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

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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 $\sqrt{12} L_{e-ph} \approx 1 \text{ μm}$, 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 $-11 \text{ dB}$ (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, $\approx 10 \text{ nW}$. Such mixers are very promising for low-noise THz heterodyne receivers. © 1996 American Institute of Physics.

During the past decade heterodyne receivers have been developed with sensitivities approaching the quantum limit in the millimeter and submillimeter bands. These devices utilize superconducting-insulator-superconducting (SIS) tunnel junction mixers. Nb SIS mixers have degraded performance above the energy gap frequency, $\approx 700 \text{ GHz}$, 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. Such devices are attractive because they have no parasitic capacitance, simplifying the radio frequency (rf) coupling, and require small LO power, $\approx 10 \text{ nW}$. 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 $\tau_{th}$. The conversion efficiency obeys the functional form

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

where the 3 dB bandwidth is given by $f_{3\text{dB}} = 1/2\pi\tau_{th}$. 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 $\approx 100 \text{ MHz}$. 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. 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. If the device length, $L$, is less than $\sqrt{12} L_{e-ph}$ with $L_{e-ph}$ the electron-phonon length, 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 to scale as $\tau_{th} \propto L^2$. In recent work, we demonstrated low noise ($T_{\text{receiver}} = 650 \text{ K}$, 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, 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 ($\approx 350 \text{ GHz}$), agree qualitatively with our recent results obtained at 530 GHz, 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 $T_c \approx 5 \text{ K}$, transition width $\Delta T_c \approx 0.5 \text{ K}$, and sheet resistance $\approx 33 \Omega$. 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. 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.

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of several months were seen.

repeated thermal cycling or storage in room air over a period
measured to 2 K. The mixer conversion efficiency as a function of intermediate frequency was thus
formance were each measured at 2 K. The mixer conversion
value, the
was measured at 2.2 K. For a LO power above some critical

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.

to weakly couple in the rf and LO. The through port was
connected to a cooled, low noise (~20 K), broadband
amplifier. 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 ef-
iciency, mixer output noise at the IF, T_out, and DSB mixer
noise temperature [T_{mix}(DSB)=T_{out}/2\eta] are smooth func-
tions 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 over-
pumped 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{L_{e-ph}} (~ 1 μm at 4.2 K), the bandwidth is expected to
be independent of length. The dashed line indicates this pho-
non cooling limit. Device E is in this limit. For
L<\sqrt{L_{e-ph}} , the dominant cooling mechanism should be
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 uncertain-
ties.

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 theo-
retical 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.
between the device and the amplifier, with LO power applied. 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 $T_{\text{mix}}(\text{DSB}) = 100 \text{ K} \pm 50 \text{ K}$. 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 is approximately 4 dB higher than that measured at 530 GHz. The mixer conversion efficiency measured here (referred to the cold rf input) is approximately 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 $L_{ee} \approx 0.05 \text{ \mu m}$ (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.

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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, 2122 (1994); and D. E. Prober, Phys. Rev. Lett. 76, 3964 (1995); and for NbC in B. S. Karasik, K. S. Liu, E. V. Pechen’, and S. I. Krasnosvobodtsev, Appl. Phys. Lett. 85, 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.
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 $\tau_{th}$ only if the self-heating parameter $[I^2 (dR/dT)/G]$ is small or $V_{th}/I_{th}$ is close to the IF amplifier input impedance, 50 Ω. (Here G is the thermal conductance to the bath.) Since $V_{th}/I_{th}$ is close to 50 Ω for the devices measured in this work, we believe that the inferred time constant is approximately equal to $\tau_{th}$.
12. For devices D and E, the dominant noise at low IF is due to thermal fluctuations, but it is much too small to measure at 1.5 GHz.