of the bolometer mixer (including RF losses in the optics), G_{IF} is the gain of the broadband (0.5-4 GHz) IF chain (including the spectrum analyzer), and ΔT_{Load} is the difference between the hot and cold load temperatures. $G_{IF}(f_{IF})$ must be carefully calibrated in order to accurately determine the bolometer mixer IF response. This was done by blocking the local oscillator optical path and biasing the bolometer at a high enough DC current to drive it completely into the normal conducting state. Under those conditions the IF output power $P_{Out,Cal}$ was strongly dominated by the IF amplifier system noise term $\Delta f \cdot k_B \cdot T_{IF} \cdot G_{IF}$. However, a small correction was made for the thermal (Johnson) noise contribution of $\Delta f \cdot k_B \cdot T_{Device} \cdot G_{IF}$ of the bolometer, which could be estimated from the slope of the IF output noise versus the DC voltage in this bias regime. The noise temperature of the IF chain was calibrated in a separate measurement using thermal noise from a variable-temperature 50 Ω termination load, and was found to vary from 108 K at 0.5 GHz to 205 K at 4 GHz. The measured IF noise temperature allowed the double sideband mixer conversion efficiency to be calculated as $\eta_{Mx} = \left(\frac{\Delta P_{Out}}{P_{Out,Cal}}\right) \cdot \left(\frac{T_{IF} + T_{Device}}{\Delta T_{Load}}\right)$. Figure 3 shows the frequency dependency of η_{Mx} at a typically good bias point just above the drop-back voltage. A fitted curve with the expected frequency dependence $\left(1 + \left(f_{IF} / f_{Roll-off}\right)^2\right)^{-1}$ [5] is also shown, where $f_{Roll-off}$ is the intermediate frequency at which η_{Mx} drops by 3 dB. The roll-off in Fig. 3 occurs at 1.7 GHz, which is close to the expected value, given the level of self-heating in the bolometer. In addition, roll-off frequencies of up to 1.9 GHz were seen at higher DC bias voltages, though the mixer conversion efficiency was lower.

In conclusion, the first Y-factor measurements with a diffusion cooled hot-electron bolometer mixer has yielded a lowest receiver noise temperature of 650 K and an estimated conversion efficiency of -11.4 dB DSB at a local oscillator frequency of 533 GHz. The 3 db roll-off in conversion efficiency in the intermediate frequency band has been measured using a separate broadband IF amplifier system, to be between 1.7 GHz and 1.9 GHz, depending slightly on the DC bias point of the bolometer. The superconducting transition of the device is centered at 4.7 K, with all non-linearity in the IV curve disappearing at 5.3 K. The higher of the two temperature values corresponds to a superconducting gap frequency of 410 GHz, well below that of the mixing experiments. The mixer conversion is not affected by a magnetic field of 400 Gauss.

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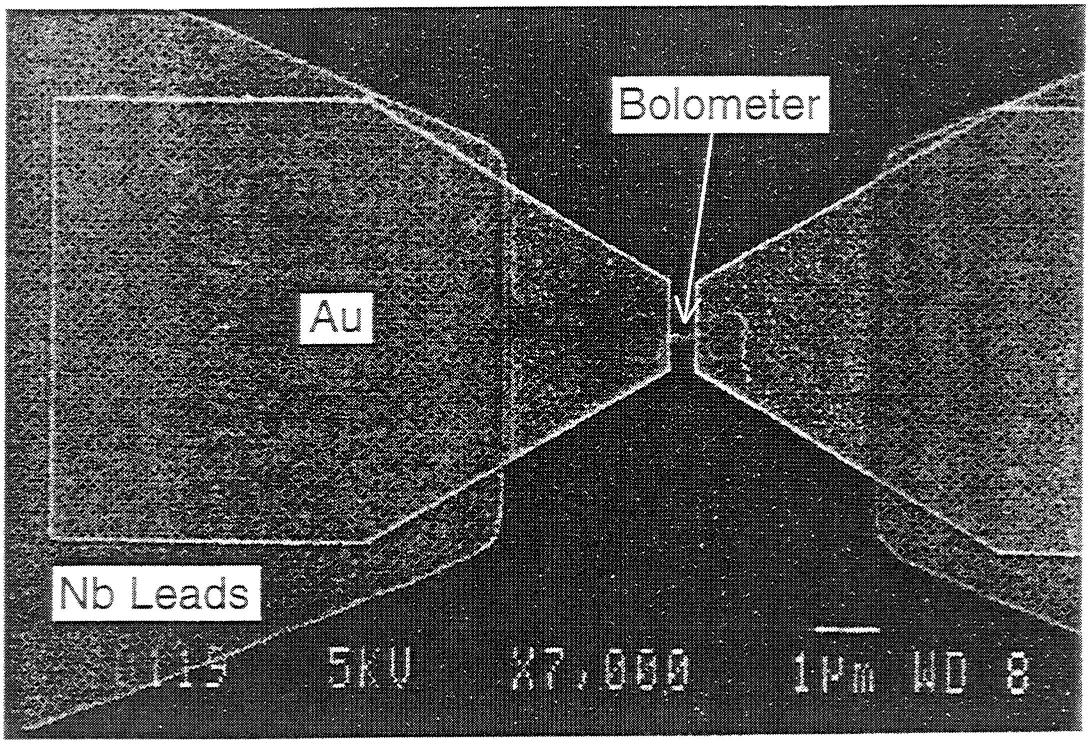

Fig.1: SEM photo of a diffusion cooled hot-electron bolometer.

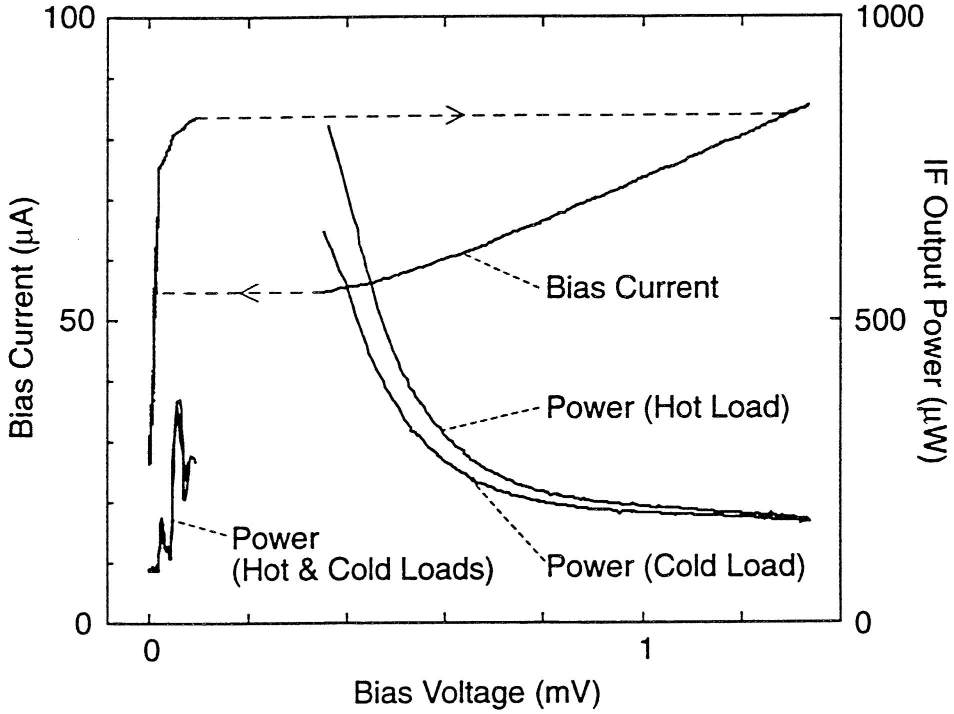

Fig.2: Local oscillator pumped IV curve of the bolometrer and output power from the low-noise amplifier chain at the intermediate frequency.

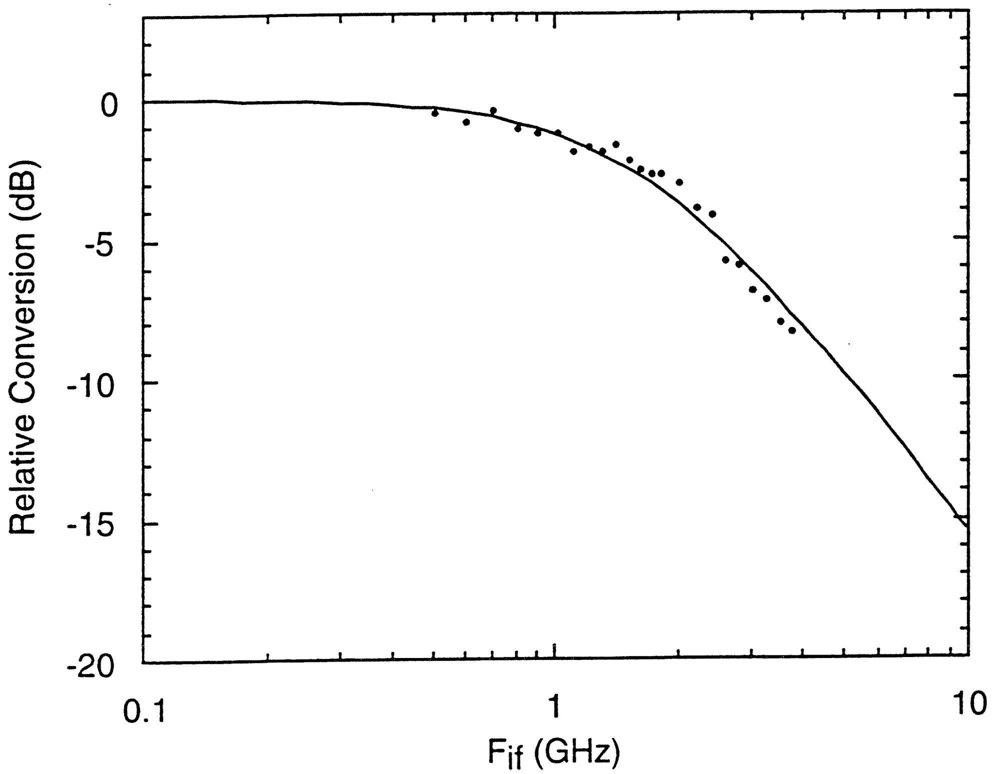

Fig.3: Measured relative conversion versus frequency and a fitted curve.