First Light with an 800 GHz Phonon-cooled HEB Mixer Receiver

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Abstract

Phonon-cooled superconductive hot-electron bolometric (HEB) mixers are incorporated in a waveguide receiver designed to operate near 800 GHz. The mixer elements are thin-film niobium nitride microbridges with dimensions of 4 nm thickness, 0.2 to 0.3 μm in length and 2 μm in width. At 780 GHz the best receiver noise temperature is 840 K (DSB). The mixer IF bandwidth is 2.0 GHz, the absorbed LO power is ~0.1 μW. A fixed-tuned version of the receiver was installed at the Submillimeter Telescope Observatory on Mt. Graham, Arizona, to conduct astronomical observations. These observations represent the first time that a receiver incorporating any superconducting HEB mixer has been used to detect a spectral line of celestial origin.

Introduction

Superconducting HEB mixers look to become the technology of choice for heterodyne detection above 1 THz. This technology has thus far fulfilled, in the laboratory at least, all the basic requirements for efficient astronomical observing at submillimeter wavelengths: low-noise performance, low local oscillator power requirement and large intermediate frequency bandwidth. However, performance in the laboratory is often a poor substitute for performance in the field. Even with the detection of molecular lines in the laboratory with this type of receiver, many people, in particular potential users, remain cautiously skeptical about whether or not this new technology will be useful in practice. In order to address this final concern directly, we have aimed our efforts in the past six months to build a complete receiver system employing a superconducting HEB mixer to take to a submillimeter telescope facility and test its performance definitively.

Our receiver employs a phonon-cooled HEB mixer [1] fabricated from niobium nitride [2]. The mixer elements are thin-film microbridges with typical thickness of 4 nm fabricated on crystalline quartz substrates. The critical temperature, T_c, is ~9 K, with a transition width of ~1 K. The sheet resistance ranges from 1000 to 2000 Ω.

Over the course of our experiments [3], we have learned that all of our mixers fabricated using conventional optical photolithography require more local-oscillator power

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than can be conveniently provided by frequency multiplied solid-state sources, especially at the highest frequencies. For example, we were able to pump an 800 GHz mixer at only two frequency points. Furthermore, with optical lithography it is difficult to make a mixer that has simultaneously a low impedance and low LO power requirement. Since our goal was to build a receiver for a telescope, we absolutely needed to be able to pump the mixer continuously across the operating band of the receiver. Also, we desired to lower the mixer impedance from about 400 Ω or so, which was typical of optically fabricated mixers, to about 100 Ω. For a phonon-cooled mixer the optimal LO power simply scales with the volume of the microbridge. With the thickness fixed, the area of the mixer can be flexibly adjusted in order to give a wide range in impedance and in the level of local-oscillator power. We have therefore fabricated NbN microbridges defined by electron beam lithography that have in-plane areas ~10 times smaller than those manufactured for our previous studies. Such mixers have LO power requirement reduced by 10 dB compared to that of larger mixers. The mixers also have favorably lower impedance. In this paper we state the performance of our HEB receiver, and show results of its operation on a telescope.

Receiver Performance

A current-voltage curve of a mixer is shown in Figure 1. This mixer is 2 μm wide and 0.3 μm long, with a normal room-temperature resistance of 90 Ω. The general shape of the IV curve is similar to the larger mixers. One major difference, however, is that the voltage scale is compressed in the voltage-total IF power curve, which is also plotted in the figure. This difference is a clue that the new mixer will require less local-oscillator power and dc power to reach the optimal operating point. Incidentally, this difference also has interesting consequences for the mixer saturation level, which is discussed below.

The mixer is incorporated in a waveguide block with a mechanically driven backshort. The block was designed to accommodate an SIS mixer, the details of which can be found in [4]. The corrugated feed illuminates a cold off-axis paraboloid and an optical flat before exiting the cryostat. Several layers of porous Teflon provides near-infrared filtering, and a 0.5 mm Teflon window seals the cryostat. The local-oscillator is a multiplied solid-state source, and a Martin-Puplett diplexer is used to combine the local-oscillator and signal beams.

Receiver noise temperature

The sensitivity of the receiver was measured using the standard *Y*-factor technique of alternatively placing a room temperature load and a cold load at the temperature of liquid nitrogen at the input of the receiver. No corrections were made. We were able to make a continuous measurement of the receiver noise temperature across the operating band of the local-oscillator source. The noise performance across the 800 GHz band is plotted in Figure 2, and across the band, the noise temperature is always less than 2 K GHz^{-1}. The best noise temperature at 780 GHz is 850 K, where we estimate that the conversion loss is 14 dB and that T_{mix}= 750 K. The receiver will actually work all the way down to the cut-off frequency of the waveguide, which is near 600 GHz.

IF bandwidth

We have measured the intermediate frequency bandwidth of a representative mixer from the same batch of mixers at a signal frequency of 20 GHz. The measurement is shown in Figure 3, which shows that the –3 dB roll-off in the gain occurs at 2.0 GHz. This is very similar to the bandwidth we have measured in a number of previous batches. Unfortunately, this value falls considerably short of the 10 GHz predicted for NbN-based mixers, and we attribute this to the quality of the film that can be grown on the chosen substrate [2]. For our present purposes, 2.0 GHz is sufficient; but, for such applications as extragalactic observations and interferometry, it will be necessary to have more bandwidth.

Gain compression and LO power

The LO power level and the linearity of the 800 GHz mixers were measured using a technique described in [5]. In this method, a second local-oscillator is coupled to the receiver at the signal port. The input power from the second source is calibrated against the receiver's response to the hot and cold loads. The technique assumes equivalence between the receiver's response to broad-band noise and monochromatic radiation. Using this technique, we determined that the LO incident at the receiver is 1 μW. The 1 dB compression point occurs about –25 dB below the LO power, which corresponds to an input power of 3 nW. This result is quite different from our result with the larger mixer, in which the 1 dB compression point was –6 dB below the LO power. We conclude that the saturation is occurring at the IF output of the receiver rather than at the RF input. That this might be the case can be simply argued: from Figure 1, we estimate that the maximum IF voltage swing in which there is constant conversion gain is about 0.1 mV. If the IF load resistance is 50 Ω, then the IF output power with maximum swing voltage is 0.1 nW. From the our estimate of the conversion loss for this mixer, about 16 dB, we see that the power at the input of the mixer is 4 nW, in good agreement with the actual measured value. Thus, the mixer saturates when there is 3 nW of power incident on the receiver within a bandwidth given the IF bandwidth. In terms of load temperature, this represents ~5×10^4 K. Thus, our *Y*-factor measurements were made well within the linear regime of the mixer.

From the constant temperature assumption, we measure that the absorbed LO power is about ~0.1 μW. Thus, there is a 10 dB loss in the LO path. From FTS measurements we know that we are losing about 3 dB in gain from the peak response near 600 GHz. Also, the losses in the diplexer and filters is maximally about 4 dB. Thus there appears to be about 3 dB of power that is lost. This may simply be the power being absorbed to heat the lattice. Further investigation is necessary to understand these losses.

Astronomical observations

The receiver was installed at the 10 m Submillimeter Telescope Observatory (SMTO) on Mt. Graham, Arizona in March, 1998. The primary task of the run was to use the HEB mixer receiver to detect known submillimeter lines of astronomical importance in order to prove that it works as a practical instrument. The mixer was mounted in a fixed-tuned block of the type developed for the SMA receivers [4], and is fixed so that over the operating band the mixer sees a real impedance of about 110 Ω. The receiver IF bandpass is centered at 1.5 GHz, and useable bandwidth of the receiver, measured after the facility spectrometer, is 600 MHz. The noise temperature at an LO frequency of 810 GHz is 1300 K, which is actually 15% noisier than the receiver's performance in the laboratory at sea level. We attribute this degradation to the cooler bath temperature at high altitude. The noise temperature at an LO frequency of 690 GHz was 650 K. The receiver noise temperature as a function of IF is shown in Figure 4. The LO was a conventional frequency multiplied solid-state Gunn oscillator. The LO was coupled to the signal beam with a Martin-Puplett diplexer employing free-standing wire grids. The stability of the receiver system was primarily determined by the changes in the LO power level. The receiver setup is identical an SIS-based system, with the exception that it is not necessary to provide a magnetic field to the mixer. Our brief experience with the HEB receiver on a telescope shows that it is easier to use than an SIS receiver.

We observed several bright sources to test the receiver under reasonably favorable sky opacities. For example, we made a five-point map of IRC+10216 in CO (J=7→6) at 805 GHz, shown in Figure 5, which beautifully illustrates that the beam of the telescope is, as expected, about 10 asec. With the same receiver, we were also able to observe the CO (J=6→5) at 690 GHz and the fine-structure transition of neutral carbon at 809 GHz.

Conclusion

We have developed a waveguide receiver employing a phonon-cooled superconductive HEB mixer, and have conducted astronomical observations with it. The receiver has sufficient bandwidth, reasonable noise performance, and is generally a very useable, practical system. We anticipate that in the coming year that we will optimize the receiver design, and make its performance competitive to SIS receivers now in operation.

Acknowledgments

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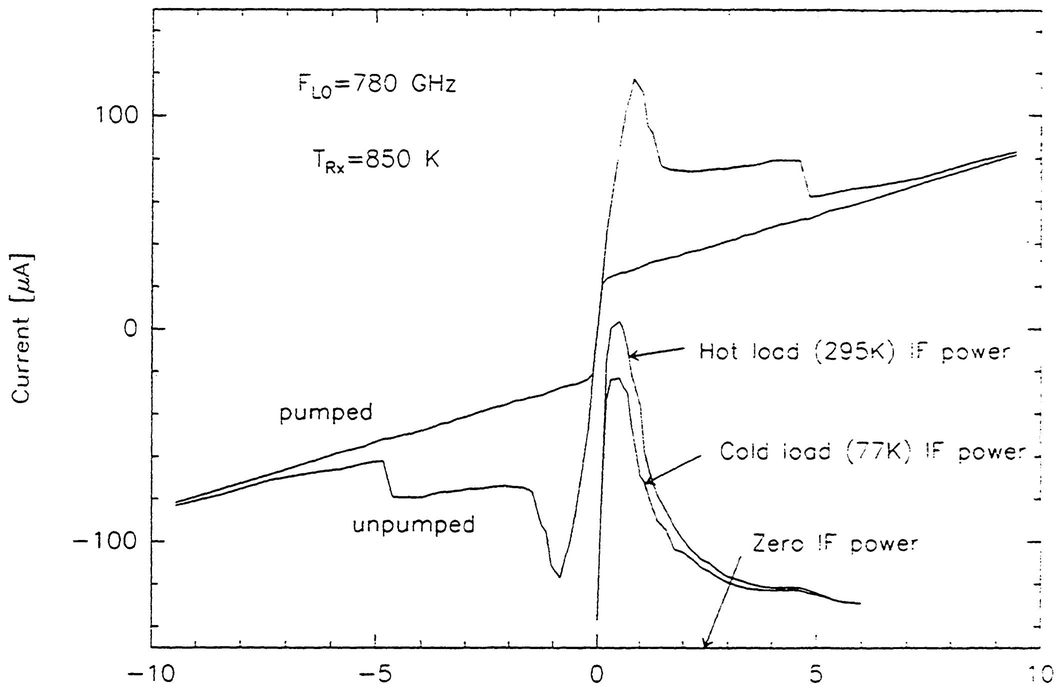

Figure 1. Current-voltage characteristic of a mixer 2 mm wide and 0.3 mm long measured at 4.2 K. At an LO setting of 780 GHz, the receiver noise temperature is 850 K (DSB). The operating bias point is 0.7 mV.

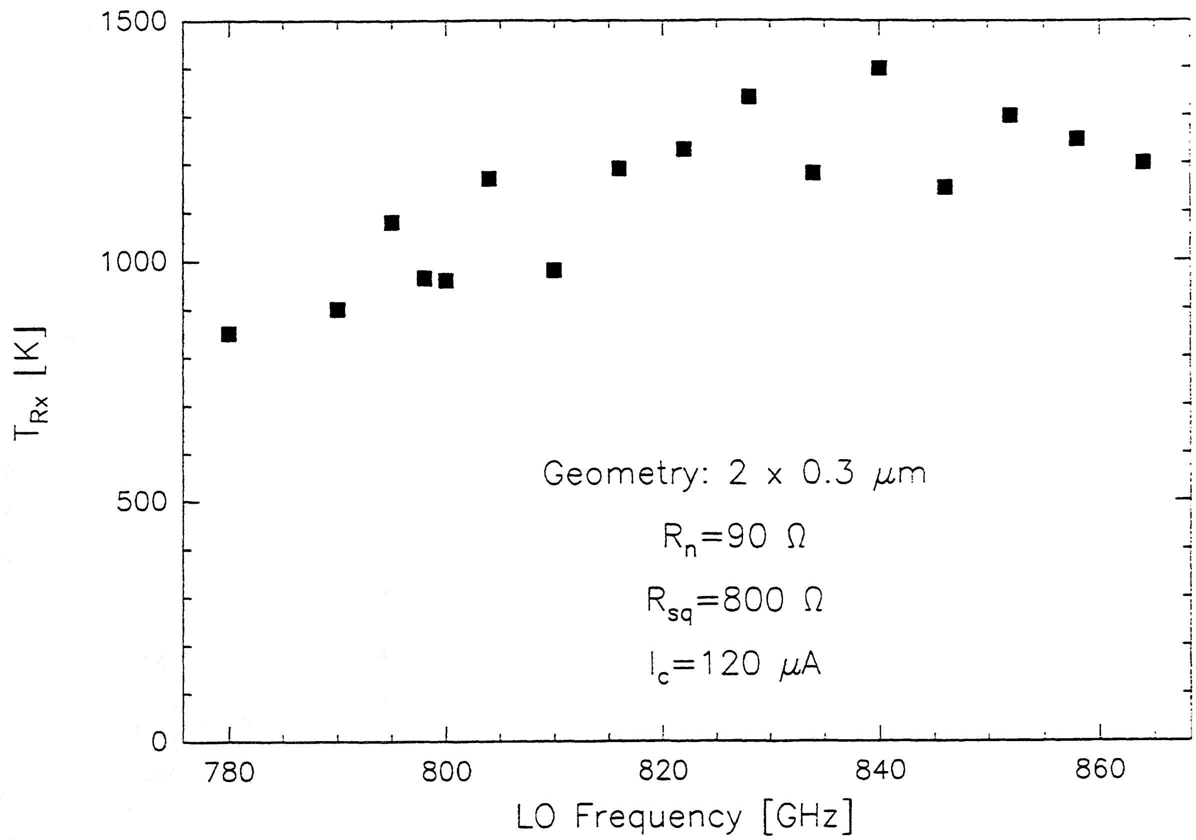

Figure 2. The receiver noise temperature across the operating band of the local-oscillator source.

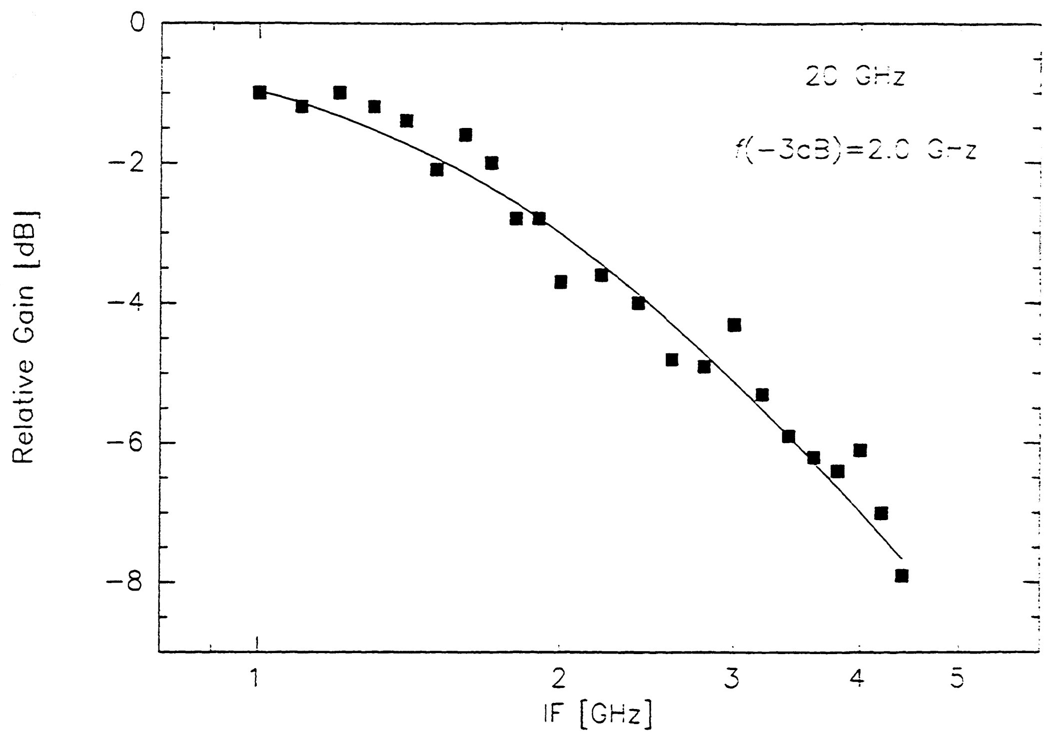

Figure 3. The IF gain bandwidth measured at a signal frequency of 20 GHz. The data are fitted to the formula $(1+(f/f_c)2)^{-1}$, where f_c=2.0 GHz.

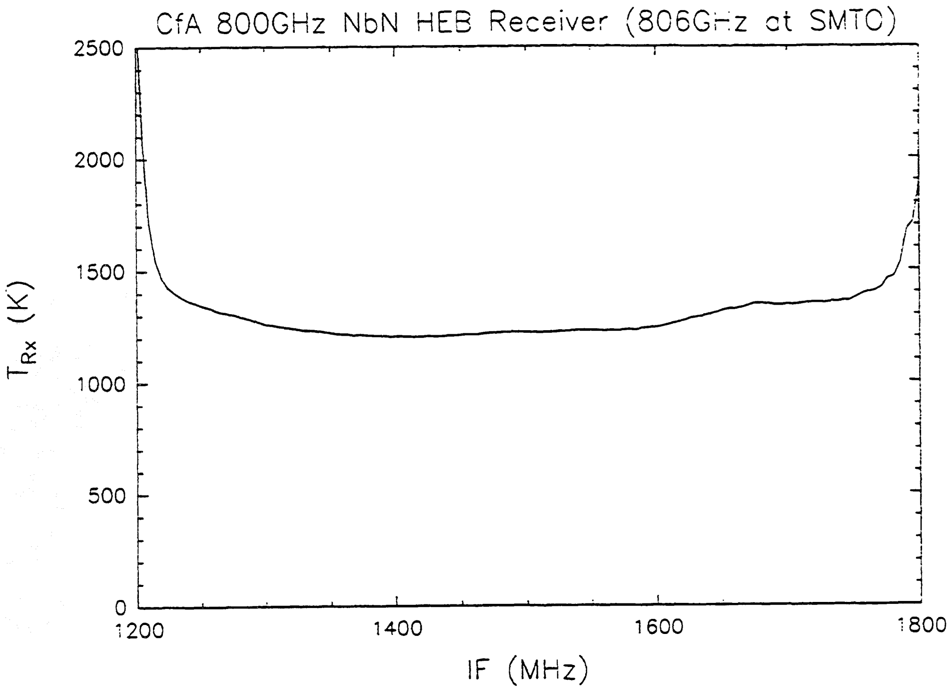

Figure 4. The receiver noise temperature measured as a function of IF for the mixer used at the telescope. This is computed after the AOS. The useful bandwidth is roughly 600 MHz, and there apparently is no degradation in the noise at the highest IF. The slight rise at 1.7 GHz is due to the response of the isolator following the mixer.

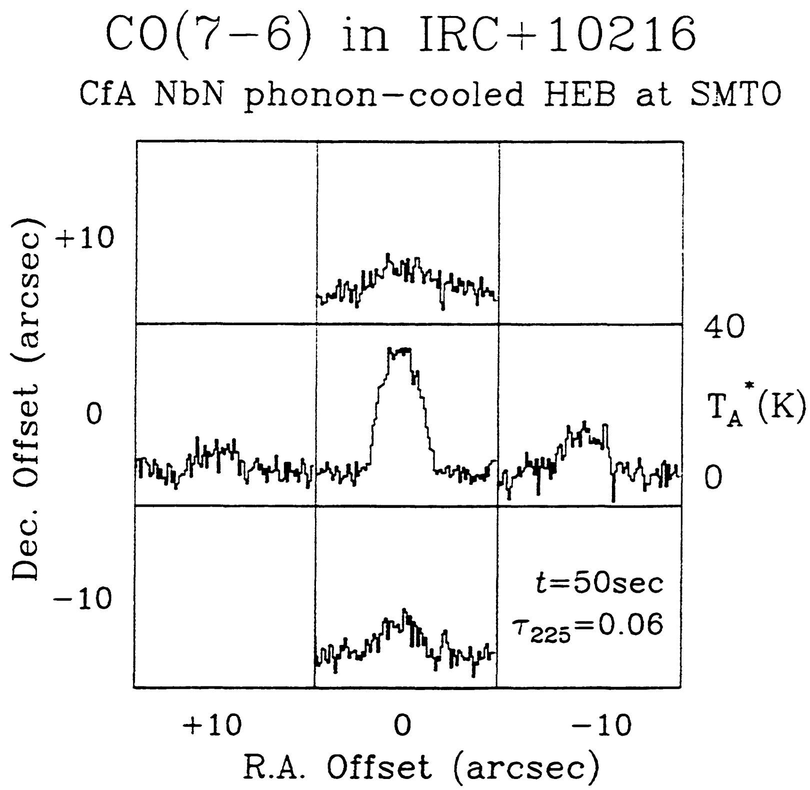

Figure 5. A five-point map of IRC+10216 in CO(7-6). The LO frequency for this measurement is 805 GHz. Each panel represents a spectra taken at different sky offsets from the central position, and within each panel, the amplitude is given in antenna temperature and the frequency span is about 100 MHz.