Impedance and Bandwidth Characterization of NbN Hot Electron Bolometric Mixers

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Abstract

We are presenting here our recent results of noise temperature and impedance measurements for NbN Hot Electron Bolometer (HEB) mixers.

The noise temperature measurements were performed over a 1-8 GHz IF band using an LO frequency of about 1.6 THz using quasi-optical coupling and a single low noise HEMT MMIC amplifier.

On the other hand, the impedance measurements were completed with a network analyzer in the presence of LO power and DC bias, over a 2-10 GHz frequency range.

The experimental results of both sets of measurements are used to predict noise and gain bandwidth of our devices and for comparison with those obtained from the standard model.

Introduction

Hot Electron Bolometer (HEB) technology has become mature enough over the past years to allow the development and implementation of observing platforms in the terahertz region such as HIFI [3], TREND [10], GREAT [4] and TELIS [7].

In such receivers, there are two parameters that are particularly important, since they may ultimately determine the threshold for the minimum signal level that can be reliably detected, namely the *IF gain bandwidth*, defined as the IF frequency at which the conversion efficiency of the mixer drops by 3 dB from its low IF value; and the *noise bandwidth*, defined as the frequency at which the mixer noise doubles compared to its zero frequency value [9].

For NbN or Nb based HEB mixers, the noise and gain bandwidth depend upon film properties such as thickness, critical temperature (T_c) and acoustic coupling between film and substrate [6]. In principle, these mixers can reach an IF gain bandwidth of a few gigahertz, whereas their noise bandwidth can be even larger [1].

Here we present experimental results obtained from characterization of two of the main properties of HEB devices that are relevant to their intermediate frequency response, namely the IF small signal impedance, which can be useful to estimate gain bandwidth without requiring a THz tunable source, and the receiver noise temperature as a function of intermediate frequency.

The measurements were performed over a wider frequency range than it has ever been done (1-8 GHz and 2-10 GHz, respectively), with the purpose of evaluating the effectiveness of HEB mixers as low-noise broadband receivers.

Experimental Setup

Two different setups were used to carry out the two sets of measurements.

A pair of mixers were selected from two different batches. The sample used for noise bandwidth quantification was fabricated on silicon substrate with an active NbN area 5 nm thick, 1 μm long and 4 μm wide. A twin-slot antenna was used with this device.

For impedance measurements, though, the device was fabricated on magnesium oxide substrate and the dimensions for the superconducting area were 4 nm thick, 2 μm long and 20 μm wide. No antenna was used in this case.

In both cases, the THz radiation was coupled to the device using a quasi-optical approach, in which a elliptical silicon lens couples both the RF and LO beams into the HEB.

The LO source was a CO_2-pumped laser running in continious wave (CW) mode in the THz regime.

A. Noise Bandwidth

Figure 1 shows the apparatus used for noise temperature characterization. The wavelenght for the local oscillator was 184 μm, which corresponds to 1.63 THz.

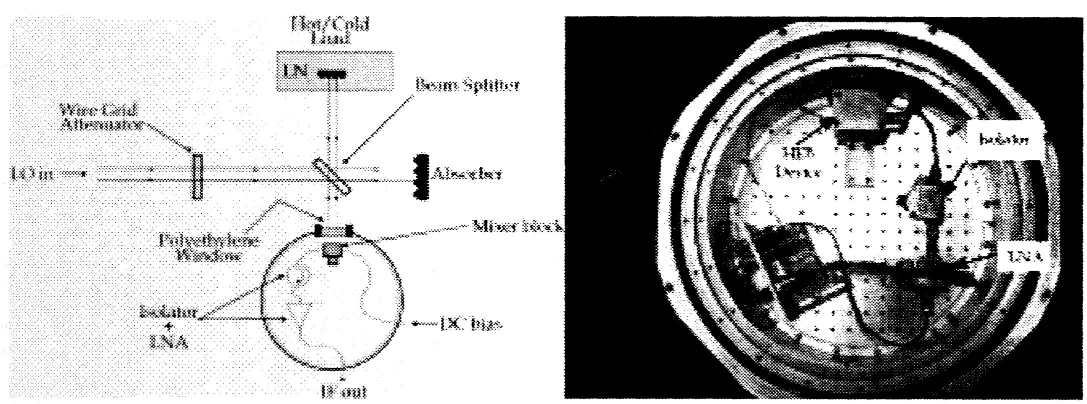

Figure 1: Laboratory setup for measuring HEB noise temperature

A hot/cold blackbody source is inserted into the beam path, and the change in IF power (Y-factor) is registered at the power meter. The noise temperature of the receiver is then computed directly from the Y-factor.

The interior of the liquid helium cryostat used to cool down the specimens is also shown in Figure 1. The bolometer chip was mounted in a mixer block, to provide it with a bias circuit along with a connection to the IF chain achieving a reasonably good match over the desired bandwidth and eliminating the need for an external bias tee.

The wide-band HEMT InP MMIC low noise cryogenic amplifier was designed by Prof. Sander Weinreb at JPL/Caltech. This amplifier has two stages, a gain of 20 dB and a equivalent noise temperature below 10 K throughout its band (1–10 GHz).

In order to minimize standing wave problems and improve stability, a cryogenic isolator was placed at the input of the LNA. Since none of the currently available cryogenic isolators can cover more than an octave, the band of interest was divided into three smaller bands; 1–2 GHz, 2–4 GHz and 4–8 GHz.

B. Impedance and Gain Bandwidth

Figure 2 illustrates the setup used for this part of the experiment.

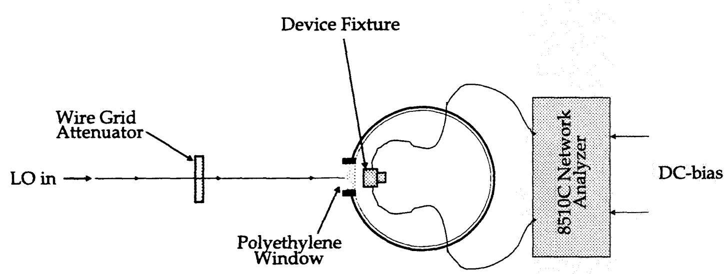

Figure 2: Setup used for IF impedance measurements

A transmission technique similar to that described in [5] was used to determine the impedance of HEB mixers by measuring the scattering parameter S_{21} as a function of frequency.

One may note that all measurements of HEB impedance such as in [5], thus far have been performed without LO power. It is obviously much more important to measure the impedance under more realistic operating conditions and near the optimum point for mixing, as done here [1].

The impedance characterization took place in the presence of laser illumination at a wavelength of 194 μm (1.55 THz), while DC bias was applied to the sample through the bias tees included in the 8510C Automatic Network Analyzer (ANA). A thru-reflect-line (TRL) calibration technique at 4 K was performed in order to establish the reference planes prior to completing the actual measurements [8].

The device was carefully put in place between the two microstrip launchers using a flip-chip technique (Figure 3A). A silicon lens was used for coupling the THz LO power to the device in a more efficient way (Figure 3B).

In order to prevent saturating the mixer with microwave power from the ANA, both the calibration and the measurement were taken to completion with a microwave power level of -48 dBm, which was found to be convenient for this study, since it was well below the LO power required to suppress the superconducting state in the HEB.

[1]One early impedance measurement was performed with LO power applied, but in that case the LO frequency was only 20 GHz [2].

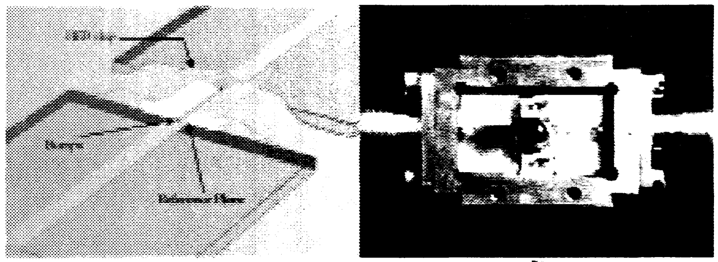

Figure 3: Device fixture used to measure IF small signal impedance

Results and Discussion

A. Noise Bandwidth

The critical current for this device was 420 μA. The optimum operating point (best Y-factor) was found for $V_0 = 1$ mV and $I_0 = 42$ μA ($R_0 = 23.8$ Ω).

The double-sideband receiver noise temperature, $T_{R,DSB}$, was computed from the experimental Y factor and plotted as a function of frequency (Figure 4).

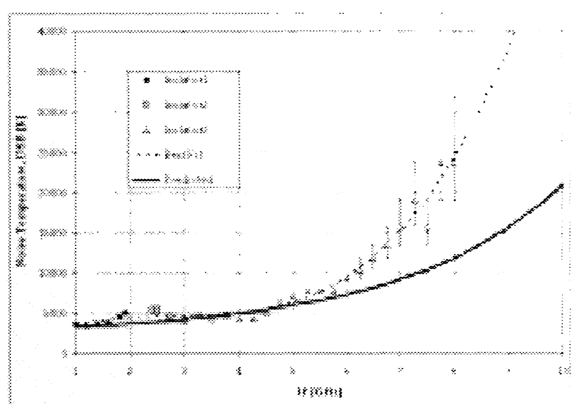

Figure 4: Measured noise temperature vs IF frequency

The dashed line represents the best fit to the experimental data set and the solid line corresponds to the predicted value based on the standard model, which was computed using fitting parameters such as the total conversion loss of the mixer, L_{Ctot}, the self-heating parameter $C = C_0 I_0^2$, the measured thermal fluctuation noise at the lowest IF frequency, T_{flM}, and the electron thermal relaxation time, τ_θ.

The agreement among the calculated receiver noise temperature and its experimental counterpart is reasonable for frequencies below 6 GHz, after which the actual noise temperature grows more rapidly compared to the theoretical calculation. The discrepancies between predicted and measured values of $T_{R,DSB}$ above 6 GHz are attributed to changes in the frequency response of the mixer block at low temperatures, extra parasitics not considered in the model of its impedance, as well as mismatch between components in the IF chain.

We can estimate the noise bandwidth from the data plotted in Figure 4, resulting in 5.32 GHz using the standard model formulae and close to 5.25 GHz using the experimental data.

By taking the ratio of the receiver output noise power with the mixer at the optimum operating point (DC and LO power applied), P_{op}, to the output noise power in the superconducting state (no DC or LO power applied), P_{sc}, it was possible to use this value (often called the U-factor, $U = P_{op}/P_{sc}$) to predict the total conversion gain of the mixer, G_C, as well as its output noise, T_{out}, expressly [8]

$$G_C = \frac{U\left(T_{bath} + T_{IF}\right)}{2T_{cold} + 2T_{R,DSB}} \tag{1}$$

$$T_{out} = \frac{U(T_{IF} + T_{bath})}{T_{cold} + T_{R,DSB}} T_{R,DSB} - T_{IF} \tag{2}$$

where T_{cold}= 77 K is the temperature of a broadband blackbody noise source present at the input of the mixer when the U-factor measurement is performed, T_{IF} is the equivalent noise temperature of the IF chain, T_{bath}= 4.2 K is the temperature of a 50-ohm load at the matched port of the circulator and $T_{R,DSB}$ is the measured double-sideband noise temperature of the receiver.

The U-factor was recorded for the same set of frequencies as shown in Figure 4, then (1) and (2) were used to compute G_C and T_{out}, respectively (Figure 5). The solid line in these plots corresponds to the predicted value, estimated also from the standard model.

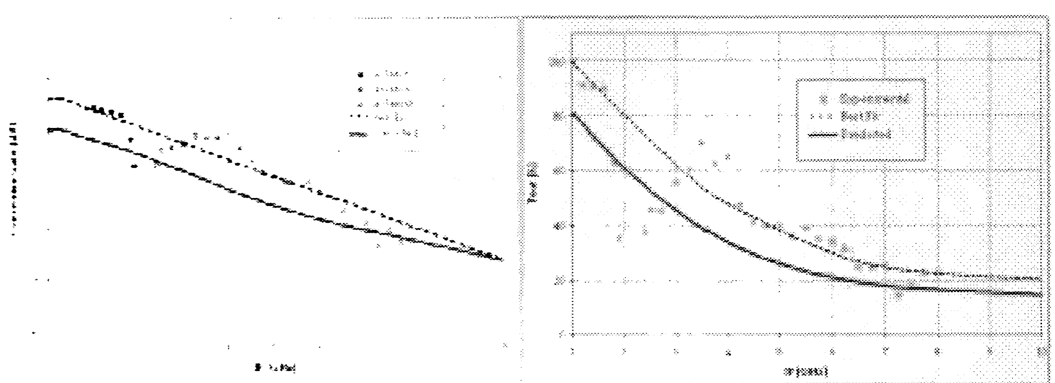

Figure 5: Measured conversion gain and mixer output noise vs IF frequency

There exists qualitative agreement between the best fit to the measured conversion loss and output noise shown in Figure 5: the discrepancy between these quantities is less than 3 dB and less than 20 K throughout the band, respectively. The actual gain bandwidth is close to 2.4 GHz.

One may note that the noise bandwidth is about 2.2 times the gain bandwidth.

B. Impedance and Gain Bandwidth

It can be shown that the gain bandwidth of an HEB can be estimated as [5]

$$B_e = \frac{1}{2\pi\tau_\theta}\left(1 - C\frac{R_L - R_0}{R_L - R_0}\right) \tag{3}$$

The dependence of the conversion gain of the mixer on IF frequency, self-heating parameter C, as well as the electron relaxation time τ_θ, also holds for the IF small signal impedance, i.e.

$$Z(\omega) = R_0\left(\frac{1+C}{1-C}\right)\left(\frac{1 - j\omega\frac{\tau_\theta}{1-C}}{1 - j\omega\frac{\tau_\theta}{1-C}}\right) \tag{4}$$

Therefore, by measuring the impedance of the mixer, it is possible to fit the experimental data to (4), obtain a suitable value for C and τ_θ, and then predict the gain bandwidth using (3).

Figure 6 shows the real and imaginary part of the impedance of the sample biased at 1.5 mV and 56 μA (R_0 = 26 ohm), after subtracting the effect of the microstrip feed lines and parasitic reactances associated to the contact bumps.

The two different predictions in Figure 6 correspond to different values of C, one obtained by fitting the measured data to (4) and one obtained from the differential slope of the IV curve (dV/dI) at that particular point, $C = \frac{dV/dI - R_0}{dV/dI + R_0}$, as predicted from the standard model [2]. The time-constant τ_θ is 47.98 ps in both cases and was obtained only using the least-square fit of the experimental impedance to (4).

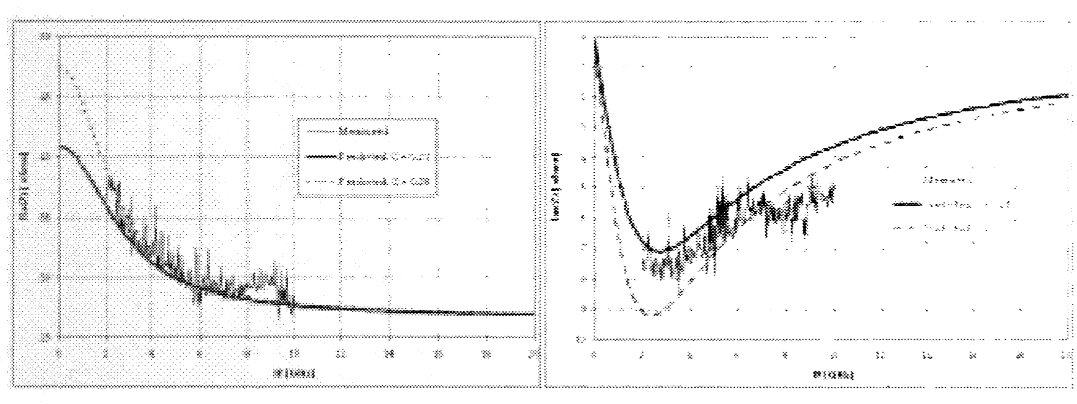

Figure 6: Measured and modelled impedance with device biased at (1.5 mV, 56 μA)

The impedance of this specimen was measured for some other quiescent points as well. The results for different settings are summarized in Table 1. The gain bandwidth was

Table 1: Predicted gain bandwidth for different operating conditions

V_0 [mV]	I_0 [μA]	dV/dI [Ω]	**Gain BW** [GHz]
0.6	14	44.7	3.6
0.6	30	27.6	3.4
1.0	23	66.2	3.3
1.0	42	38.1	3.5
1.5	56	47.5	3.3

estimated using (3) and the appropriate value for C and τ_θ obtained from the impedance measurements.

Though there is previous empirical evidence that suggests that there is a bias dependance of the IF bandwidth with bias voltage [6], our observations indicate only small changes in the bandwidth as V_0 changes. This is because we biased the device close to the optimum point for minimum noise temperature.

The predicted bandwidths exceed that for the device used in the noise bandwidth measurements. It is expected that a device on an MgO substrate should yield larger bandwidth, as observed.

Large values of V_0 would yield higher bandwidths at the expense of poor sensitivity.

Conclusions

A systematic study of the bandwidth properties of hot electron bolometric mixers has been reported in this paper.

The noise temperature of an HEB mixer was measured using a single MMIC low-noise amplifier based on InP HEMT transistors. This measurement allowed us to estimate the noise bandwidth, gain bandwidth and mixer output noise with moderate accuracy. The results are somewhat consistent with those obtained from the standard model.

The impedance of a sample mixer was characterized by means of an Automatic Network Analyzer using a TRL calibration at cryogenic temperatures. By using the impedance data, it was possible to predict the bandwidth of the device under test without having a tunable THz source. The predicted bandwidth agrees with previously reported results for similar devices.

Further experiments will improve the accuracy of the measurements and the data will be useful for improvement of the current models of superconducting HEBs.

Acknowledgements

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References

[1] S. Cherednichenko, M. Kroug, H. Merkel, E. Kollberg, K. Yngvesson, B. Voronov, and G. Gol'tsman. IF Bandwidth of Phonon Cooled HEB Mixers Made from NbN Films on MgO Substrates. In *Proceedings: 11th International Symposium on Space Terahertz Technology, Ann Arbor, MI*, May 2000.

[2] H. Ekstroem, B. Karasik, E. Kollberg, and K. Yngvesson. Conversion Gain and Noise of Niobium Superconducting Hot-Electron Mixers. *IEEE Transactions on Microwave Theory and Techniques*, 43(4):938–947, April 1995.

[3] T. Graauw and F.P.Helmich. Herschel-HIFI: The Heterodyne Instrument For The Far-Infrared. In *Proc. of 'The Promise of the Herschel Space Observatory Symposium*, December 2000.

[4] R. Guesten, P. Hartogh, H.-W. Huebers, U. Graf, K. Jacobs, H.-P. Roeser, F. Schaefer, R. Schieder, R. Stark, and J. Stutzki. GREAT The First-Generation German Heterodyne Receiver For SOFIA. In *Proc. SPIE*, 2000.

[5] B. Karasik and W. McGrath. Microwave Transmission Technique for Accurate Impedance Characterization of Superconductive Bolometric Mixers. *IEEE Transactions on Applied Superconductivity*, March 1998.

[6] M. Kroug. *NbN Hot Electron Bolometer Mixers for a Quasi-Optical THz Receiver*. PhD thesis, Chalmers University of Technology, Sweeden, 2001.

[7] U. Mair, M. Krocka, G. Wagner, M. Birk, H.-W. Huebers, H. Richter, A. Semenov, P. Yagoubov, R. Hoogeveen, T. de Graauw, A. Maurellis, A. Selig, V. Koshelets, S. Shitov, B. Ellison, B. Kerridge, D. Matheson, R. Siddans, and J. Reburn. TELIS Development of a New Balloon Borne THz/Submm Heterodyne Limb Sounder. In *Proceedings: 13th International Symposium on Space Terahertz Technology, Cambridge 2002*, December 2002.

[8] F. Rodriguez-Morales. Impedance and Bandwidth Characterization of NbN Hot Electron Bolometric Mixers. Master's thesis, University of Massachusetts Amherst, USA, 2003.

[9] R. Schoelkopf, P. Burke, D. Prober, A. Skalare, B. Karasik, M. Gaidis, W. McGrath, B. Bumble, and H. LeDuc. Noise Bandwidth of Diffusion-Cooled Hot-Electron Bolometers. *IEEE Transactions on Applied Superconductivity*, 7(2):3576–3579, June 1997.

[10] K. Yngvesson, C. Musante, M. Ji, F. Rodriguez, Y. Zhuang, E. Gerecht, M. Coulombe, J. Dickinson, T. Goyette, , J. Waldman, C. K. Walker, A. Stark, and A. Lane. Terahertz Receiver With NbN HEB Device (Trend) - A Low-Noise Receiver User Instrument for AST/RO at the South Pole. In *Proceedings: 12th International Symposium on Space Terahertz Technology, San Diego CA*, Febr 2001.