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An array scalable zero-bias far-IR detector with noise thermometry readout

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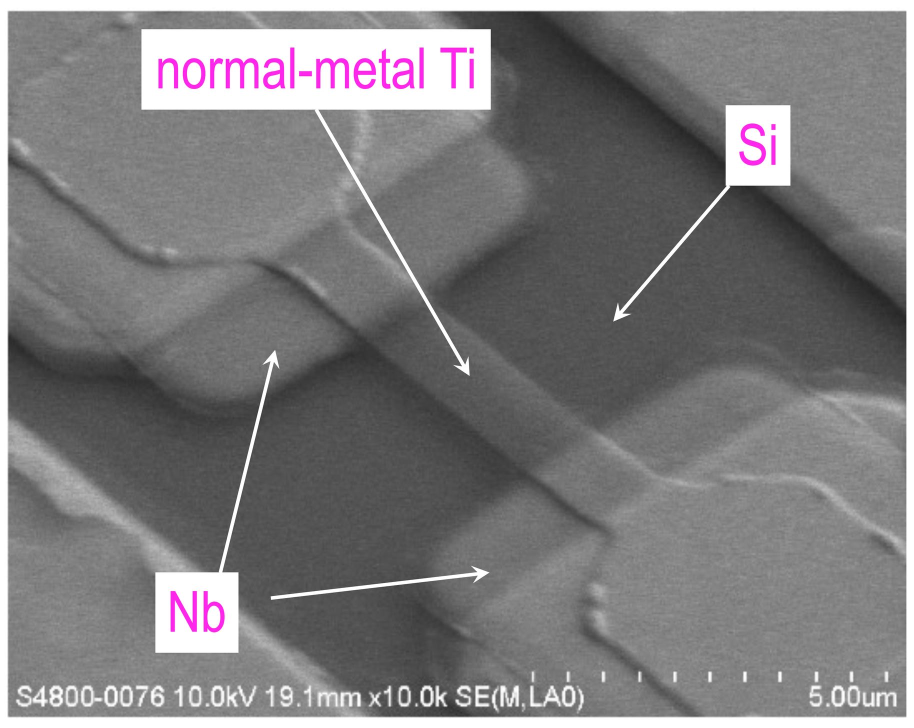


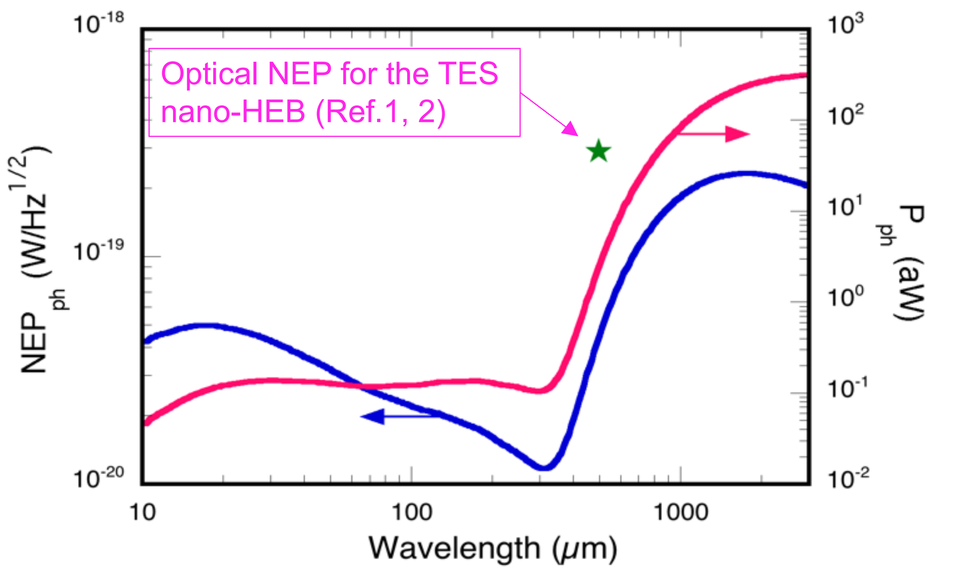
SEM image of a 2μm x 1μm x 25nm twin-slot antenna coupled ZBHEB used in the current experimental work. The ultimate device size would be 0.5μm x 0.25μm x 20nm.

1. ZB-HEB concept

We develop an ultrasensitive far-IR detector based on the Zero-Bias (ZB) Hot-Electron Bolometer (HEB). Beside the advantage of high sensitivity, the ZBHEB does not require any dc or microwave bias, has a very large dynamic range of 60-100 dB and can be operated at arbitrary temperature in the 0.05-9 K range, depending on the radiation background. Johnson Noise Thermometry (JNT) allows for the FDM readout of up to 1,000 ZBHEBs using a single broadband QL parametric LNA and a filter-bank channelizer.

The ZBHEB readout uses microwave noise power emitted by the bolometer as the measure of the sensor electron temperature, T_e. The thermal responsivity is determined by both the phonon (e-ph) cooling and microwave-photon mediated cooling (γ). The latter is critical at 50-100 mK. The ultimate detector NEP $\approx 2 \times 10^{-21}$ W/Hz$^{1/2}$ @ 50 mK.

2. Ultimate far-IR detector sensitivity requirements

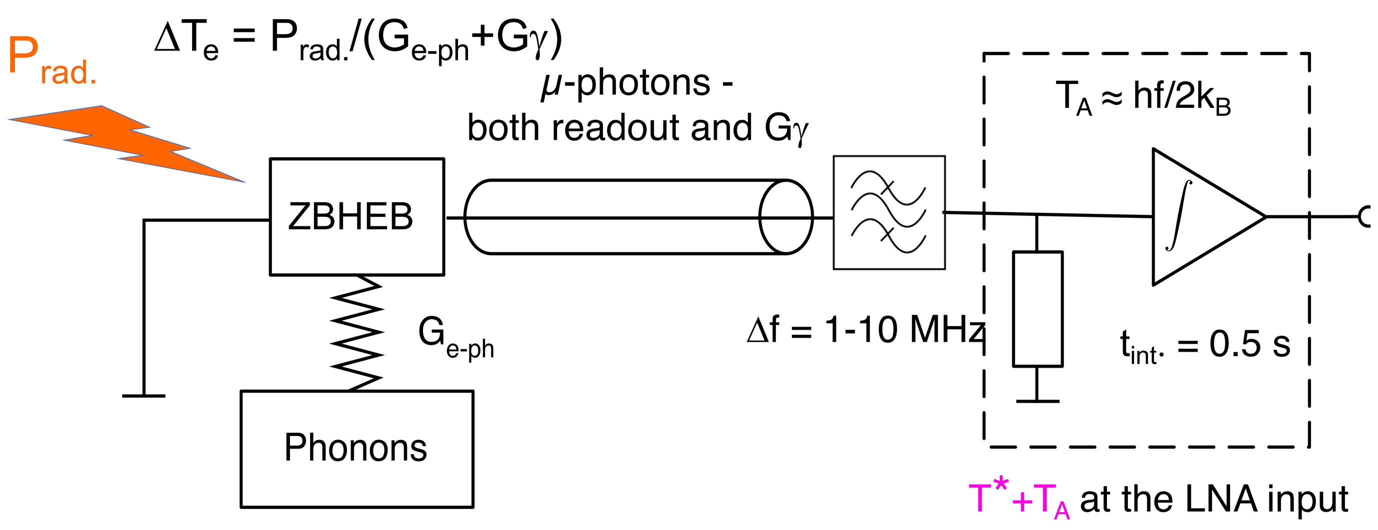


Cosmic background limited NEP and radiation power impinging a single-mode detector on a space-borne spectrometer (telescope mirror temperature ≈ 4K)

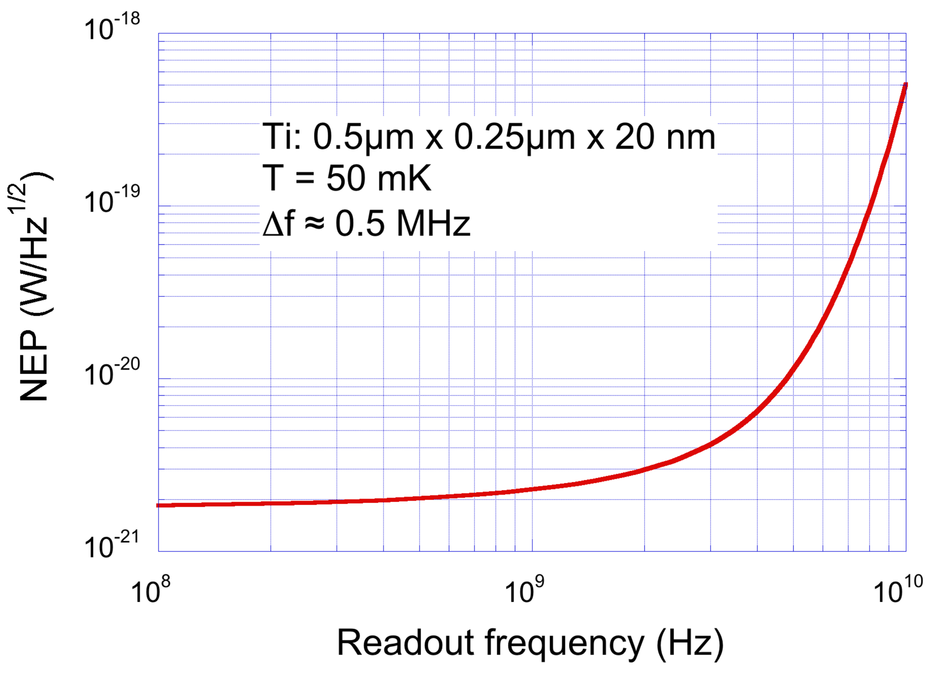
Our previous work has developed a superconducting (= TES) nano-HEB detector with an optical NEP $\approx 3 \times 10^{-19}$ W/Hz$^{1/2}$. This is close to that required for the moderate resolution spectrometers ($\nu/\delta\nu \sim 1000$) on a future space telescope with cold mirror ($T_{mirror} \approx 5$ K).

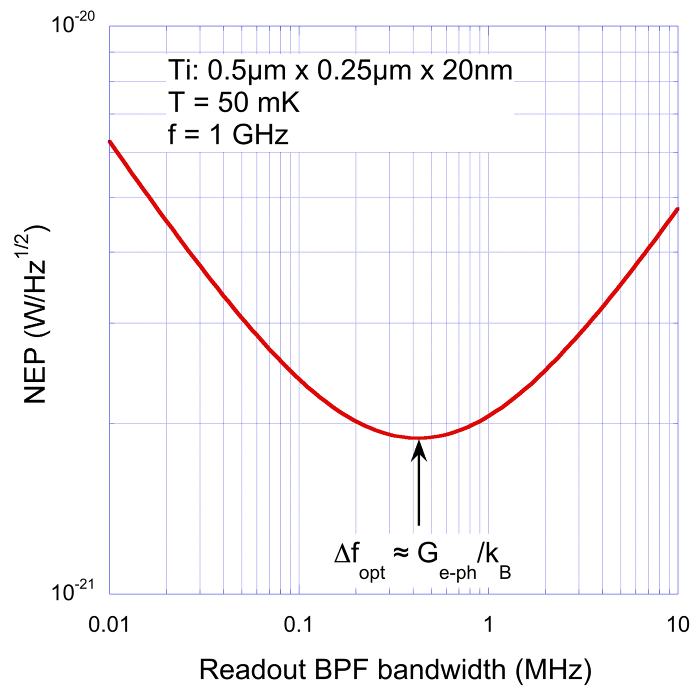
The ZBHEB eliminates the complexity of large arrays of TES where multiple bias lines and multiplexed SQUID amplifiers are required. Also, this detector can be achieved via a simpler fabrication process.

3. Johnson Noise Thermometry and NEP



- $P_J = hf\Delta f[n(n+1)]^{1/2} = k_B T^* \Delta f$ – Johnson noise power
- $P_f = hf\Delta fn$ = microwave power emitted by the ZBHEB
- $G_\gamma = dP_f/dT \approx k_B \Delta f$ (n>>1)
- T^* is the effective noise temperature (= T_e when n >>1)
- **n** is the photon occupation number





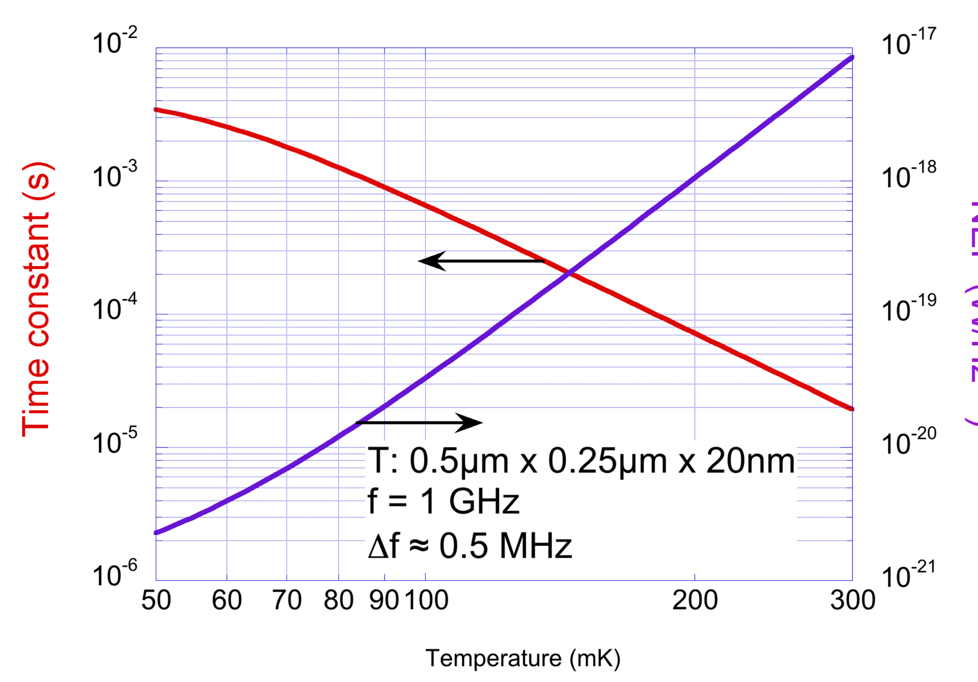
Ref. 3

NEP of a small- size ZBHEB read by a quantum-limited amplifier ($T_A = h\nu/2k_B$), e.g., the Kinetic Inductance (KI) Parametric Amplifier (Ref.4) or the Josephson Travelling Wave Parametric Amplifier (JTWPA) (Ref. 5). Microwave-photon-mediated thermal transport dominates for submicron-size ZBHEB devices @ 50mK. NEP_{TEF} and NEP_{JNT} contribute almost equally in the total minimum NEP. The optimal filter bandwidth (Δf_{opt}) is set by the trade-off between G_γ (~ Δf) and Dicke radiometer fluctuation (~ $\Delta f^{-1/2}$)

- $S_{JNT} = dP_f/P_{rad}$ is the JNT responsivity
- $NEP_{JNT} = k_B(2\Delta f)^{1/2}(T^*+T_A)/S_{JNT}$
- $NEP_{TEF} = [4k_B T^2(G_{e-ph}+G\gamma)]^{1/2}$

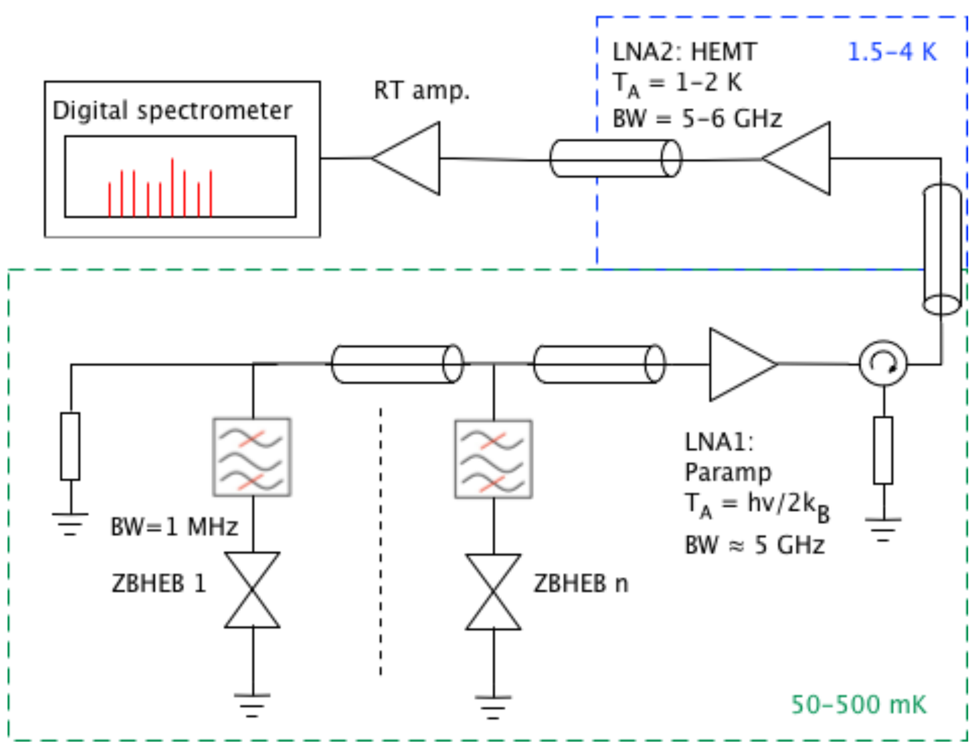
For small devices (small G_{e-ph}), NEP_{JNT} >> NEP_{TEF}. In this case, NEP remains constant within a broader frequency range of several GHz. This allows for more frequency channels (pixels) be implemented with a single amplifier without degradation of NEP. Promising materials are graphene and Bi.

4. Time constant and single-photon detection



- An expected energy fluctuation of the sensor is $\delta E \approx NEP \times \tau^{1/2} = 0.7$ meV = 0.17 THz, that is 1-THz photons can be counted with high fidelity.
- For higher background applications (ground based, suborbital), ZBHEB can be operated in the 50-500 mK range.

5. ZBHEB array consideration

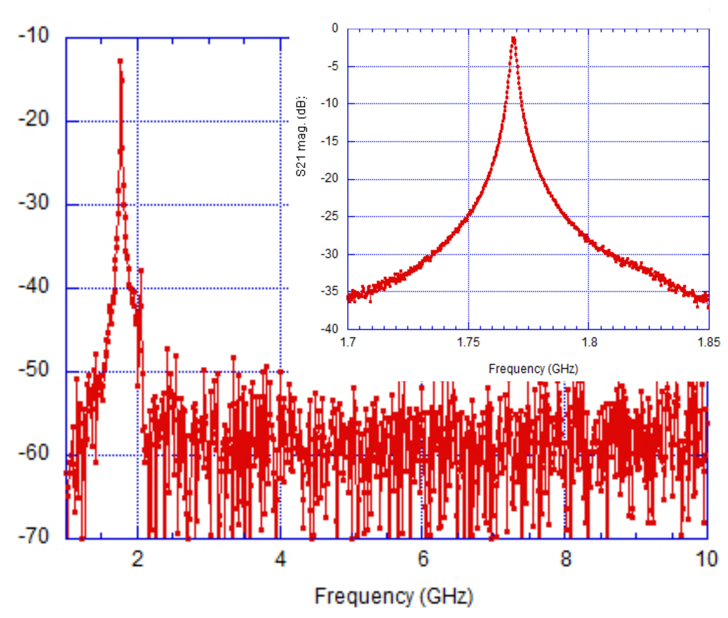


6. Optical load and dynamic range

- $P_{ph} \approx 0.1$ fW would cause a small increase of T_e (by 7 mK in the smallest devices). This does not deteriorate the ZBHEB sensitivity (remains background limited).
- The maximum optical load is determined by the power needed to heat the electrons to the critical temperature of superconducting contacts (≈ 9 K), $P_{rad.}$ = 7 nW, or the power leading to the saturation of the LNA output.
- For a ZBHEB operating at 50 mK, the dynamic range will be ≈ 100 dB with a KI PA and ≈ 65 dB with an JTWPA.

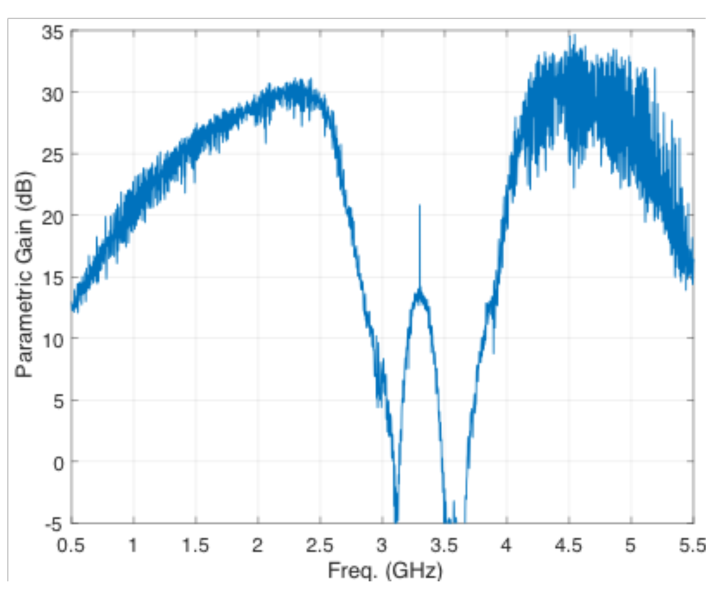
7. Experimental progress to date

Cryogenic microwave BPF with Q ~ 1000



A combination of a custom superconducting Nb filter based on a CPW microresonator and a commercial 1-2 GHz BPF yields a narrowband BPF with Q ~ 1000. The latter filter was required in order to suppress harmonic resonances in the microresonator which otherwise would increase Δf and Gγ. More work will be needed in order to come up with the design providing 100s of ~ 1-MHz passbands without frequency collision and crosstalk.

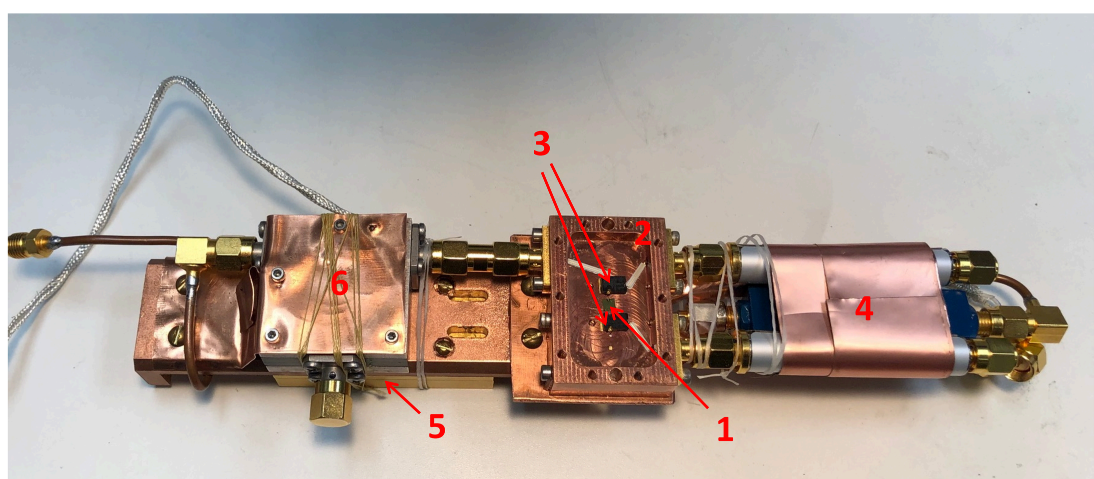
Novel L-band KI parametric amplifier



A novel L-band Kinetic Inductance parametric amplifier is being developed for this work (P. Day). The previously developed amplifiers of these kind were all for higher frequencies (5-9 GHz). The L-band is important for this detector since the entire Johnson noise spectrum is confined within the range $\approx k_B T/h = 1$ GHz @ 50mK.

The new L-band amplifier has a very high gain ~ 25-30 dB, the noise temperature measurements are forthcoming.

Experimental setup for noise thermometry in a dilution refrigerator

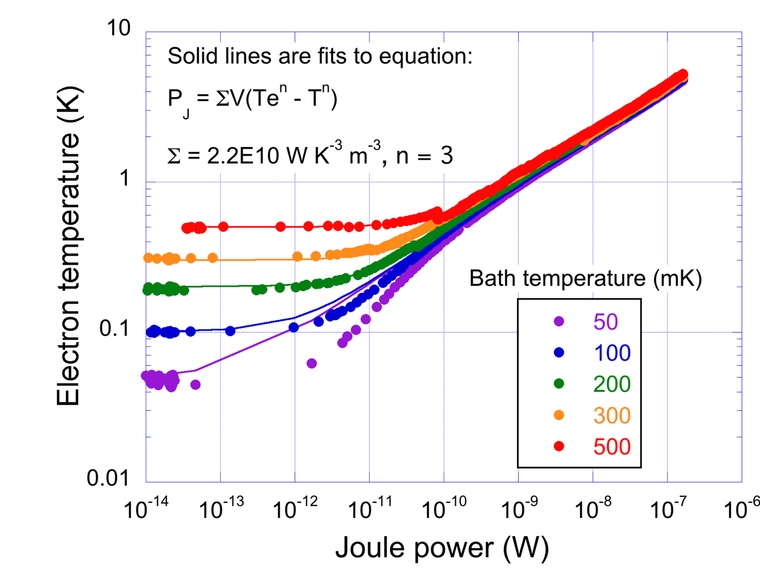


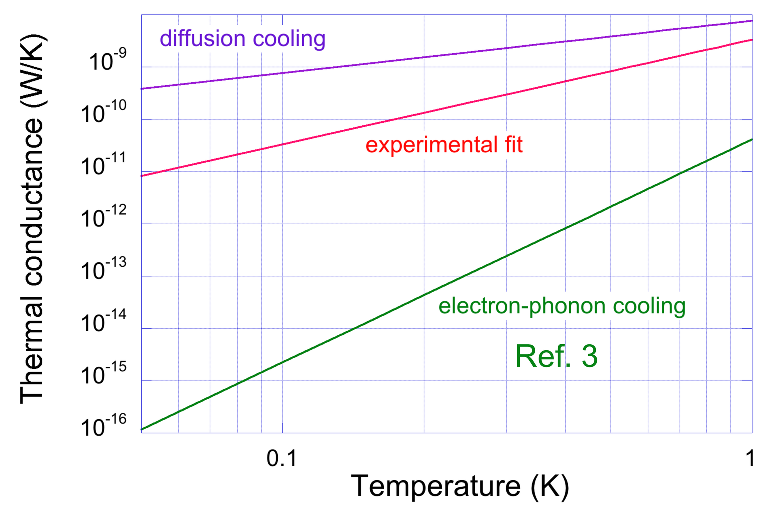
Currently, preliminary measurements of the electrical NEP are in progress.

A 4mm x 4mm Si chip with a ZBHEB device (1) is mounted in an rf tight Cu box (2). In order to simulate the absorbed radiation power, a dc current is sent through the device using two chip bias-T's (3). The bias lines are filtered using two dc-80 MHz BPFs (4). The device output noise signal propagates through the Q=1000 BPF (on the back side of the assembly, (5)) and then through the cryogenic L-band isolator (6). A 1-K HEMT amplifier placed just above the LHe level is used for readout. In the future, the HEMT amplifier will be replaced by the KI parametric amplifier.

The detector by itself does not require current bias. The bias is used only for electrical NEP tests.

Thermal conductance using noise thermometry with a 1-K LNA





In the current device, the thermal conductance is much higher than anticipated because of the potential heat leak in Nb Andreev contacts. The expected NEP is dominated by $NEP_{JNT} \approx 2 \times 10^{-17}$ W/Hz$^{1/2}$.

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