Applied Physics Letters

Length scaling of bandwidth and noise in hot-electron superconducting mixers

Cite as: Appl. Phys. Lett. **68**, 3344 (1996); https://doi.org/10.1063/1.116052
Submitted: 07 March 1996 . Accepted: 10 April 1996 . Published Online: 04 June 1998

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

Length scaling of bandwidth and noise in hot-electron superconducting mixers

P. J. Burke,[a)] R. J. Schoelkopf, and D. E. Prober
Departments of Applied Physics and Physics, Yale University, 15 Prospect Street, New Haven, Connecticut 06520-8284

A. Skalare, W. R. McGrath, B. Bumble, and H. G. LeDuc
Center for Space Microelectronics Technology, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109

(Received 7 March 1996; accepted for publication 10 April 1996)

Mixing experiments have been performed at frequencies from 4 to 20 GHz on Nb thin-film superconducting hot-electron bolometers varying in length from 0.08 to 3 μm. The intermediate frequency (IF) bandwidth is found to vary as L^{-2}, with L the bridge length, for devices shorter than $\sqrt{12}\,L_{e-ph}\approx 1$ μm, with L_{e-ph} the electron-phonon length. The shortest device has an IF bandwidth greater than 6 GHz, the largest reported for a low-T_c superconducting bolometric mixer. The conversion efficiencies range from -5 to -11 dB (single sideband, SSB). For short bridges, the mixer noise temperature is found to be as low as 100 K (double sideband, DSB), with little length dependence. The local oscillator power required is small, $\approx$10 nW. Such mixers are very promising for low-noise THz heterodyne receivers. © *1996 American Institute of Physics.* [S0003-6951(96)04523-8]

During the past decade heterodyne receivers have been developed with sensitivities approaching the quantum limit in the millimeter and submillimeter bands.[1] These receivers utilize superconducting-insulator-superconducting (SIS) tunnel junction mixers. Nb SIS mixers have degraded performance above the energy gap frequency, $\approx$700 GHz, and are expected to sharply degrade above twice this frequency. Schottky diodes are used at frequencies above 1 THz, but are much noisier and require large local oscillator (LO) power, of order mW. Hot-electron bolometric mixers using the heating-induced nonlinearity in a superconductor near T_c have achieved low noise and reasonable conversion efficiency.[2] Such devices are attractive because they have no parasitic capacitance, simplifying the radio frequency (rf) coupling, and require small LO power, $\approx$10 nW. Bolometric mixers are expected to perform well in the THz frequency range, without limits related to the gap frequency, since they rely only on heating of the electrons in the device.

The main limitation for any bolometric mixer is that the IF bandwidth is limited by the thermal time-constant τ_{th}. The conversion efficiency obeys the functional form

$$\frac{\eta(f)}{\eta(0)}=\frac{1}{1+(f/f_{3\mathrm{dB}})^2}, \tag{1}$$

where the 3 dB bandwidth is given by $f_{3\mathrm{dB}}=1/2\pi\tau_{th}$. Superconducting hot-electron bolometers using micron-size bridges of Nb rely on the electron-phonon interaction as the cooling mechanism. These have demonstrated an IF bandwidth of $\sim$100 MHz.[2] Typical applications such as remote sensing of atmospheric chemistry and radioastronomy require an IF bandwidth of several GHz. One approach for increasing the IF bandwidth is to use a material with a shorter electron-phonon time such as NbN.[3] However, NbN IF bandwidths in receivers are typically only 0.7–1 GHz.

In this letter we present measurements on devices which systematically test outdiffusion of hot electrons as the cooling mechanism.[4] If the device length, L, is less than $\sqrt{12}\ L_{e-ph}$ (with $L_{e-ph}\equiv\sqrt{D\tau_{e-ph}}$, D the diffusion constant, and τ_{e-ph} the inelastic electron-phonon time), very fast cooling can be achieved via outdiffusion of hot electrons into normal metal leads. In this regime the thermal response time is expected[5] to scale as $\tau_{th}\propto L^2$. In recent work,[6] we demonstrated low noise (T_{receiver}=650 K, DSB) and a 1.7 GHz IF bandwidth at an rf frequency of 530 GHz. In the present work, we report systematic measurements of the IF bandwidth versus device length. We demonstrate the crossover from phonon cooling to diffusion cooling,[7] provide confirmation of the expected scaling of the device bandwidth with length, and report the largest IF bandwidth yet obtained in a low-T_c bolometric mixer. In addition, we present direct measurements of output noise. The results presented here, which are for rf frequencies below the gap frequency of the Nb bridges ($\sim$350 GHz), agree qualitatively with our recent results obtained at 530 GHz,[6] which is above the gap frequency for the Nb bridge measured there. Since the mixing process is thermal, and since the results presented here agree qualitatively with those presented in Ref. 6, these measurements are expected to be representative of, and provide design guidance for, devices used in future THz heterodyne receivers.

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 K, transition width $\Delta T_c\sim$0.5 K, and sheet resistance $\approx$33 Ω. 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.[8] The device parameters are given in Table I. Each device was mounted at the end of a section of 50 Ω microstrip, using a "flip-chip" configuration to assure a broadband match.[9] A cooled directional coupler was used

[a)]Electronic mail: burkep@minerva.cis.yale.edu

 0003-6951/96/68(23)/3344/3/$10.00

TABLE I. Device parameters and mixer results.

Device	L^{a} (μm)	R_N (Ω)	η^{b} (dB)	$f_{3\ dB}$ (GHz)	T_{out} (K)	$T_{mix}{}^{c}$ (DSB,K)
A	0.08	54	−10	>6	20	100
B	0.16	77	−12	2.5	15	120
C	0.24	96	−13	1.5	16	160
D	0.6	93	−5	0.47	⋯	⋯
E	3	98	−6	0.13	⋯	⋯

[a] ±0.05 μm.
[b] For devices A–C, value η is with isolator, averaged for 1.25–1.75 GHz, optimized for minimum *mixer* noise; for devices D, E value is $\eta(0)$ from fit to Eq. (1), optimized for maximum conversion efficiency.
[c] The error is ±50% due to an error of ±2 dB on the conversion efficiency and ±10% on the output noise.

to weakly couple in the rf and LO. The through port was connected to a cooled, low noise (≈20 K), broadband amplifier.[10] The cable losses, amplifier gain, and coupler performance were each measured at 2 K. The mixer conversion efficiency as a function of intermediate frequency was thus measured to ±2 dB. No adverse effects on the devices due to repeated thermal cycling or storage in room air over a period of several months were seen.

The *coupled* conversion efficiency η as a function of IF was measured at 2.2 K. For a LO power above some critical value, the I–V curve is nonhysteretic and the conversion efficiency, mixer output noise at the IF, T_{out}, and DSB mixer noise temperature $[T_{mix}(\text{DSB}) \equiv T_{out}/2\eta]$ are smooth functions of bias voltage. The conversion efficiency in this ''overpumped'' case is reduced by 2–3 dB relative to the maximum conversion efficiency attainable with a hysteretic I–V curve, but the *mixer* noise temperature is lower by about 25%. For this reason, we present data in the overpumped case for those devices where noise measurements are presented. Devices D and E were measured with a LO power which achieved the maximum (coupled) conversion efficiency. We stress that the conversion efficiencies at *low IF* in the *overpumped* case are the same for all five devices, within the experimental uncertainties. The LO power used was between 8 and 85 nW, with device E requiring 85 nW. We also checked the dependence of the conversion efficiency on the LO frequency. Only the shortest device showed such a dependence, due to the fact that the LO frequency was not much greater than the IF bandwidth for this device.

In Fig. 1 we show the measured conversion efficiency, normalized to the fitted value at low IF, $\eta(f)/\eta(0)$, as a function of IF. The results for the five devices clearly show an increase in the IF bandwidth with decreasing device length. We also plot fits to Eq. (1). The −3 dB bandwidths inferred from these fits are shown in Table I.[11] We believe that 6 GHz is a lower limit on the IF bandwidth for device A, since the conversion efficiency changes with IF by an amount comparable to the experimental uncertainties, for the IF frequencies used.

The results of the fits in Fig. 1 are plotted as a function of device length in Fig. 2. When L is much larger than $\sqrt{12}\ L_{e-ph}$(≈ 1 μm at 4.2 K), the bandwidth is expected to be independent of length. The dashed line indicates this phonon cooling limit. Device E is in this limit. For $L \ll \sqrt{12}\ L_{e-ph}$, the dominant cooling mechanism should be

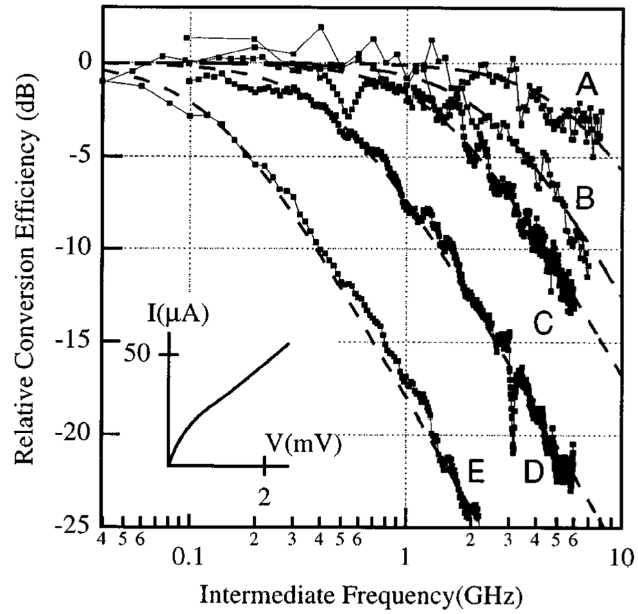

FIG. 1. Relative SSB conversion efficiency vs intermediate frequency. The bold letters label data from devices as listed in Table I. The inset shows the overpumped I–V curve for device B.

diffusion, and the dotted line shows the expected L^{-2} dependence.[5] The solid line shows the prediction for the net effect of both phonon and diffusion cooling mechanisms, assuming the thermal conductances add. The data indeed agree with the prediction within the experimental uncertainties.

We measured the output noise at the IF for devices A, B, and C, using an isolator (bandwidth 1.25–1.75 GHz) be-

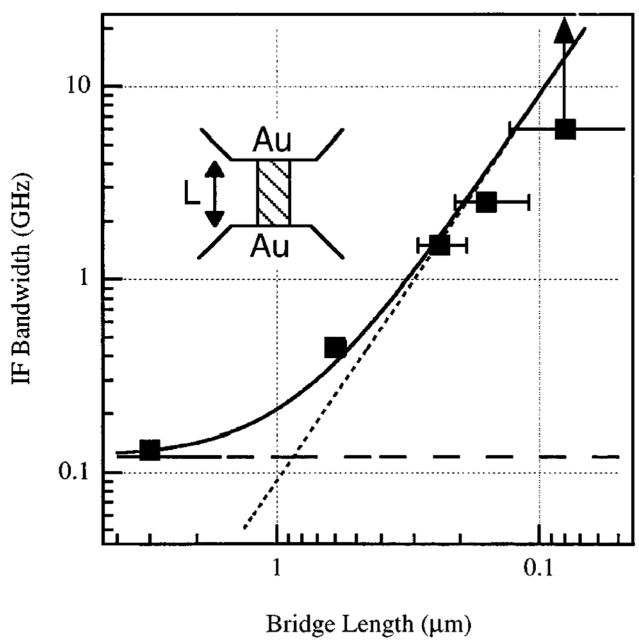

FIG. 2. Bandwidth vs length. Squares are experimental data. Lines are theoretical predictions showing the expected L^{-2} dependence for the diffusion cooled case (dotted line), the phonon-cooled case (dashed line), and the sum of both mechanisms (solid line). The inset shows the device geometry. The Nb bridge is shaded.

tween the device and the amplifier, with LO power applied.[12] The conversion efficiency was measured at the same time, and under identical conditions (including LO). This conversion efficiency agreed with the broadband measurements without an isolator described above. The mixer noise temperature was calculated from the output noise temperature and the conversion efficiency. Of the three devices measured, device A showed the lowest mixer noise, with $T_{\mathrm{mix}}(\mathrm{DSB}) = 100$ K$\pm$50 K. For receivers above 0.5 THz, this noise temperature would be very competitive with existing technologies. Thus, while decreasing device length dramatically increases the bandwidth, there is no apparent sacrifice in noise performance nor in LO power requirement. The output noise presented in this work ($\approx$20 K) is comparable to the output noise of $\approx$40 K measured at 530 GHz.[6] The mixer conversion efficiency measured here (referred to the cold rf input) is aproximately 4 dB higher than that measured at 530 GHz; however the latter includes optical component losses.

An important issue for future research is how short the device can be before new physical phenomena become significant. When L is of order the electron-electron inelastic length $L_{e-e} \approx 0.05$ μm (Ref. 13) electrons diffuse out of the bridge before sharing their energy with each other. This is the case for device A, which is in the ''mesoscopic'' regime. A qualitatively new theory may be needed for this case.

We thank A. A. Verheijen for contributions to early experiments, and B. Karasik, M. Gaidis, and U. Meirav for useful discussions. We thank Hewlett Packard for the loan of a network analyzer. The research described in this letter was performed by Yale University and the Center for Space Microelectronics Technology, Jet Propulsion Laboratory, California Institute of Technology, and was jointly sponsored by the NSF and by the NASA Office of Space Access and Technology, and Office of Space Science. Funding for P. J. Burke was provided by a NASA Graduate Student Fellowship as well as a Connecticut High Technology Fellowship.

[1] M. J. Wengler, Proc. IEEE **80**, 1810 (1992); R. Blundell and C. E. Tong, Proc. IEEE **80**, 1702 (1992).

[2] E. M. Gershenzon, G. N. Gol'tsman, I. G. Gogidze, Y. P. Gusev, A. I. Elant'ev, B. S. Karasik, and A. D. Semenov, Sov. Phys. Superconductivity **3**, 1582 (1990).

[3] G. N. Gol'tsman, B. S. Karasik, O. V. Okunev, A. L. Dzardanov, E. M. Gershenzon, H. Ekström, S. Jacobsson, and E. Kollberg, IEEE Trans. Appl. Supercond. **5**, 3065 (1995).

[4] D. E. Prober, Appl. Phys. Lett. **62**, 2119 (1993).

[5] It is predicted in Ref. 4 for cooling by diffusion that $\tau_{th} = L^2/(12D)$, with L the bridge length and D the diffusion constant. Thus, when $L = \sqrt{12} L_{e-ph}$, the electron-phonon time τ_{e-ph} is equal to the time constant due to diffusion cooling. For the diffusion cooled devices presented here, we predict $\tau_{th}(\mathrm{ns}) \approx 0.8L^2$, with L in μm. We find experimentally that $\tau_{th}(\mathrm{ns}) \approx 1.8L^2$. This discrepancy appears to be within the uncertainties in the predicted as well as the measured prefactor. While the above prediction for τ_{th} is exact for a non-superconducting bridge, it also can be used below T_c because the quasiparticle excitations which carry away heat have energy $\sim kT$ which is much larger than the gap energy near T_c.

[6] 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).

[7] Evidence for such a crossover in the nonsuperconductor AuPd has recently been presented in W. Kanskar and M. N. Wyborne, Phys. Rev. Lett. **73**, 2123 (1994); and D. E. Prober, Phys. Rev. Lett. **75**, 3964 (1995); and for NbC in B. S. Karasik, K. S. Il'in, E. V. Pechen', and S. I. Krasnosvobodtsev, Appl. Phys. Lett. **68** 853 (1996). Our work is the first demonstration of such a crossover in Nb, and is also the first test of this crossover under actual receiver conditions, such as strong self-heating and large LO power.

[8] B. Bumble and H. G. LeDuc (unpublished).

[9] The power coupling to the device in the normal state from the cold rf input was measured to be above 90% from 0.1–12 GHz. The match is expected to remain this good to above 20 GHz.

[10] A cooled dc bias tee (Anritsu K250) was used. The dc load line was 20 Ω.

[11] Due to electrothermal feedback effects [H. Ekström, B. Karasik, E. Kollberg, and K. S. Yngvesson, Proceedings of 5th International Symposium on Space THz Technology, University of Michigan, Ann Arbor, MI, 169 (1994)], the time constant inferred from the bandwidth is equal to the ''bare'' thermal time constant τ_{th} only if the self-heating parameter $[I^2(dR/dT)/G]$ is small or $V_{\mathrm{dc}}/I_{\mathrm{dc}}$ is close to the IF amplifier input impedance, 50 Ω. (Here G is the thermal conductance to the bath.) Since $V_{\mathrm{dc}}/I_{\mathrm{dc}}$ is close to 50 Ω for the devices measured in this work, we believe that the inferred time constant is approximately equal to τ_{th}.

[12] For devices D and E, the dominant noise at low IF is due to thermal flucuations, but it is much too small to measure at 1.5 GHz.

[13] P. Santhanam and D. E. Prober, Phys. Rev. B **29**, 3733 (1984); we use $D = 1$ cm^2/s, $R_{sq} = 33$ Ω, and $T = 5.5$ K.