Zero-Point Fluctuations Limited SIS Receiver at 500 GHz

Andrey Baryshev*, Willem Luinge
SRON-Groningen, P.O. Box 800, 9700 AV Groningen, The Netherlands

Valery Koshelets, Sergey Shitov
Institute of Radio Engineering and Electronics RAS, Mokhovaya St. 11, Moscow, 103907, Russia

T.M. Klapwijk
Department of Applied Physics and Material Science Centre, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands

Abstract. We report on a 471 GHz quasi-optical superconductor-insulator-superconductor (SIS) receiver with an uncorrected DSB noise temperature as low as 40±3 K. The results are analyzed using a novel method which does not require the determination of the embedding impedances and hence does not suffer from numerical instabilities. Excellent agreement with theory is only found after the zero-point quantum fluctuations (ZPF) for the noise temperatures are included, demonstrating that the intrinsic noise temperature of the SIS mixer is given by $\frac{hf}{2k_b}$, which is 11 K at 471 GHz.

SIS mixer noise temperatures in the submm band are approaching the quantum limit [1], [2], [3]. The inclusion of ZPF is essential for a full understanding of the low system noise level. We present a full analysis of noise sources of an experimental SIS heterodyne receiver at 471 GHz.

The analysis is based on splitting the SIS receiver into n linear elements connected in series. The noise power P in a bandwidth Δf is represented by a noise temperature $T^n = P/k_b\Delta f$ [4]. The bandwidth Δf is usually determined by a narrow band filter in the if chain. The receiver gain G_{sys} and receiver noise temperature T_{sys} can be written as

$$G_{sys} = \prod_{i=1}^{n} G_i, \quad T_{sys} = T_1 + \sum_{i=2}^{n} \frac{T_i}{\prod_{k=2}^{n} G_k}, \tag{1}$$

where G_i is gain and T_i is effective noise temperature of the i-th element. Loss in an element is represented by $G_i < 1$. Values of T_{sys} and G_{sys} can be measured by using the standard Y-factor technique and shot noise calibration of the if chain [5]. Just in front of the mixer an element unk is introduced describing the gain (loss) G_{unk} and noise temperature T_{unk} not explained by other known elements. The values G_{unk} and T_{unk} for one element can be determined from (1) if the properties of all other elements are known.

The Callen and Welton formula for noise power density

$$T^n = \frac{hf}{2k_b} coth(\frac{hf}{2k_bT}) \tag{2}$$

was used to include ZPF in the description of all receiver elements. The value given by (2) deviates significantly from the physical temperature at low temperatures. The blackbody calibration source noise temperatures were also corrected using (2).

The properties of optical elements can be calculated as follows. The output signal of a thin transparent film placed in front of receiver can be described as

$$T_{out} = T_{rad}\gamma_r + T_{abs}\gamma_a + T_{in}(1-\gamma_r)(1-\gamma_a),$$

where $\gamma_r = \frac{P_{ref}}{P_{in}}$ is the power reflection coefficient, $\gamma_a = \frac{P_{abs}}{P_{in}}$ is the power absorption coefficient, T_{abs} is the film temperature and T_{rad} is the power reflected towards the receiver. For example, T_{rad} is the room temperature for the beamsplitter and T_{rad} is equal to 4.2 K corrected by (2) for the dewar window. Equation (2) was applied to both T_{rad} and T_{abs} in order to include ZPF. The optical element gain and input noise temperature can be written as:

$$G_i = (1-\gamma_r)(1-\gamma_a), \qquad T_i = \frac{T_{rad}\gamma_r + T_{abs}\gamma_a}{(1-\gamma_r)(1-\gamma_a)}. \tag{3}$$

The values of γ_r and γ_a of the beamsplitter, the dewar window and the heat filters were determined with a Michelson Fourier Transform Spectrometer.

The unpumped SIS junction was used for if amplifier and detector chain calibration. The SIS junction's if output power can be described by the shot noise formula:

$$T_n = \frac{eR_dI}{2k_b} \coth(\frac{eV}{k_bT}), \tag{4}$$

where R_d is differential resistance, V, I are bias voltage and current. The signal at the output of the if amplifier can be described as [5], [6]:

$$\begin{aligned} T_{out} = \big[\ & T_{in}\ M(R_l,R_d) \\ & +\ T_{iso}(1-M(R_l,R_d)+T_{amp}\ \big]\ G_{amp}, \end{aligned} \tag{5}$$

where R_l is the if chain impedance connected to the SIS junction, T_{amp} and G_{amp} are the noise temperature and

---

*Submitted to Applyed Physics Letters 5 September 1998, E-mail:andrey@sron.rug.nl the gain of if amplifier, T_{iso} is the temperature of the isolator 50 Ω load and

$$M(R_l, R_d) = 1 - \left(\frac{|R_l - R_d|}{|R_l + R_d|}\right)^2 \tag{6}$$

is the power coupling coefficient. Values of R_l, G_{amp}, T_{amp} and T_{iso} were obtained by fitting to the experimental dependance of the if output signal with bias voltage. The load impedance R_l may not necessarily be 50 Ohm because of if wiring transformation. The bias dependent if amplifier element G_i and T_i can be written as

$$G_i = G_{amp}, \quad T_i = \frac{(1 - M(R_l, R_d))T_{cir} + T_{amp}}{G_{amp}}. \tag{7}$$

Multiple Andreev reflection [6] was ignored because the subgap current for our $NbAlO_xNb$ SIS junction is low enough.

DSB mixer operation with the calibration signal applied in lower and upper sidebands (LSB, USB) with equal input impedance of mixer for LSB, USB and LO path is considered. The mixer gain from [1] can be simplified as:

$$G_{mix} = \underbrace{M(Z_{emb}, R_{rf})}_{G_{unk}} \underbrace{\frac{1}{4} R_{rf} {\frac{dI_{dc}}{dV_{rf}}}^2 R_d}_{G_M} \underbrace{M(R_d, R_l)}_{G_{IF}}, \tag{8}$$

where R_{rf} is the junction input impedance, R_d is the dynamic resistance of the pumped I-V curve and $M(a, b)$ is the power coupling coefficient from (6). According to (8) the mixer can be split into three parts with gains: G_{unk}, G_M, G_{IF}. The mixer DSB conversion gain for the junction, that is perfectly matched both to if and rf ports, is described by G_M. The ZPF ($\frac{hf}{2\ k_b}$) is the effective noise temperature of this element. The if chain mismatch is represented by G_{IF}. Subgap current shot noise determines the effective noise temperature for this element (4). The rf loss due to the tuning element mismatch is represented by G_{unk}. All rf losses in the lens and the loss due to the receiver beam efficiency are attributed to G_{unk}. For example, if the receiver beam is partly limited by the cold (4.2K) diaphragm then the element noise temperature T_{unk} could be calculated by an expression similar to (3) having $T_{abs} = 0$ and $T_{rad} = 4.2\ K$ corrected by (2).

The imaginary part [1] of the quantum conductance is not considered in this paper. In order to avoid this inaccuracy the bias point in the center of the photon step was used for the calculation.

Pumping parameter $\alpha = \frac{eV_{rf}}{hf}$ can be obtained with the reasonable accuracy by fitting the measured pumped I-V curve to the calculated one using [1]. The dynamic resistance R_d for the pumped I-V curve can be also measured. The junction input impedance R_{rf} can be calculated using the unpumped I-V curve and the determined pumping level α. Finaly the values for G_{unk} and T_{unk} can be derived from (1). The SIS mixer can be described without the numerically unstable calculation of the SIS junction embedding impedance by following the procedure described above.

The analyzed receiver contains a double dipole antenna SIS mixer with integrated tuning elements. This mixer is designed as a reference unit to measure the ultimate performance of the Integrated Receiver [7]. The rf design of the mixer has been described in detail in [8]. The tuning circuit consist of an end-loaded stripline connected to a double dipole antenna via a matching stripline transformer. The Josephson effect noise was suppressed by an integrated magnetic field control line. The receiver chip (4x4x0.5 mm) was mounted on to a silicon elliptical lens. An antireflection coating was applied to the lens. A backreflector was mounted behind the antenna. The mixer block was mounted on the dewar cold plate behind a Zitex heat filter at 4.2 K, a 150 μm quartz plate heat filter at 78 K and a 15 μm thick Kapton dewar window at 295 K. A mylar beamsplitter (6μm) was used to combine the LO signal with the calibration sources. The blackbodies at 295 K and 78K have been used as calibration source. The SIS junction was connected to a low noise 1.5 GHz HEMT amplifier via a bias tee and isolator. A Thompson Carcinotron in the 460-500 GHz range has been used as the LO. The $NbAlO_xNb$ junction with an area of 1.5 μm^2 and a normal resistance R_n =14 Ω was used. The subgap over normal resistance ratio was about 30 for this mixer.

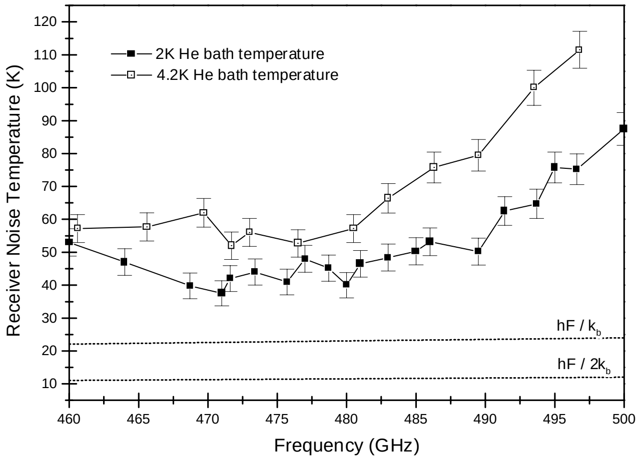

FIG. 1. DSB Receiver Noise Temperature for Two He Bath Temperatures, Uncorrected for Beamsplitter

The measured uncorrected DSB receiver noise temperature *vs.* LO frequency is presented in Fig. 1. The best noise temperature measured was 40±3 K uncorrected for the beamsplitter at 471 GHz, that is only about 3 times the ZPF of 11.4 K. The point at 471 GHz was used for the determination of the receiver parameters. The measured unpumped and pumped junction I-V curves as well as the if output power are shown in Fig. 2. The contributions of the receiver elements calculated by the method described above using the data from Fig. 2 are shown in Table 1. The main uncertainty for the calculated data was in the measurement of R_d. Other sources of measurements error were the uncertainty in the cold blackbody radiator temperature (78±2 K) and the uncertainty in measurement of the Y-factor (±0.04 dB). The low rf loss G_{unk} =-0.5 dB represents a good tuning circuit match and high beam efficiency for the receiver. The measured noise temperature T_{unk} =12 K corresponds T_{rad}=100 K in (3). This noise temperature could be attributed to 300 K background radiation accepted by part of receiver beam even if 78 K load is in front of the receiver.

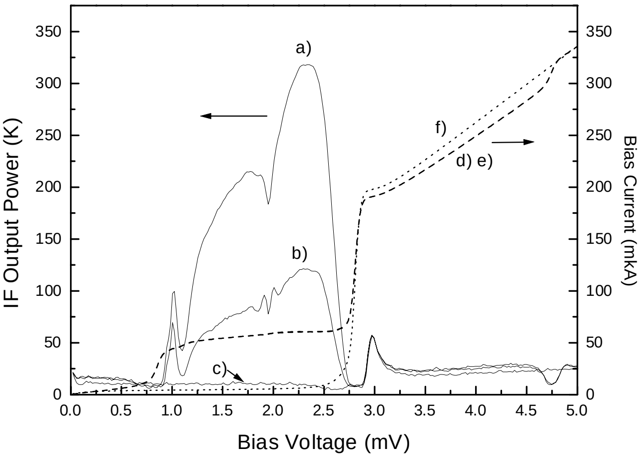

FIG. 2. I-V curves and if output power for SIS receiver, a) Pumped SIS Junction if Output Power for 295 K Load, b) Pumped SIS Junction if Output Power for 78 K Load, c) Unpumped SIS Junction if Output Power, d) Pumped SIS Junction I-V Curve for 295 K Load, e) Pumped SIS Junction I-V Curve for 78 K Load, f) Unpumped SIS Junction I-V Curve

TABLE I. Noise temperature T_i and gain G_i of SIS receiver elements for f_{LO} =471 GHz and junction bias Voltage = 1.7 mV. T_{front} is the noise contribution of the element referred to the receiver input.

Element name	T_i (K)	G_i (dB)	T_{front} (K)
Beamsplitter	7±2	-0.10±0.02	7±2
Dewar input window	4±2	-0.11±0.02	4±2
Quartz IR filter (78K)	2±1	-0.10±0.02	2±1
Zitex IR filter (4.2K)	1.0±0.5	-0.17±0.02	1.0±0.5
rf loss element (unknown)	12±5	-0.5±0.3	13±5
Conversion gain (zero-point fluctuations)	11.4±0.01	-0.2±0.4	14±5
if mismatch	3±2	-1.1±0.4	5±3
if amplifier	5±2	0.0±0.4	8±3
Receiver		-2.3±0.1	54±3

It was not possible to solve (1) without taking into account ZPF in all elements of receiver.

We conclude that ZPF in all receiver components is a key factor limiting the receiver noise temperature. The method proposed above is suitable for optimization of SIS receiver performance and allows to confirm indirectly that DSB noise temperature of SIS heterodyne receiver is limited by ZPF $\frac{hf}{2k_b}$. The quantum limited performance (T_{sys} =40 K) has been observed at 500 GHz. All noise contributions of our receiver are understood.

We would like to thank Lyudmila Filippenko for samples fabrication, Duc Van Nguen, Hans Golstein, Heino Smit and Sjef Kikken for mechanical and electronic arrangements and Herman van de Stadt, Nick Whyborn, Gert de Lange for helpful comments and discussion. This work is supported in part by Russia Program for Basic Research, Russian SSP "Superconductivity" and ESA contract 11/653/95/NL/PB.

---

[1] J.R. Tucker, M.J. Feldman, *Quantum Detection at millimeter wavelengths*, P.1055-1112, Reviews of Modern Physics, Vol. 57, No. 4, October 1985

[2] M.C. Gaidis, H.G. Leduc, Mei Bin, D. Miller, J.A. Stern, and J. Zmuidzinas, *Characterisation of Low Noise Quasi-Optical SIS Mixers for the Submillimeter Band*, IEEE Transactions of Microwave Theory and Techniques, p. 1130-1139, 1996

[3] A. Karpov, J. Blondell, M. Voss, K.H. Gundlach, *Four photons sensitivity heterodyne detection of submillimeter radiation with superconducting tunnel junctions*, IEEE Trans on Appl. Superconductivity, Vol. 5, N 2, pp. 3304-3307, 1995.

[4] A.R. Kerr, M.J. Feldman, S.-K. Pan *Receiver Noise Temperature, the Quantum Noise Limit, and the Role of the Zero-Point Fluctuations*, Eight Int Symp on Space Terahertz Technology proceedings, p. 101-111, 1997.

[5] D.P. Woody, *Measurement of the Noise Contributions to SIS Heterodyne Receivers*, ASC'94 Proceedings, 1995

[6] P. Dieleman and T.M. Klapwijk, *Shot noise beyond the Tucker theory in niobium tunnel junction mixers*, Applied Physics Letters, Vol 72, Number 13, p. 1653-1655, 1998

[7] V.P. Koshelets, S.V. Shitov, L.V. Filippenko, A.M. Baryshev, H. Golstein, T. de Graauw, W. Luinge, H. Schaeffer, H. van de Stadt, *First Implementation of a Superconducting Integrated Receiver at 450 GHz*, Appl. Phys. Lett., Vol. 68, No. 9, pp. 1273-1275, 1996.

[8] S.V. Shitov, A.B. Ermakov, L.V. Filippenko, V.P. Koshelets, W. Luinge, A.M. Baryshev, J.-R. Gao, P. Lehikoinen, *Recent Progress on the Superconducting Imaging Receiver at 500 GHz*, Proc. of 9-th Int. Symp. on Space Terahertz Technology, 17-19 March 1998, Pasadena Hilton, Pasadena, California, USA, pp. 263-272.