Phonon-cooled NbN HEB Mixers for Submillimeter Wavelengths

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Abstract

The noise performance of receivers incorporating NbN phonon-cooled superconducting hot-electron bolometric mixers is measured from 200 GHz to 900 GHz. The mixer elements are thin-film (thickness ~ 4 nm) NbN with ~5 to 40 μm^2 area fabricated on crystalline quartz substrates. The receiver noise temperature from 200 GHz to 900 GHz demonstrates no unexpected degradation with increasing frequency, being roughly $T_{RX} \approx$ 1–2 K GHz^{-1}. The best receiver noise temperatures are 410 K (DSB) at 430 GHz, 483 K at 636 GHz, and 1150 K at 800 GHz.

Introduction

Superconducting hot-electron bolometric mixers are emerging as the alternative technology to SIS mixers for heterodyne detection above 1 THz. This technology promises good sensitivity (T_{RX} < 1 K GHz^{-1}), low local-oscillator power requirement (< 1 μW), and a large useable IF bandwidth (several GHz). This type of mixer should have good performance up to infrared wavelengths. It also utilizes the same components as those used in an SIS-based receiver system (except a magnetic field is not needed), making the technological transition convenient and straightforward.

The goal of our present series of experiments is to study the performance of the phonon-cooled NbN hot-electron mixer [1, 2] at frequencies where we have a good understanding of the measurement techniques, and where we can also make direct comparisons to the performance of SIS mixers. In our experiments near 200 GHz [3], we demonstrated the operation of the superconducting HEB mixer in a practical receiver, measuring its linearity, stability and saturation level, and also detecting molecular line emission from a laboratory gascell. The sensitivity of the receiver was T_{RX} = 750 K (DSB) at 244 GHz, with 1.5 GHz IF and 500 MHz bandwidth. While this sensitivity is not competitive with that of SIS receivers operating in the same frequency band, similar noise performance should in principle be possible at frequencies beyond 1 THz, unlike for current SIS mixers made from niobium.

Following this successful proof-of-principle experiment, which proved that the superconducting HEB mixer is a properly behaving heterodyne detector, we built and tested a receiver operating at 400 GHz [4]. The block and mixer are nearly scaled versions of those operating at 200 GHz. Measurements at these frequencies yielded good receiver noise performance, typically better than 2 K GHz^{-1}, and at some frequencies better than 1 K GHz^{-1}. The best receiver noise temperature in this frequency band is 410 K at an LO frequency of 430 GHz. We attribute the improvement in the noise performance to better quality NbN film [5]. In this paper we report measurements made at higher frequencies, in the 600 GHz and 900 GHz bands.

Mixer and Receiver

The mixer element is an electron-phonon cooled [lattice-cooled] HEB mixer. The mixer element is formed from reactive magnetron sputtering of NbN on *z*-cut crystalline quartz [5]. The substrate material is chosen because the waveguide block is designed for its dielectric constant, and is chosen over fused quartz because of its superior thermal conductance. The film is etched to form a bridge with 5 $\mu\mathrm{m}^2$ to 40 $\mu\mathrm{m}^2$ area across two overlaid TiAu electrodes which couple the mixer to the waveguide. Because the length and width are not critical dimensions in the operation of the mixer, a mixer with a range of impedance can easily be fabricated. Additionally, by adjusting these dimensions the local-oscillator power requirement can be varied as its value depends on the volume of the mixer.

For our mixers the typical film thickness is 40 Å, and the bridge is 5–20 μm wide and 2 μm long. The room temperature resistance is ~ 1500 Ω / . The film has $T_c \sim 8$ K, $\Delta T_c \sim 1$ K, and j_c ($T = 4.2$ K) ~ 1 × 10^6 A cm^{-2}. The mixer has an IF bandwidth of about 2 GHz, which is sufficient for our present measurements. Further increase in IF bandwidth is possible by reducing the film thickness or by improving the quality of the film [5]. Changing the substrate to one on which better film can be grown is possible, but would obviously entail a different design for the mixer. The (absorbed) local-oscillator power is ~ 1 μW.

freq. band [GHz]	waveguide dimension [a × b mm]	substrate size [t × w × l mm]
200	1.1 × 0.28	0.13 × 0.51× 7.5
400	0.51 × 0.12	0.058 × 0.28 × 6.3
600	0.37 × 0.091	0.041 × 0.16 × 2.0
900	0.25 × 0.066	0.030 × 0.13 × 2.0

Table 1. Waveguide and substrate dimensions

The receivers operating at 600 GHz and 900 GHz are scaled versions of those operating at 200 GHz [3] and 400 GHz [4]. Further details of the mixer design can be found in [6]. The dimensions of the waveguide mixer are summarized in Table 1. The mixer is suspended across a waveguide, and the mixer block has a mechanically driven backshort. The mixer is operated at $T_{\mathrm{physical}} \geq 4.2$ K. The waveguide is coupled to the input beam with a corrugated feed, which illuminates an off-axis paraboloid. The beam passes through several layers of porous Teflon IR filters at 4.2 K and 80 K, and through a 0.5 mm Teflon window, which seals the cryostat. A Martin-Puplett diplexer employing free-standing wire-grids is used to ensure adequate LO coupling.

The local-oscillator power is supplied by a multiplied solid state source, except those measurements made above 820 GHz. For those measurements a backward-wave oscillator is used.

Measurements

The receiver sensitivity is measured using the *Y*-factor method of alternately placing a hot load at 295 K and a cold load at 77 K at the input of the receiver. Previous measurements [3] have shown that the mixers used in our study do not suffer from direct detection saturation effects due to the broad band response to the input radiation. Furthermore, all the receiver noise temperatures reported are *not* corrected to account for losses. The sensitivity refers to the double-sideband receiver noise temperature. Except for the measurements near 200 GHz, the IF output power is detected after a 200 MHz wide filter centered at 1.4 GHz.

The current-voltage (*I-V*) curves of 600 GHz and 900 GHz mixers are shown in Figure 1, with the insets showing the IF power output as a function of DC voltage bias in response to hot and cold loads placed at the input of the receiver. These *I-V* characteristics are similar to those of mixers giving the best noise performance at the lower frequency bands, although it is not possible definitively to predict which mixer will give good RF noise performance by mere inspection of its *I-V* curve. In our experiments, we pre-select mixers with high T_c, high j_c, low resistance, and a large ratio of the critical current to current measured in the resistive region, which is usually fairly constant over a broad bias range. About 6 mixers were tested at both 600 GHz and 900 GHz, and the noise performance of all the mixers was typically better than 3 K GHz^{-1}.

LO frequency [GHz]	DSB L_c [dB]	T_{mix} [K]	T_{RX} (DSB) [K]
244	~−18	~500	750
430	-10.5	370	410
636	-13	400	483
800	-16	990	1150

Table 2. Best noise performance in each frequency band, with estimates of the conversion loss and mixer noise temperature.

Table 2 summarizes the performance of the mixers that gave the best noise performance in each frequency band. In the same Table, estimates of the DSB conversion loss and mixer noise temperature are also stated. The sensitivity of the receivers is plotted as a function of LO frequency in Figure 2. The frequency of each point is verified by measuring it with the Martin-Puplett interferometer.

Conclusion

We have used the electron-phonon cooled version of the superconducting hot-electron bolometric mixer in a waveguide receiver, and performed noise temperature measurements from 200 GHz to 900 GHz. The best receiver noise temperatures are better than 1 K GHz^{-1}. Further improvements in the noise temperature should be possible when the mixer design is optimized, specifically when the RF and IF mixer impedance are better matched to their respective circuits.

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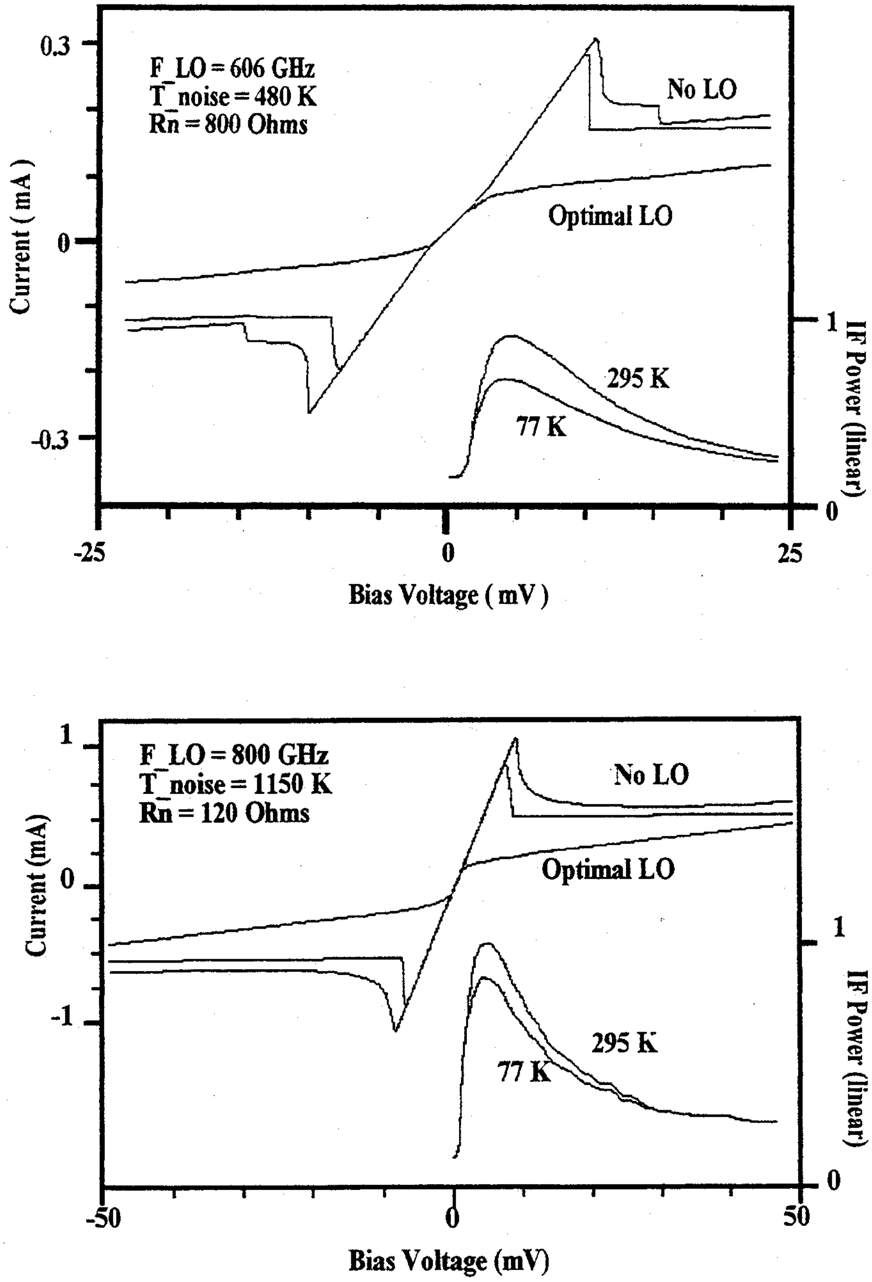

Figure 1. I-V curves of mixers operating at 600 GHz (top) and 800 GHz (bottom). The lower right hand corner in each figure shows the IF power as a function of DC voltage bias in response to hot and cold loads placed at the receiver input.

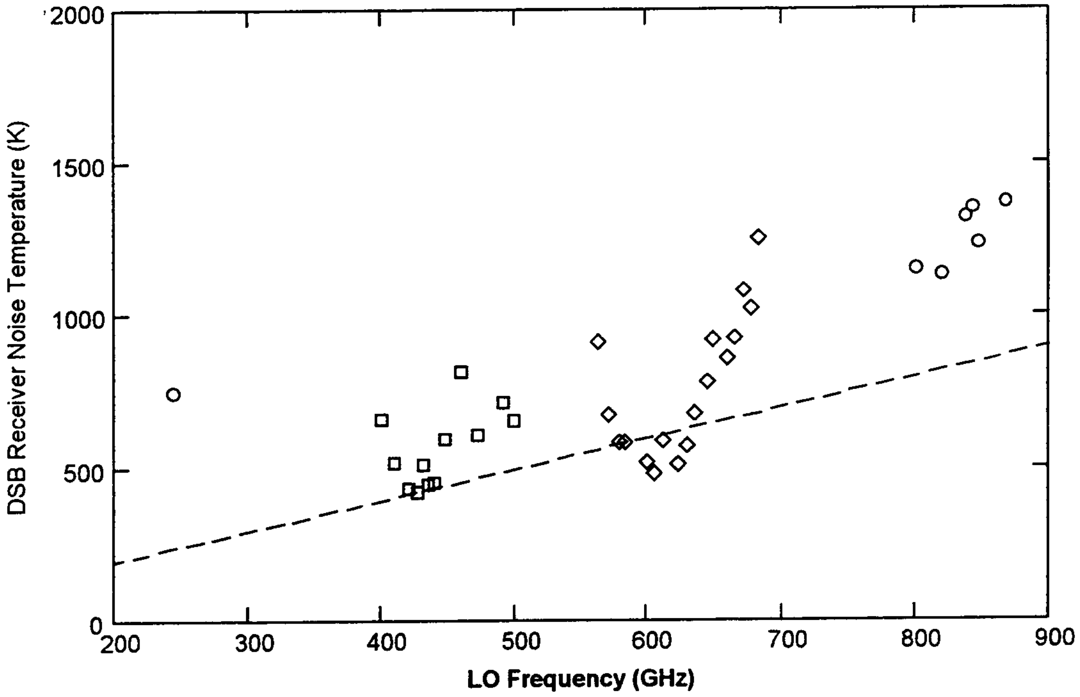

Figure 2. Performance of the best mixer in each frequency band. The dashed line indicates 1 K GHz^{-1}.