Noise bandwidth of diffusion-cooled hot-electron bolom

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Abstract—**We present studies of the input and output noise of diffusion cooled hot-electron bolometer mixers. By simultaneously measuring the gain and noise (with a 14 GHz LO) as a function of intermediate frequency for a 0.16 μm diffusion cooled Nb device, we show that the noise bandwidth (4 GHz) is larger than the gain bandwidth (2.4 GHz). The output noise is 55 K, and the mixer noise is very low, 340 K DSB. This shows that diffusion cooled devices have low noise over a broad enough intermediate frequency band for practical applications in THz receivers.**

I. INTRODUCTION

In recent years, research [1] has shown that hot-electron bolometers are excellent candidates as ultra-low noise front-end mixers for THz heterodyne receivers. Very low noise results have already been acheived[2] ($T_{Receiver} = 650\ K\ DSB$ at $530\ GHz$). The intermediate frequency (IF) *gain* bandwidth was a limitation for past bolometric mixers. We recently showed that the IF gain bandwidth can be as large as 6 GHz when the device length is short enough that diffusion-cooling of hot electrons out the ends dominates over phonon-emission as the cooling mechanism[3]. (NbN phonon-cooled mixers can operate with an IF to a few GHz[4].) The IF *noise* bandwidth has not been extensively studied in diffusion cooled mixers; in this paper we present a study for one such device.

The main limitation for any bolometric mixer is that the IF *gain bandwidth* (defined as the IF frequency at which the conversion efficiency drops by 3dB from its low frequency value) is limited by the thermal time-constant τ_{th}. The conversion efficiency obeys the functional form

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

where the 3dB gain bandwidth is given by $f_{gain3dB} = 1/2\pi\tau_{th}$[5]. The dominant intrinsic noise source for a well optimized superconducting bolometric mixer is predicted to be thermal fluctuation noise[1]. Id dominant noise source for diffusion-co obviously an important issue for receiv the required first step for mixer opti ical calculations[6] predict that the p an IF load due to thermal fluctuation spectrum as Eq. 1. In addition to t noise, there is also Johnson noise, a crossover frequency above which John than the thermal fluctuation noise. Th $T_{mix}(DSB)$ ⊟ $T_{out}/2\eta$ (with η the S ciency) should depend on frequency as

$$T_{mix}(f) = \frac{T_J}{2\eta(0)}(1 + (2\pi\tau_{th} f)^2$$

where T_J is the Johnson noise, and T_f quency value of the thermal fluctuatio the *noise bandwidth* $f_{noise3dB}$ as the f the mixer noise is 3dB higher than value. The above equations give[1]

$$\frac{f_{noise3dB}}{f_{gain3dB}} = \sqrt{\frac{T_J + T_{fl}}{T_J}}$$

Therefore, the noise bandwidth can gain bandwidth if the thermal fluctuati at low frequencies. To include the noise T_{amp}, T_J should be replaced by $T_J +$

A significant increase in the IF hot-electron bolometers was predicted served[2], [3] for short devices. Specifi length is less than $\sqrt{12}\ L_{e-ph}$ (with D the diffusion constant and τ_{e-ph} the phonon time)[7], the thermal conduct trons to the "bath" can be primarily hot electrons out the ends of the brid length ($\sqrt{12}\ L_{e-ph}$) is about 1 μm in paper, we present measurements of the version efficiency, and mixer noise for Nb device of length 0.16 μm. The elec are predominantly cooled by diffusio bandwidth (2.4 GHz) is within the ba used, 0.1-7.5 GHz, allowing measure low the thermal rolloff. While the spec noise has been measured in phonon-c ter mixers[8] and 2DEG bolometers[9] with thermal-fluctuations, this is the and 3 for a diffusion-cooled device.

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II. DEVICE FABRICATION AND EXPERIMENTAL PROCEDURE

The device studied was fabricated from a 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 $\approx$ 28 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[10].The device was mounted at the end of a section of 50 Ω microstrip, using a "flip-chip" configuration to assure a broadband match. A cooled directional coupler was used to weakly couple in the RF and LO. The through port was connected to a cooled, low noise ($\approx$ 25 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.

The amplifier system noise and gain were calibrated in-situ to the plane of the device. The device was heated above T_c, and five temperatures between 7 and 19 K were used to measure the gain and noise temperature of the amplifier. This calibration applies for a source impedance given by R_n. (The normal state resistance was 80 Ω.) In order to reduce the effects of device-amplifier mismatch, a 3 dB attenuator was placed in front of the cooled amplifier. Therefore, the effective amplifier noise temperature was about 50 K over the band, 0.1-7.5 GHz. The effective frequency resolution was 100 MHz. In order to more accurately measure the noise, we used an isolator (band 1.25-1.75 GHz) and measured the average noise and average conversion efficiency within this band in a separate experiment.

The main source of error in the measurement of the output noise is the change of the device differential impedance with frequency. Furthermore, the impedance at the measurement point can be different than the impedance (R_n) during calibration. There is an outgoing noise-wave from the amplifier that is reflected off the device and then amplified. By biasing the device on the supercurrent branch, where the reflection coefficient is unity, and measuring the amplifier output power, we can get an estimate of the outgoing noise wave. We find the magnitude of this noise wave to be 15 K, so that the error for the measurement is at most $\pm 15K$. We measured the return loss off the device, and find it to be 8 dB for frequencies below 2.4 GHz and greater than 10 dB for frequencies above 2.4 GHz, so the reflected noise wave should be smaller than 15 K. For the measurements with the isolator, the maximum error due to impedance mismatch is smaller, $\pm 5K$. Due to limited information, corrections for impedance mismatch effects were not applied to the data.

III. MEASUREMENT RESULTS

A. DC bias voltage dependence of low frequency noise

We measured the output noise and conversion efficiency at low frequencies (100-200 MHz) as a function of dc bias

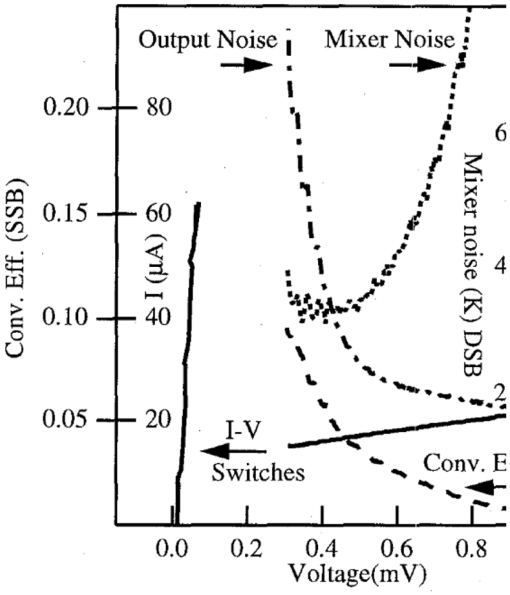

Fig. 1. Conversion efficiency, output noise, and mixe bias voltage. The inset shows the I-V curve.

for the LO power which maximized the (coup sion efficiency. The measurements were all p a bath temperature of 2 K. In Fig. 1, we sh put noise and conversion efficiency, as well a noise, determined by dividing the output noise version efficiency, as a function of dc bias v output noise was measured at a frequency we roll-off (100-200 MHz), where the spectrum sh the conversion efficiency was measured with a matic source. The output noise and conversic both peak very rapidly just before the devi into the superconducting state, but the mixer atively insensitive to dc bias over a region of mV wide.

B. Comparison of theory and experiment of lo noise

The magnitude of the thermal fluctuation erned by the steepness of the resistance vs. t curve. Flucuations in the electron temperatu sistance fluctuations proportional to the magr temperature flucuation. In Fig. 2 we show th resistance vs. temperature curve. The pe dR/dT is approximately 200 Ω/K. The lo noise temperature referred a perfectly match is predicted to be [6]

$$T_{fl} = \frac{I_0^2}{R_L}\left(\frac{dR}{dT}\right)^2\frac{T_e^2}{G},$$

where I_0 is the dc bias current, T_e is the electr ture, and G the thermal conductance from the the bath. If we take $T_e = T_c = 5.5\ K$, G=20 below)[1], and $I_0 = 15\ \mu A$ (the current near the

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[1] The thermal conductance due to diffusion is given by LT/R_{eff}, where L is the Lorentz number

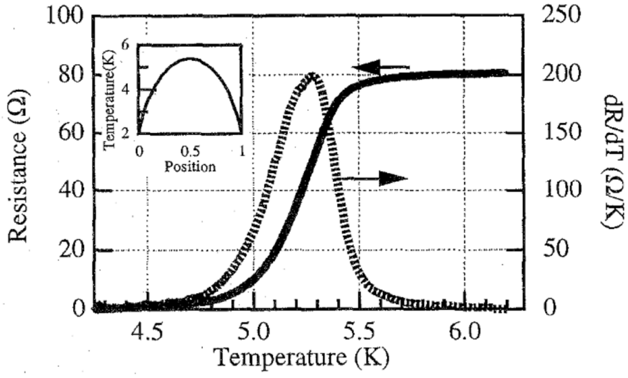

Fig. 2. Measured resistance vs. temperature curve. The inset shows a uniform-heating temperature profile predicted for a 20 μA bias.

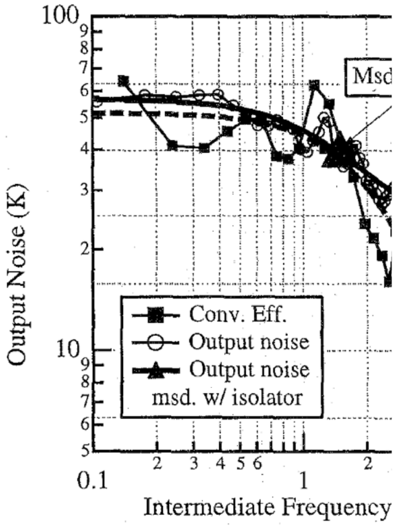

Fig. 3. Output noise and conversion effic
frequency. The theoretical fits are shown
efficiency) and a dotted (output noise) line.

we find $T_{fl} = 270K$. This is significantly higher than the value measured at low frequencies, 55 K. We mention two possible reasons for this disagreement. First, the electrons may not be at the temperature where dR/dT is steepest. Even for the lumped element case, little is know quantitatively about the electron temperature as a function of dc bias voltage when $T_{bath} < T_c$. Another possible explanation is that, in contrast to phonon-cooled devices where the temperature may be uniform along the length of the bridge, the temperature profile in diffusion cooled devices is not uniform. For diffusion cooled devices the ends of the bridge are assumed to be heat sunk very well to the bath temperature $T_{bath} << T_c$, while at least part of the bridge must be at or near T_c for there to be any resistance. Therefore, it is possible that only a fraction of the bridge is at T_c, reducing the contribution to the thermal fluctuation noise. In the inset of Fig. 2, we show an analytical temperature profile, for uniform dc heating caused by $15\mu A$ of current. The profile indeed shows that only a fraction of the bridge is near T_c, while most of the electrons are above or below[2] T_c. Additionally, the concept of a local temperature can only be meaningfully employed for length scales larger than $L_{e-e} \equiv \sqrt{D\tau_{e-e}}$, the electron-electron inelastic length. For the device measured here, $L_{e-e} \approx 0.05\mu$m[3]. Therefore, the concept of a smooth temperature profile over the length of 0.16 μm is only approximately correct, and a more sophisticated model will have to be developed to quantitatively predict the value of the output noise. Given these uncertainties in the theoretical model for the bridge, the deviation from the prediction of Eq. 4 may be reasonable.

C. *Spectrum of output noise*

We measured the output noise and conversion efficiency as a function of IF at the dc bias which gave the highest conversion efficiency. In Fig. 3 we plot the measured output noise vs. frequency. The single solid point was measured with an isolator in place. We fit the data
to a white background (Johnson noi
tion with the form of Eq. 1 (therma
We allowed the magnitude of the Jol
thermal fluctuation noise to vary, a
mal rolloff of the thermal fluctuation
gives $T_{fl}(0) = 35\ K, T_J = 21\ K, 1,$
The Johnson noise floor at high fre
thermal fluctuation noise is negligibl
$T_c = 5.5K$, since the electrons are he
dc and LO power. Thus, the measure
the Johnson noise floor is not reached
the measurment, though, we cannot s
this is the case.

We also measured the conversio
monochromatic source; this is also pl
the same dynamic range (13dB) as th
parsion of the relative spectral depe
and efficiency. The fit of Eq. 1 to the
gives $1/2\pi\tau_{th} = 2.4\ GHz$. Thus, the
noise is in fair (40%) agreement with
ciency. The agreement between the fr
of the conversion gain and the outpu
thermal fluctuation noise is the domi
diffusion cooled hot-electron bolomet

D. *Noise bandwidth*

In Fig. 4, we plot the mixer noise
lated by dividing the output noise by
ciency) vs. intermediate frequency.
noise and the conversion efficiency we
neously under identical conditions.
is 4 GHz, which is 1.7 times larger
width. If the high frequency output
$T_c = 5.5\ K$, then Eq. 3 predicts t
would be approximately 3 times the

$R_n/12$[7]. Again, the "bare" G can be used if electrothermal feedback effects are not strong[5].

[2] The proposed mechanism for the reduction of the output noise would also reduce the conversion efficiency, but the mixer noise would presumably be unaffected.

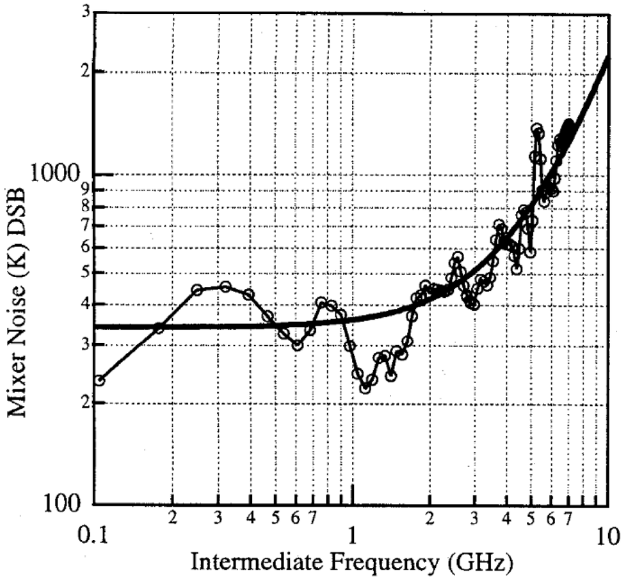

Fig. 4. Mixer noise *vs.*intermediate frequency.

E. DC and AC heating in the normal state; thermal conductance

Another technique can be used to determine the thermal conductance G from the electrons to the bath. With the bath held above T_c, the device output noise was measured as a function of applied dc power. Above T_c at microwave frequencies, the only noise source is Johnson noise. This can be used as a thermometer to measure the *average* electron temperature across the length of the bridge. In Fig. 5, we plot the electron temperature vs. the dc power, as well as vs. applied rf power. (The magnitude of the rf power was determined in a separate calibration.) The slope at the origin gives an effective thermal conductance of 30 nW/K, which is in fair agreement with the diffusion prediction of 20 nW/K[7] from the Wiedemann-Franz law. The simple combination of noise thermometry and dc substitution should also allow for easy calibration of coupled LO power at THz frequencies.

IV. CONCLUSIONS

We have shown that the frequency dependence of the output noise of diffusion cooled bolometers is the same as the conversion efficiciency, and in agreement with predictions based on a model of thermal fluctuation noise. The noise bandwidth is larger than the gain bandwidth by a factor of 1.7 in this case. Thus, diffusion cooled bolometers can have low noise (340 K DSB) over a wide range of intermediate frequencies.

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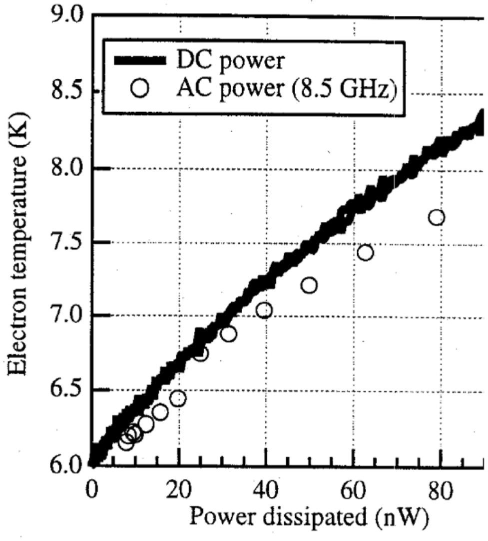

Fig. 5. Electron temperature vs. applied po

REFERENCES

[1] E.M. Gershenzon, G.N. Gol'tsman, I.G. Gogidz A.I. Elant'ev, B.S. Karasik, and A.D. Semeno Superconductivity **3**, 1582 (1990), and reference

[2] A. Skalare, W.R. McGrath, B. Bumble, H.G. Burke, A.A. Verheijen, R.J. Schoelkopf, and Appl. Phys. Lett., **68**, 1558 (1996); W.R. McGr at Int. Symp. on Millimeter and Submillimeter V plications, III, Denver, CO Aug. 1996; presen Skalare et al., and by B. Karasik et al., Applied tivity Conf., Pittsburgh, PA, Aug. 1996; IEEE T Supercond., submitted.

[3] P.J. Burke, R.J. Schoelkopf, D.E. Prober, A. McGrath, B. Bumble, and H.G. LeDuc, Appl. P 3344 (1996).

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

[5] Due to electro-thermal feedback effects (H. Karasik, E. Kollberg, and K.S. Yngvesson, IE Microwave Theory and Techniques, **43**, 938 (19 constant inferred from the bandwidth is equal thermal time constant τ_{th} only if the self-heati $[I^2(dR/dT)/G]$ is small or V_{dc}/I_{dc} is close to th input impedance, 50 Ω. (Here G is the therma to the bath.) From the differential (75 Ω) and a resistance for the device measured in this work, measured time constant is approximately equal

[6] B.S. Karasik, A.I. Elantiev, Appl. Phys. Lett., 6 B.S. Karasik, A.I. Elantiev, Proc. 6th Intl. S Tech. (1995).

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

[8] H. Ekström, B. Karasik, Appl. Phys. Lett., **66**,

[9] J.-X. Yang, J. Li, C.F. Musante, and K.S. Yng Phys. Lett., **66**, 1983 (1995).

[10] B. Bumble and H.G. LeDuc, submitted to IEEE on Applied Superconductivity.