Applied Physics Letters

Spectrum of thermal fluctuation noise in diffusion and phonon cooled hot-electron mixers

Cite as: Appl. Phys. Lett. **72**, 1516 (1998); https://doi.org/10.1063/1.121044
Submitted: 05 December 1997 . Accepted: 23 January 1998 . Published Online: 04 June 1998

P. J. Burke, R. J. Schoelkopf, D. E. Prober, A. Skalare, B. S. Karasik, M. C. Gaidis, W. R. McGrath, B. Bumble, and H. G. LeDuc

APPLIED PHYSICS LETTERS VOLUME 72, NUMBER 12 23 MARCH 1998

Spectrum of thermal fluctuation noise in diffusion and phonon cooled hot-electron mixers

P. J. Burke,[a)] R. J. Schoelkopf, and D. E. Prober
Departments of Applied Physics and Physics, Yale University, New Haven, Connecticut 06520-8284

A. Skalare, B. S. Karasik, M. C. Gaidis, W. R. McGrath, B. Bumble, and H. G. LeDuc
Center for Space Microelectronics Technology, Jet Propulsion Laboratory, Caltech, Pasadena, California 91109

(Received 5 December 1997; accepted for publication 23 January 1998)

A systematic study of the intermediate frequency noise bandwidth of Nb thin-film superconducting hot-electron bolometers is presented. We have measured the spectrum of the output noise as well as the conversion efficiency over a very broad intermediate frequency range (from 0.1 to 7.5 GHz) for devices varying in length from 0.08 μm to 3 μm. Local oscillator and rf signals from 8 to 40 GHz were used. For a device of a given length, the spectrum of the output noise and the conversion efficiency behave similarly for intermediate frequencies less than the gain bandwidth, in accordance with a simple thermal model for both the mixing and thermal fluctuation noise. For higher intermediate frequencies the conversion efficiency decreases; in contrast, the noise decreases but has a second contribution which dominates at higher frequency. The noise bandwidth is larger than the gain bandwidth, and the mixer noise is low, between 120 and 530 K (double side band). © *1998 American Institute of Physics.* [S0003-6951(98)00912-7]

Recent research on hot-electron bolometer mixers has enhanced the prospect of achieving quantum-noise-limited performance ($T_Q = h\nu/k$) in heterodyne receivers at THz frequencies. Hot-electron bolometer mixers of both the phonon cooled[1] and diffusion cooled[2–4] type have already shown excellent noise performance. We have recently predicted[5] and shown[2,6] that for Nb devices diffusion cooling provides much larger intermediate frequency (IF) gain bandwidth than can be obtained with phonon cooling, due to faster thermal response. The IF noise bandwidth has been predicted to be even larger than the gain bandwidth.[7–9] We have studied this for Nb hot-electron mixers, where the gain bandwidth achieved with phonon cooling alone is very limited.

The main limitation for any bolometric mixer is that the IF *gain bandwidth* (defined as the IF at which the conversion efficiency drops by 3 dB from its low IF value) is limited by the thermal time-constant τ_{th}. The device rf to IF conversion efficiency, η, is predicted to obey[10–12]

$$\eta(f) = \frac{P_{LO}}{2R}\left(\frac{I_{dc}(dR/dT)}{G}\right)^2 \frac{1}{1+(2\pi f \tau_{th})^2} \tag{1}$$

$$= \eta(0)\frac{1}{1+(2\pi f \tau_{th})^2}, \tag{2}$$

where P_{LO} is the LO power, I_{dc} the dc current, G the thermal conductance to the bath, R the resistance, and dR/dT the change in resistance with temperature. Here $\eta(0)$ is the conversion efficiency at an IF of zero. The 3 dB gain bandwidth is given by $1/(2\pi\tau_{th})$.[12]

In the simplest model for the hot-electron superconducting mixer, the superconductor is treated as a resistor whose resistance depends on just the electron temperature, T_e. This is the only model to date. In this model, the output noise is predicted to be the sum of two contributions, one due to thermal fluctuation noise, and the other due to Johnson noise, and is given by[8]

$$T_{out}(f) = \frac{1}{RG}[I_{dc}T_e(dR/dT)]^2 \frac{1}{1+(2\pi f \tau_{th})^2} + T_J \tag{3}$$

$$= T_{TF}(0)\frac{1}{1+(2\pi f \tau_{th})^2} + T_J, \tag{4}$$

with T_J the Johnson noise temperature, expected to be $\approx T_c = 5.5$ K, and $T_{TF}(0)$ the thermal fluctuation noise temperature at zero IF. For a well-optimized device, the dominant intrinsic noise source should be thermal fluctuation noise.[7] The noise referred to the input of the device is the mixer noise, $T_{mix}(\mathrm{DSB})(f) \equiv T_{out}(f)/2\eta(f)$; this dominates receiver performance. Since the thermal fluctuation noise decreases with frequency in the same fashion as the conversion efficiency, the mixer noise does not increase with IF until the output noise is dominated by the Johnson noise. Therefore, the noise bandwidth (defined as the frequency at which the mixer noise is twice its zero IF value) can be substantially larger than the gain bandwidth.

In this letter we present systematic measurements of the spectrum of the output noise, conversion efficiency, and mixer noise for phonon and diffusion cooled Nb devices of various thermal time constants. The devices vary in length from 0.08 μm ($<L_{eph} \equiv \sqrt{D\tau_{eph}}$) to 3 μm ($>L_{eph}$); τ_{eph} is the phonon cooling time and D the diffusion constant. In recent work[6] we demonstrated that diffusion cooling could increase the gain bandwidth from 100 MHz, the value for phonon cooling alone, to over 6 GHz. We found that the gain bandwidth $(2\pi\tau_{th})^{-1}$ followed the prediction,[5,13,14] $\tau_{th}^{-1} = \tau_{eph}^{-1} + \pi^2 D L^{-2}$. Measurements of the spectrum of the output noise are equally important. The noise spectrum was

[a)]Present address: MS114-36 Condensed Matter Physics, Caltech, Pasadena, CA 91109; electronic mail: pjburke@cco.caltech.edu

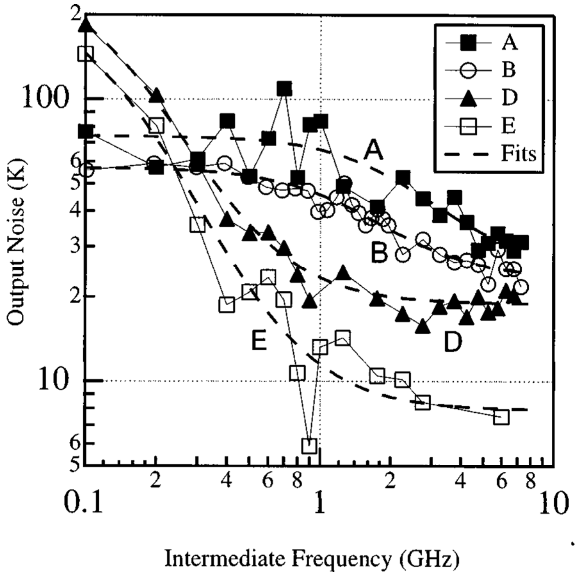

FIG. 1. Output noise vs intermediate frequency. The dashed lines are theoretical predictions of Eq. (4), where a three-parameter fit of Eq. (4) to the data has been performed. The three parameters varied are $T_{TF}(0)$, T_J, and τ_{th}.

measured in phonon cooled NbN devices.[15] We present here the first measurements of the noise spectrum in diffusion cooled devices. The main question which we experimentally address is: Is the time constant which governs the frequency dependence of the conversion efficiency [Eq. (2)] numerically equal to the time constant which governs the frequency dependence of the output noise [Eq. (4)] as predicted by the simple thermal model? Since the mixing process is thermal, these measurements are expected to be representative of, and provide design guidance for, devices used in future THz heterodyne receivers. We compare below to THz measurements.

The devices studied were all fabricated from the same thin (100 Å) Nb film, deposited on a quartz substrate. The patterned film has a transition temperature of $T_c \approx 5.5$ K, transition width $\Delta T_c \sim 0.5$ K, and sheet resistance $\approx 29\ \Omega$. The length of the bridge was defined by the normal metal (1000 Å thick Au) contacts using direct write e-beam lithography in a self-aligned process.[16] (The normal state resistances were between 50 and 100 Ω.) Each device was mounted at the end of a section of 50 Ω microstrip, using a "flip-chip" configuration to assure a broadband impedance match. A cooled directional coupler was used to weakly couple in the rf signal and the local oscillator (LO). The through port was connected to a cooled, low noise (≈ 25 K), broadband amplifier. The amplifier system noise and gain were calibrated *in situ* to the plane of the device by using the Johnson noise in the normal state above T_c as a known source of power.

We plot in Fig. 1 the output noise versus frequency, together with three-parameter functional fits to Eq. (4). The three parameters varied are $T_{TF}(0)$, T_J, and τ_{th}, and the fit results are given in Table I. In these experiments, the dc and LO power were adjusted for maximum (coupled) conversion efficiency at a bath temperature of 2 K. These operating conditions were somewhat different than those treated in our recent publication. A complete account of all the data will be presented in a future publication.[18] We also measured $\eta(f)$ under identical conditions and fit the results to Eq. (2). The value of τ_{th} determined from these fits is shown in Table I. For a given device, the thermal time constants inferred from the fits of $\eta(f)$ to Eq. (2) are in fair agreement with the thermal time constants inferred from fits of $T_{out}(f)$ to Eq. (4). The zero IF value of $T_{mix}(f)$ was determined by calculating $T_{mix}(f)$ at each value of IF from the measured values of $\eta(f)$ and $T_{out}(f)$ and extrapolating to zero IF. Similarly, the noise bandwidth was determined by a fit to $T_{mix}(f)$, and the results are shown in Table I. The mixer noise is low, and the noise bandwidth is indeed larger than the gain bandwidth.

At high frequencies $[>(2\pi\tau_{th})^{-1}]$, the dominant noise source should be Johnson noise, with $T_J \approx 5.5$ K. Experimentally, we do not find this to be the case. (Device E was not well matched to the amplifier input impedance, so that the measured output noise at high frequencies was not expected to be equal to the electron temperature.) The excess we find for devices A, B, and D is approximately 13–19 K, larger than the maximum estimated uncertainty of ± 5 K. This may indicate an unidentified noise source. Further investigations will be necessary to elucidate this finding. Nonetheless, the data clearly demonstrate that there is a frequency scale associated with the dominant part of the output noise that scales with device length as it does for the gain bandwidth.

TABLE I. Device parameters and output noise.

Dev.	L (μm)	$(2\pi\tau_{th})^{-1}$ (GHz) from fit of η(f) to Eq. (2)	from fit of $T_{out}(f)$ to Eq. (4)	$T_{TF}(0)$ (K) from fit of T_{out} to Eq. (4)	T_J (K)	Noise BW GHz	$T_{mix}(0)=T_{out}(0)/2\eta(0)$[b] (K,DSB)
A	0.08	⩾6	2.3	49	25	>6	120
B	0.16	2.4	1.4	34	23	3.9	320
C	0.24	1.5	…[a]	…	…	…	200
D	0.6	0.3	0.13	262	19	0.73	120
E	3	0.08	0.13	223	8	0.75	530
Ref. 2	0.27	1.7					560
Ref. 3	0.3						450
Ref. 4	0.3	1.2				≃1.5	300

[a]Device C was electrically damaged before the noise spectrum could be measured.

[b]The experimental technique used to determined $T_{mix}(0)$ in Refs. 2–4 was slightly different than that for this letter. In all cases, however, the mixer noise is defined as $T_{out}/2\eta$; η is the intrinsic device conversion efficiency with no rf coupling circuit losses.

In the lower half of Table I the estimated mixer noise temperatures are indicated from recent experiments with 550 GHz,[2] 1.2 THz,[3] and 2.5 THz (Ref. 4) signals. These measurements were generally tuned for lowest *receiver* noise by varying the applied dc and LO power. This condition depends on the details of the IF amplifier and rf coupling circuits, and is similar but not equivalent to the optimum conversion efficiency case presented in this letter. The devices used in Refs. 2–4 were approximately 0.3 μm in length, with sheet resistances between 10 and 70 Ω. In addition, the *unpumped* (no LO power applied) output noise of the devices measured for the present work, and those of Refs. 2–4, differed from one another, ranging from 57 K to <12 K, indicating variation between the devices unrelated to the frequency of the applied LO and signal. Given these device-to-device variations, the measured mixer noise in all experiments is seen to be fairly consistent.

While the frequency dependence of the conversion efficiency and the major part of the output noise agree with the simple thermal model, the magnitude of the conversion efficiency and output noise are difficult to predict. This is because dR/dT, which appears in the predictions for $\eta(f)$ and $T_{out}(f)$, depends sensitively on the electron temperature which is difficult to determine accurately, and because the electron temperature varies spatially for the diffusion cooled devices (A–D). All theories to date have considered the device as a lumped element, whereas a distributed system approach would be more appropriate.

There are two methods for estimating dR/dT. For method 1, the resistance R (taken to be V_{dc}/I_{dc} with LO power applied) can be used to infer the effective electron temperature and also dR/dT using the R vs T curve measured with a small bias current and no LO power. Method 2 infers dR/dT from the measured $I-V$ curve with LO power applied, using[11]

$$dR/dP=\frac{dR/dT}{G}=\frac{1}{I_{dc}^2}\,\frac{dV/dI-V_{dc}/I_{dc}}{dV/dI+V_{dc}/I_{dc}}. \tag{5}$$

G is found from the electrical resistance using the Wiedemann–Franz relationship.[5] This second method extracts the effective value of dR/dT under conditions where the temperature varies spatially.

The resultant predictions[17] for the conversion efficiency and for the thermal fluctuation noise are compared to the experimental data in Table II for the optimum efficiency case. For devices B and C the second method gives reasonable agreement between theory and experiment. Since the length of device A is comparable to the electron–electron length ($\sqrt{D\tau_{ee}}$, with τ_{ee}^{-1} the electron–electron scattering rate), a local equilibrium temperature cannot be well defined and the simple thermal model may not apply quantitatively to this device. We have also calculated the predicted output noise and conversion efficiency as a function of dc bias using method 2 [Eq. (5)] for all the devices studied in both the optimum efficiency and overpumped cases.[13,18] We find qualitative agreement between the theoretical and experimental dc bias dependence of the output noise and efficiency for all devices except device A. However, neither method provides consistent quantitative predictions of device performance for a variety of operating conditions. Thus, device performance cannot yet be predicted from first principles and must continue to be investigated experimentally. We find it to be excellent. Lower T_c devices made of Al may have improved performance.

TABLE II. Predicted and experimental conversion efficiency and output noise.

	$\eta(0)$ (dB)			$T_{out}(0)=T_{TF}(0)+T_J$ (K)		
Dev.	Calculated, method 1	Calculated, method 2	Exp.[a]	Calculated, method 1	Calculated, method 2	Exp.[b]
A	-5.3	-17.5	-5.6	60.5	9	37[c]
B	-3.2	-7.0	-11.0	180.5	78.5	57
C	$+0.2$	-9.4	-9.9	223.5	20.5	44
D[d]	-	-0.5	-5.4	-	179.5	118
E	-	0.0	-8.6	-	409.5	105

[a] ± 2 dB.
[b] A value of 5.5 K was assumed for T_J in the theoretical prediction.
[c] The output noise for device A quoted in this table was measured under slightly different operating conditions than that plotted in Fig. 1.
[d] The low frequency limit of the noise and efficiency was not well determined for devices D and E, so the experimental value at 125–175 MHz is quoted in this table.

The authors thank A. Kozhevnikov for assistance with the experiments. This research was supported by the NSF and by the NASA Office of Space Science. Funding for P.J.B. was provided by a NASA Graduate Student Fellowship as well as a Connecticut High Technology Fellowship.

[1] J. Kawamura, R. Blundell, C. Y. Tong, G. Gol'tsman, E. Gershenzon, and B. Voronov, Appl. Phys. Lett. **70**, 1619 (1997).
[2] A. Skalare, W. R. McGrath, B. Bumble, H. G. LeDuc, P. J. Burke, A. A. Verheijen, R. J. Schoelkopf, and D. E. Prober, Appl. Phys. Lett. **68**, 1558 (1996).
[3] A. Skalare, W. McGrath, B. Bumble, and H. G. LeDuc, IEEE Trans. Appl. Supercond. **7**, 3568 (1997).
[4] B. S. Karasik, M. C. Gaidis, W. R. McGrath, B. Bumble, and H. G. LeDuc, Appl. Phys. Lett. **71**, 1567 (1997).
[5] D. E. Prober, Appl. Phys. Lett. **62**, 2119 (1993).
[6] P. J. Burke, R. J. Schoelkopf, D. E. Prober, A. Skalare, W. R. McGrath, B. Bumble, and H. G. LeDuc, Appl. Phys. Lett. **68**, 3344 (1996).
[7] E. Gershenzon, G. Gol'tsman, I. G. Gogidze, Y. P. Gusev, A. I. Elant'ev, B. S. Karasik, and A. Semenov, Superconductivity **3**, 1582 (1990).
[8] B. Karasik and A. Elantev, in *Proceedings of the 6th Internation Symposium on Space Terahertz Technology*, edited by J. Zmuidzinas and G. Rebiez (CalTech, Pasadena, CA, 1995), pp. 229–246.
[9] B. S. Karasik and A. I. Elantiev, Appl. Phys. Lett. **68**, 853 (1996).
[10] F. Arams, C. Allen, B. Peyton, and E. Sard, Proc. IEEE **54**, 612 (1966).
[11] H. Ekström, B. Karasik, E. Kollberg, and K. Yngvesson, IEEE Trans. Microwave Theory Tech. **43**, 938 (1995).
[12] We neglect here the modification of the thermal time constant, conversion efficiency, and thermal fluctuation noise due to electro-thermal feedback effects. This is justified because the device resistances are all close to the input impedance of the IF amplifier, 50 Ω.
[13] P. J. Burke, Ph.D. thesis, Yale University, 1997 (available from authors).
[14] B. Karasik, K. Il'in, E. Pechen, and S. Krasnosvobodtsev, Appl. Phys. Lett. **68**, 2285 (1996).
[15] H. Ekström and B. Karasik, Appl. Phys. Lett. **66**, 3212 (1995).
[16] B. Bumble and H. G. LeDuc, IEEE Trans. Appl. Supercond. **7**, 3560 (1997).
[17] We have included the effects electro-thermal feedback in the numerical predictions for the output noise and conversion efficiency. The modifications were at most 40%.
[18] P. J. Burke, R. J. Schoelkopf, D. E. Prober, A. Skalare, B. Karasik, M. Gaidis, W. McGrath, B. Bumble, and H. LeDuc (unpublished).