Superconductive NbN Hot-Electron Bolometric Mixer Performance at 250 GHz

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Abstract

Thin film NbN (<40 Å) strips are used as waveguide mixer elements. The electron cooling mechanism for the geometry is the electron-phonon interaction. We report a receiver noise temperature of 750 K at 244 GHz, with f_{IF} = 1.5 GHz, Δf = 500 MHz, and $T_{physical}$ = 4 K. The instantaneous bandwidth for this mixer is 1.6 GHz. The local oscillator (LO) power is 0.5 μW with 3 dB uncertainty. The mixer is linear to 1 dB up to an input power level 6 dB below the LO power. We report the first detection of a molecular line emission using this class of mixer, and that the receiver noise temperature determined from Y-factor measurements reflects the true heterodyne sensitivity.

1. Introduction

Gershenzon et al [1] proposed the lattice-cooled superconductive hot-electron bolometric (HEB) mixer. The mixer elements are thin-film (thickness ~5 nm) superconductors, formed to structures 1 μm in width and several microns in length. The thermal time constant of the electrons in the film is determined by the interaction time between the electrons and the lattice, $\tau_{e\text{-}ph}$. The excess heat drawn by the lattice of the thin-film is carried away by the substrate. With niobium nitride as the film material, subsequent studies [2] predicted low-noise mixer performance, T_{RX} ~ 250 K, and high instantaneous bandwidths exceeding 3 GHz at submillimeter wavelengths.

The lattice-cooled bolometric mixer is different from the diffusion-cooled transition edge bolometric mixer [3], where the electrons are cooled through a heat-diffusion process. The appropriate size for such a device requires a very small geometry, about 0.2 μm by 0.05 μm for a structure fabricated with a 10 nm thick niobium film. Measurements with receivers incorporating these mixers have shown they can have excellent noise performance [4].

Early work on lattice-cooled mixers fabricated from niobium showed promising performance, but the IF bandwidth of Nb-based mixers is still too small to be practically useful [1, 5]. Experiments on NbN-based mixers at millimeter-wavelengths have shown noise performance near 500 K at 100 GHz [6], 2000 K at 200 GHz [7], and 3000 K at 350 GHz [8]. The best instantaneous bandwidth measured for a NbN mixer is 1.8 GHz [7]. Gerecht et al [9] have performed mixing experiments at 2.5 THz, but a noise measurement has not yet been reported.

Questions remain regarding the linearity, saturation level and stability of the HEB mixers. Particularly, a concern exists whether or not the receiver sensitivity, determined using the Y-factor method of alternately placing hot and cold broadband loads at the receiver input, accurately reflects the true heterodyne response. Measurements performed to address these concerns are presented below.

2. Experimental setup

The mixer elements used in our study are made from ~40 Å NbN film, reactively sputtered on crystalline quartz substrates. The film is etched to form narrow strips, typically 1 μm in width and 4 μm in length. The ends of the film are overlaid with TiAu structures which form the antenna coupling the mixer element to the waveguide. In order to provide a range of mixer impedance, a number of strips may be added in parallel. The TiAu film is patterned to form the low-pass filters through which the intermediate frequency (IF) signal passes and DC bias is applied. The substrate supporting the mixer element is suspended across a reduced-height waveguide. A horn-lens combination is used to couple the input radiation to the mixer which has a single backshort tuner. The mixer block, horn and lens are mounted on the cold plate of a liquid-helium cooled cryostat. Two layers of Zitex-A at the 80 K radiation shield provide infrared blocking, and a room temperature Teflon window seals the vacuum cryostat. Outside the cryostat a wire-grid polarizer is used as a diplexer to combine local-oscillator (LO) and signal. The mixer output is fed through an isolator to a 1.5 GHz HEMT amplifier mounted on the cryostat cold plate. In Figure 1 we show an optical photograph of a typical mixer element and a schematic of the mixer and suspended substrate structure.

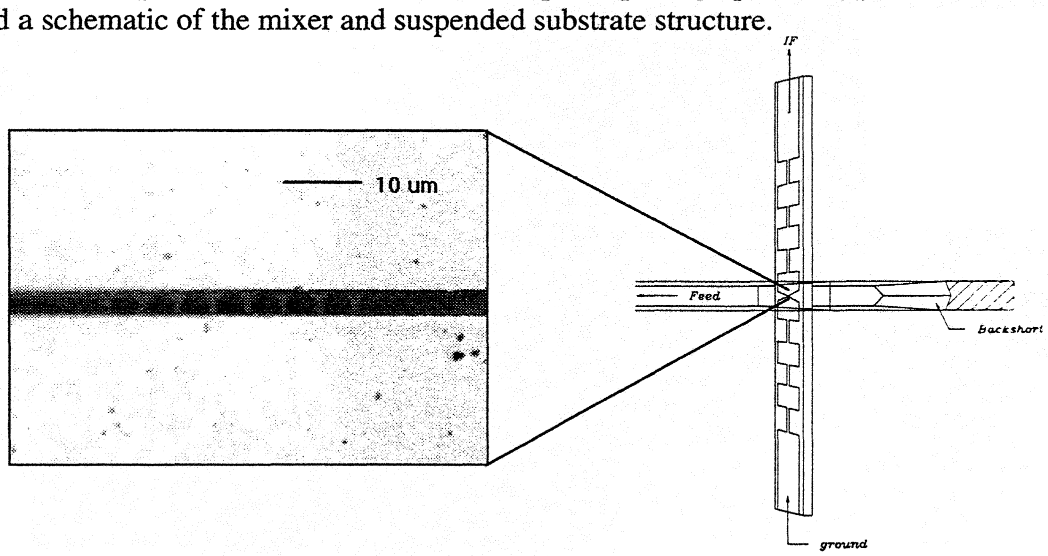

Figure 1. To the left is an optical photograph of a typical HEB mixer element: the light strips are the NbN film on crystalline quartz, and the light regions above and below the strips are the TiAu pads. For this mixer there are eight strips in parallel. To the right a schematic of the suspended substrate is shown.

Four separate measurements were performed to characterize our HEB mixer receiver. The noise temperature was measured using the hot-cold load method, with no corrections applied for the losses at the receiver input. The IF bandwidth was measured using a harmonic generator as the source and sweeping the LO source in frequency while maintaining the same mixer operating point. In this measurement the IF amplifier is bypassed and the mixer output is brought directly outside the cryostat. The saturation and linearity measurement requires the use of a second multiplied Gunn oscillator as a signal source, the output power of which was measured using a harmonic mixer. In this experiment the room temperature load is placed approximately 50 cm from the receiver cryostat, and the signal feed is inserted through a small opening in the load so as not to measurably change the mixer output when the source is switched off. In the same experiment the LO power required for optimum mixer operation is also measured [10]. Finally, we have made molecular line emission measurements using a gas-cell containing a 50 cm column of room temperature gas. The receiver calibration is made by inserting the gas cell between the hot and cold loads used for Y-factor noise measurements.

3. Experimental results

Current-voltage (I-V) characteristics for typical HEB mixers are plotted in Figure 2. For most mixers we have found that the optimal operating point for low noise mixing occurs just before the current switches to a higher value as the voltage bias is reduced, as traced in Figure 2b. When the device is hysteritic, the optimal point is not stable. For this reason, it is better to select devices that are not hysteritic under optimal operating conditions. It is possible to over-pump mixers with the LO or to raise their physical temperature to eliminate this instability, but this results in poorer sensitivity. The I-V characteristic of our most sensitive mixer is shown in Figure 2(a). The unpumped I-V curve is hysteritic, but the pumped curve is single-valued and the operating point is stable.

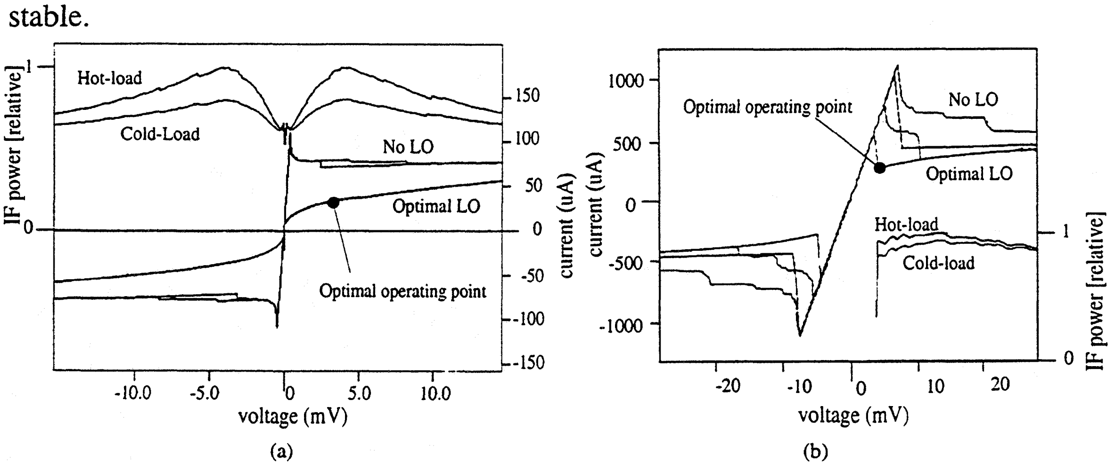

Figure 2. The current-voltage characteristics are similar for most mixers. The majority of "good" devices exhibit some hysterisis. Most of the mixers we have tested behave as (b); the best mixer tested has an I-V characteristic shown in (a).

The best receiver noise temperature we have measured is 750 K at 244 GHz, using a 1.5 GHz IF with 500 MHz bandwidth, and with the mixer at a physical temperature of 4 K. The IF output as a function of bias is also shown in Figure 2(a). The bandwidth of the mixer determined from the gain curve, plotted in Figure 3, is 1.6 GHz. Previous devices, fabricated from thicker films, show bandwidths in the range 500–800 MHz. One mixer was tested at a signal frequency of 20 GHz. This showed an instantaneous bandwidth of 1.8 GHz, a gain curve of which is also shown in Figure 3. The upper limit to the IF bandwidth for NbN mixers is expected to be ~10 GHz [2], and it is not clear why reported measurements have not shown evidence for wider bandwidths than ~2 GHz. Regardless, a 1.8 GHz bandwidth is extremely useful since many astronomical receiver systems have IF output at 1.5 GHz with a 500 MHz bandwidth.

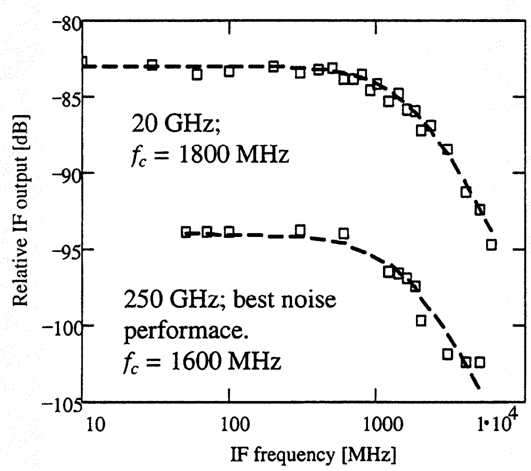

Figure 3. Mixer gain curves for the mixer which had the best noise performance and the mixer for which the best bandwidth was measured. The 3 dB cutoff frequencies are at 1.6 GHz and 1.8 GHz, respectively.

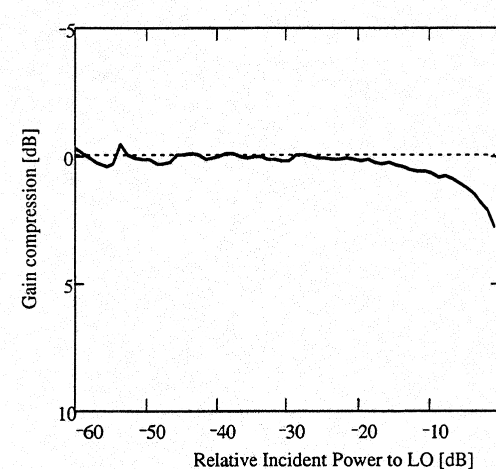

Figure 4. Gain compression measurement for a mixer with 80 μA critical current. The 1 dB compression point occurs 6 dB below P_{LO}.

The LO power level, P_{LO}, and linearity of two mixers were measured using the technique described in [10]. For a mixer with I_c = 1600 μA, the optimum LO power was 4 μW, with 3 dB uncertainty. The mixer was linear to within 0.4 dB up to at least an input power 30 dB below that of the LO. (It was not provide higher power to the receiver in the same measurement.) For a mixer with I_c = 80 μA, the LO power was 0.5 μW, with 3 dB uncertainty. This mixer was linear to within 1 dB up to an input power level 6 dB below that of the LO. This is shown in Figure 4. The two measurements suggest that the optimal LO power level scales with the critical current of the mixers. The mixer for which the best noise temperature was measured had I_c = 110 μA, therefore the LO power was also ~0.5 μW. The RF bandwidth for these mixers is probably very broad, ~300 GHz, and a simple calculation suggests that the mixers that require ~0.5 μW LO power will remain saturation-free until the input temperature is ~10^4 K.

Finally, the HEB receiver was used to detect line emission from carbonyl sulfide (OCS), presented in Figure 5. The line frequency is 243.21804 GHz, representing the J = 20→19 transition. The gas was kept at a pressure of 15 mTorr, below the pressure-broadening regime. With these parameters, the full-width half-maximum of the line is calculated to be 400 kHz and the opacity 0.80 [11]. With a sideband gain ratio of unity and no optical losses, the expected strength of the line is 87 K above 77 K. With a line strength of 60 K, we calculate a 17% loss through the gascell. The two-double windows

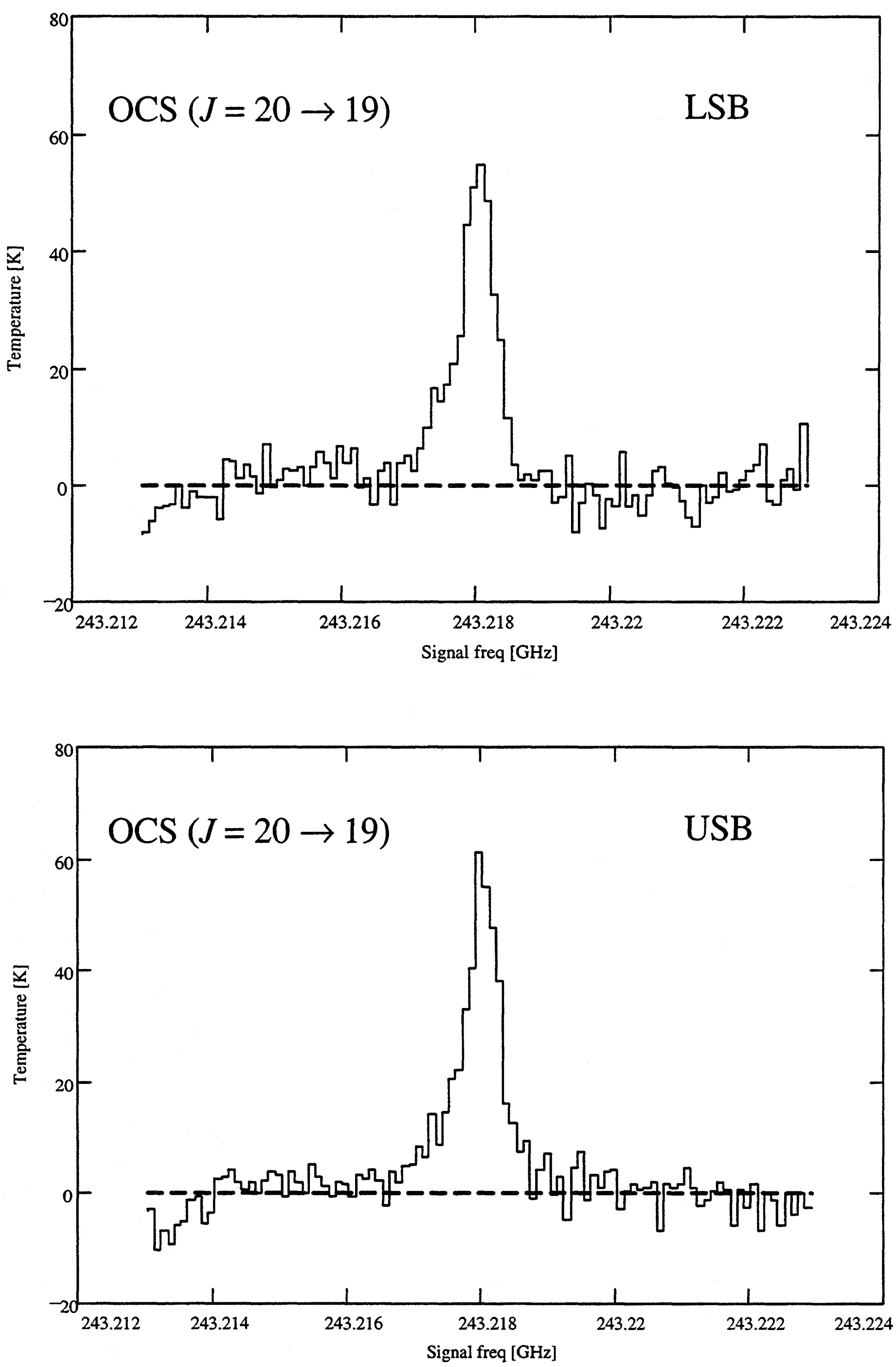

Figure 5. Spectrum of carbonyl sulfide (OCS). The dashed line indicates 77 K.

of the gascell are made of polyethylene, and each has an estimated reflection loss of 4%, neglecting any internal reflections. The power absorption coefficient at 200 GHz is ~0.02 cm^{-1}, and with about 1 cm of total window thickness, the losses in the windows contribute a further 2% loss. We therefore estimate a total window loss of 18%. This compares well with a 17% loss predicted by measured line strength of OCS, implying that the receiver noise measured using the Y-factor method correctly represents the heterodyne sensitivity. In this measurement the IF frequency in the primary down conversion is 1.35 GHz, and the resolution bandwidth is 100 kHz.

4. Conclusion

We have shown that the lattice-cooled HEB mixer is usable in a practical receiver. In particular, doubts regarding linearity, saturation and stability have been addressed. Although the best receiver noise measured at 200 GHz is well above that of current SIS receivers, it is expected that this noise will not increase significantly with frequency, and that the HEB receiver may offer superior noise performance to SIS receivers above about 1 THz.

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