Noise bandwidth of diffusion-cooled hot-electron bolometers

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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

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

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]. Identification of the dominant noise source for diffusion-cooled bolometers is obviously an important issue for receiver applications and the required first step for mixer optimization. Theoretical calculations[6] predict that the power coupled into an IF load due to thermal fluctuation noise has the same spectrum as Eq. 1. In addition to thermal fluctuation noise, there is also Johnson noise, and there will be a crossover frequency above which Johnson noise is larger than the thermal fluctuation noise. Thus the *mixer* noise $T_{mix}(DSB) \equiv T_{out}/2\eta$ (with η the SSB conversion efficiency) should depend on frequency as follows:

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

where T_J is the Johnson noise, and $T_{fl}(0)$ is the low frequency value of the thermal fluctuation noise. We define the *noise bandwidth* $f_{noise3dB}$ as the frequency at which the mixer noise is 3dB higher than its zero frequency value. The above equations give[1]

$$\frac{f_{noise3dB}}{f_{gain3dB}} = \sqrt{\frac{T_J + T_{fl}(0)}{T_J}} \tag{3}$$

Therefore, the noise bandwidth can be larger than the gain bandwidth if the thermal fluctuation noise dominates at low frequencies. To include the noise of the IF amplifier T_{amp}, T_J should be replaced by $T_J + T_{amp}$ above.

A significant increase in the IF gain bandwidth of hot-electron bolometers was predicted[7] and recently observed[2], [3] for short devices. Specifically, if the device length 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)[7], the thermal conductance from the electrons to the "bath" can be primarily due to diffusion of hot electrons out the ends of the bridge. This crossover length ($\sqrt{12}\ L_{e-ph}$) is about 1 μm in Nb at 4.2 K. In this paper, we present measurements of the output noise, conversion efficiency, and mixer noise for a diffusion-cooled Nb device of length 0.16 μm. The electrons in this device are predominantly cooled by diffusion, but the IF gain bandwidth (2.4 GHz) is within the band of the amplifiers used, 0.1-7.5 GHz, allowing measurement above and below the thermal rolloff. While the spectrum of the output noise has been measured in phonon-cooled NbN bolometer mixers[8] and 2DEG bolometers[9] and found to agreee with thermal-fluctuations, this is the first test of Eqs. 2 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 for the LO power which maximized the (coupled) conversion efficiency. The measurements were all performed at a bath temperature of 2 K. In Fig. 1, we show the output noise and conversion efficiency, as well as the mixer noise, determined by dividing the output noise by the conversion efficiency, as a function of dc bias voltage. The output noise was measured at a frequency well below the roll-off (100-200 MHz), where the spectrum should be flat; the conversion efficiency was measured with a monochromatic source. The output noise and conversion efficiency both peak very rapidly just before the device switches into the superconducting state, but the mixer noise is relatively insensitive to dc bias over a region of about 0.25 mV wide.

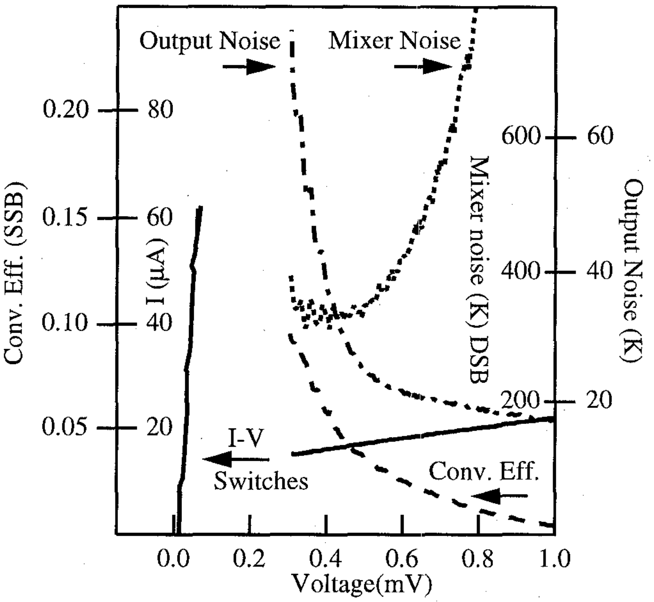

Fig. 1. Conversion efficiency, output noise, and mixer noise vs. dc bias voltage. The inset shows the I-V curve.

B. Comparison of theory and experiment of low frequency noise

The magnitude of the thermal fluctuation noise is governed by the steepness of the resistance vs. temperature curve. Flucuations in the electron temperature cause resistance fluctuations proportional to the magnitude of the temperature flucuation. In Fig. 2 we show the measured resistance vs. temperature curve. The peak value of dR/dT is approximately 200 Ω/K. The low frequency noise temperature referred a perfectly matched load R_L is predicted to be [6]

$$T_{fl} = \frac{I_0^2}{R_L}\left(\frac{dR}{dT}\right)^2\frac{T_e^2}{G}, \tag{4}$$

where I_0 is the dc bias current, T_e is the electron temperature, and G the thermal conductance from the electrons to the bath. If we take $T_e = T_c = 5.5\ K$, G=20 nW/K (see below)[1], and $I_0 = 15\ \mu A$ (the current near the dropback),

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

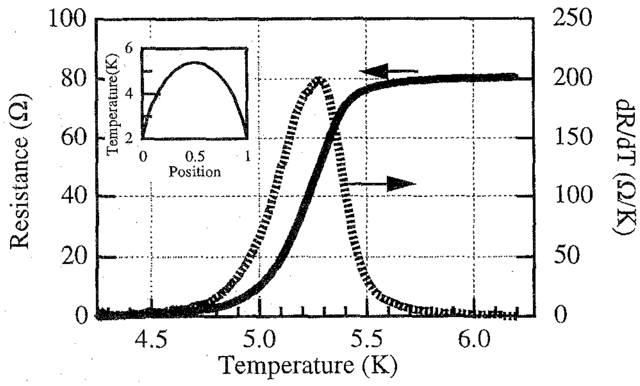

Fig. 2. Measured resistance vs. temperature curve. The inset shows a uniform-heating temperature profile predicted for a 20 μA bias.

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 noise) plus a contribution with the form of Eq. 1 (thermal fluctuation noise). We allowed the magnitude of the Johnson noise and the thermal fluctuation noise to vary, as well as the thermal rolloff of the thermal fluctuation noise. The best fit gives $T_{fl}(0) = 35\ K, T_J = 21\ K, 1/2\pi\tau_{th} = 1.5\ GHz$. The Johnson noise floor at high frequencies, where the thermal fluctuation noise is negligible, is expected to be $T_c = 5.5K$, since the electrons are heated up to T_c by the dc and LO power. Thus, the measurements indicate that the Johnson noise floor is not reached. Given the error on the measurment, though, we cannot say conclusively that this is the case.

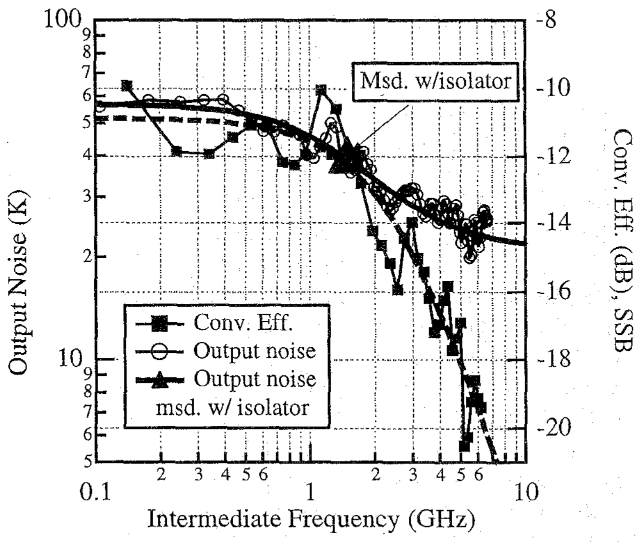

Fig. 3. Output noise and conversion efficiency *vs.* intermediate frequency. The theoretical fits are shown as a solid (conversion efficiency) and a dotted (output noise) line.

We also measured the conversion efficiency with a monochromatic source; this is also plotted in Fig. 3, with the same dynamic range (13dB) as the noise to allow comparsion of the relative spectral dependence of the noise and efficiency. The fit of Eq. 1 to the conversion efficiency gives $1/2\pi\tau_{th} = 2.4\ GHz$. Thus, the rolloff of the output noise is in fair (40%) agreement with the conversion efficiency. The agreement between the frequency dependence of the conversion gain and the output noise suggests that thermal fluctuation noise is the dominant noise source in diffusion cooled hot-electron bolometers.

D. Noise bandwidth

In Fig. 4, we plot the mixer noise temperature (calculated by dividing the output noise by the conversion efficiency) vs. intermediate frequency. Note that the mixer noise and the conversion efficiency were measured simultaneously under identical conditions. The noise bandwidth is 4 GHz, which is 1.7 times larger than the gain bandwidth. If the high frequency output noise were to fall to $T_c = 5.5\ K$, then Eq. 3 predicts the noise bandwidth would be approximately 3 times the gain bandwidth.

$R_n/12$[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.

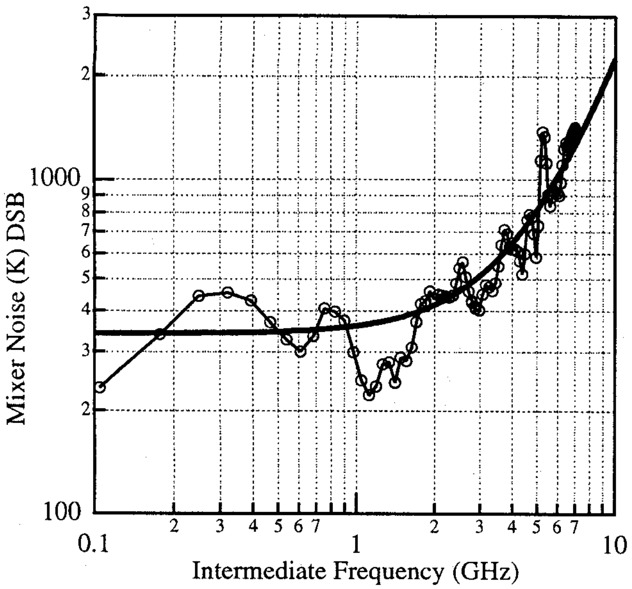

Fig. 4. Mixer noise *vs.*intermediate frequency.

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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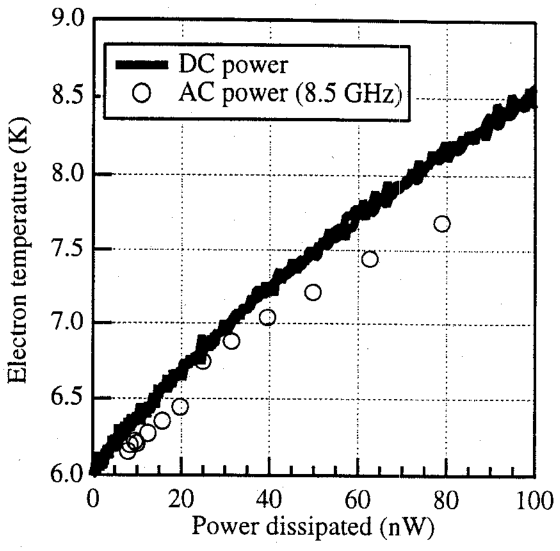

Fig. 5. Electron temperature vs. applied power.

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