FY24 R&TD Innovative Spontaneous Concepts (ISC)

# Towards the multifold increase of sensitivity of the THz HEB mixers

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**Strategic Focus Area:** Innovative Spontaneous Concepts

**Objectives:** The objective was to demonstrate a large (up to 10 dB) increase in the conversion gain in the existing NbN and $MgB_2$ Hot-Electron Bolometer (HEB) mixer devices by operating them in the Negative Electro-Thermal Feedback (nETF) regime. We plan to compare the mixer gain with that in the Positive Electro-Thermal Feedback (pETF) mode in the same mixer devices. All superconducting HEB mixers have operated in the pETF regime so far. Implementation of the nETF is seen as a promising way for the overall improving the sensitivity of the mixer and moving it closer to the quantum limit. The noise temperature improvement needs to be established both theoretically and experimentally and relate to the effect of the nETF. The ultimate goal is to set a new state-of-the-art (SOA) noise temperature of the THz HEB mixers at several THz frequencies (e.g., 1.9, 2.5, 4.7 THz).

**Background:** Superconducting HEB mixers are the detectors of choice for astrophysical heterodyne instruments that have been of primary interest to JPL scientists and engineers. To maintain the competitive edge over European, Japanese, and Chinese groups, more advanced/sensitive HEB mixers must be achieved. Currently, SIS mixers with nearly quantum-limited (QL) sensitivity dominate below 1.3 THz. At higher frequencies, HEB mixers are the only option. However, despite the superconducting material and mixer design advances, they are still behind the SIS mixers in sensitivity. The best HEB receivers demonstrate the double sideband (DSB) noise temperature of ≈ 10 x QL at the frequencies in the 1.5-5 THz range. Thus, the SOA NbN HEB mixers at, say, 2.5 THz demonstrate only ~ 25% of their sensitivity potential. In the field observations, this leads to the 16-times longer observation time than theoretically necessary to achieve the needed signal-to-noise ratio. The above example is quite optimistic; many practical receivers do not reach the current experimental limit.

**Approach and Results:** To operate the Transition-Edge Sensor (TES) HEB with the negative differential resistance, -Z , the device must be "voltage-biased" within the signal bandwidth, that is, the bias resistor $R_L$ <Z. In the direct detector TES, it is achieved by using a low-impedance readout (e.g., SQUID amplifier). In the HEB mixer circuit, $R_L$ = 50 Ohm since HEMT and SiGe GHz amplifiers are used **(Fig. 1)**. An attempt to bias the HEB mixer into the nETF mode leads to either linear oscillations due to the interaction of stray reactive parameters, or to the large-amplitude non-linear oscillations with an amplitude across the entire bias range where Z<0. We have simulated this transition by varying the LO power on the HEB device and monitoring the amplitude of the IF signal (a mixing product of 2.5 THz signals from the far-IR gas laser and the frequency-multiplier chain - FMC source). We observed an increase of the IF amplitude with the decrease of the LO power followed by the abrupt drop of the IF signal amplitude **(Fig. 2)**. An interpretation of the behavior is as follows. The conversion gain increases as the bias conditions approach those corresponding to Z<0 (nETF). When the region with Z<0 forms, MHz oscillations start and wash out the bias point so only a greatly reduced time-averaged IF signal is present. To analyze the situation, we built a circuit model using LTSpice software **(Fig. 3)**. The thermal inertia effects were simulated with an equivalent RC-circuit yielding the same electrical reaction of the HEB device to the change of bias. The transfer function and circuit impedance plots clearly demonstrate the presence of the resonance caused by the interaction of the bias-T inductor and the intrinsic equivalent capacitance of the HEB **(Fig. 4)**. The resonance could be reduced or moved away by modifying the circuit (replacing the large L of the bias-T with a smaller custom inductor and shunting the HEB with an external RC circuit). This has been confirmed experimentally. However, the solution to the problem requires a full circuit stability analysis using the Nyquist criterion and this is still a work in progress. An important experimental finding was the proof that the oscillatory behavior of the HEB device is not material dependent (NbN vs $MgB_2$) as speculated in the literature but driven by the circuit parameters. This gives an assurance that such an essentially engineering problem can be solved in the near future.

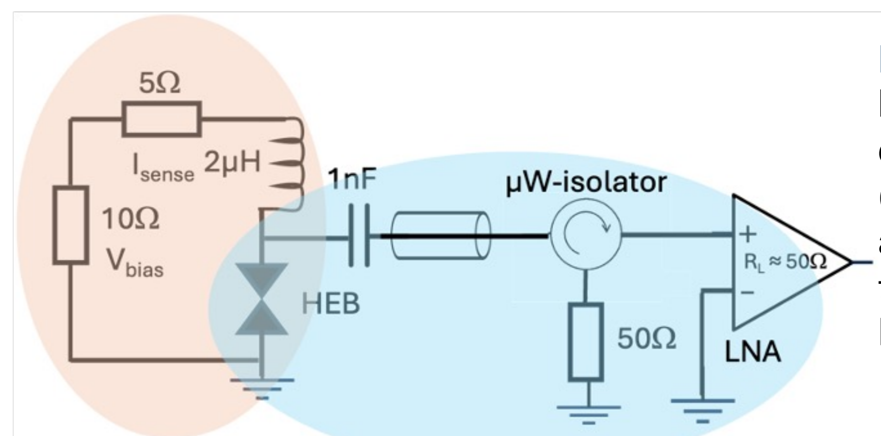


**Fig. 1.** Typical HEB mixer bias & IF circuit incudes a dc loop (pink). The IF part (blue) has a coax line with a microwave isolator and the GHz (e.g., L-band) LNA.

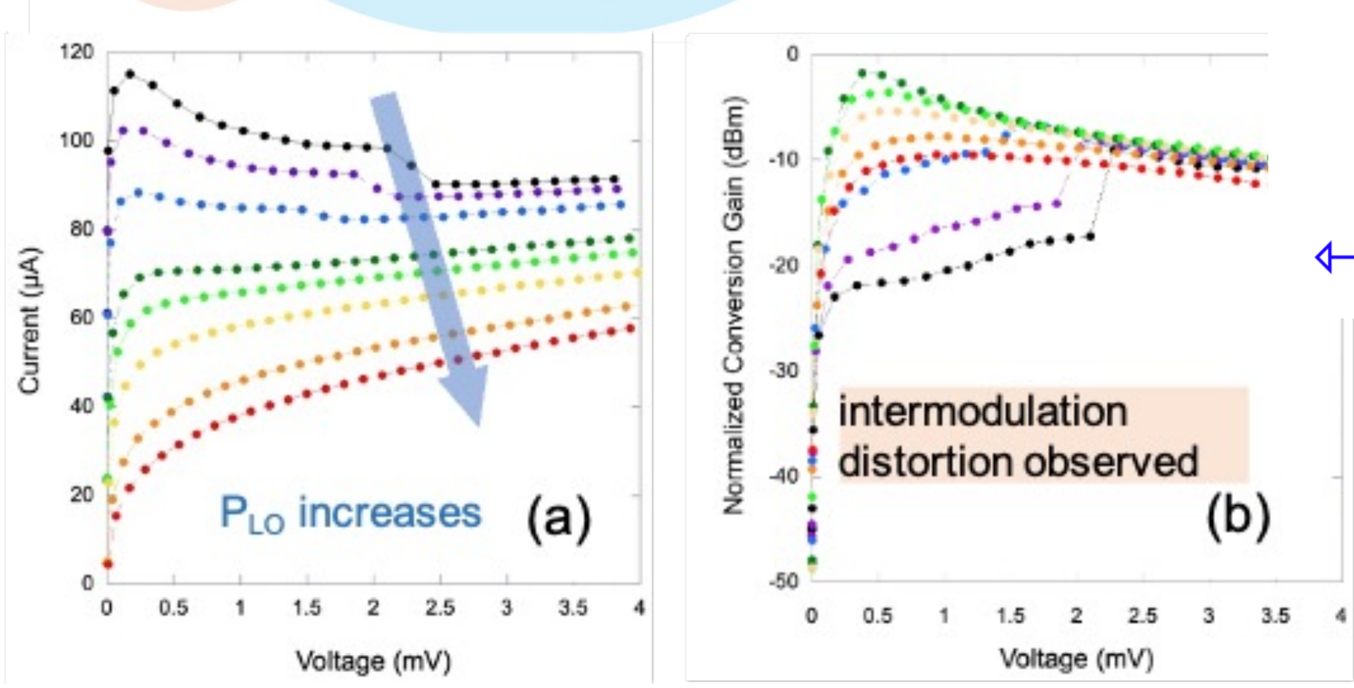


**Fig. 2.** (a) IVCs vs LO power in an NbN HEB at 4.3 K. (b) conversion gain vs LO power. As the LO power decreases, the IVC develops a negative-Z branch. The conversion gain first increase but then drops abruptly. This is because there is no stable bias in the oscillatory regime so the conversion gain readings are just time averaged.

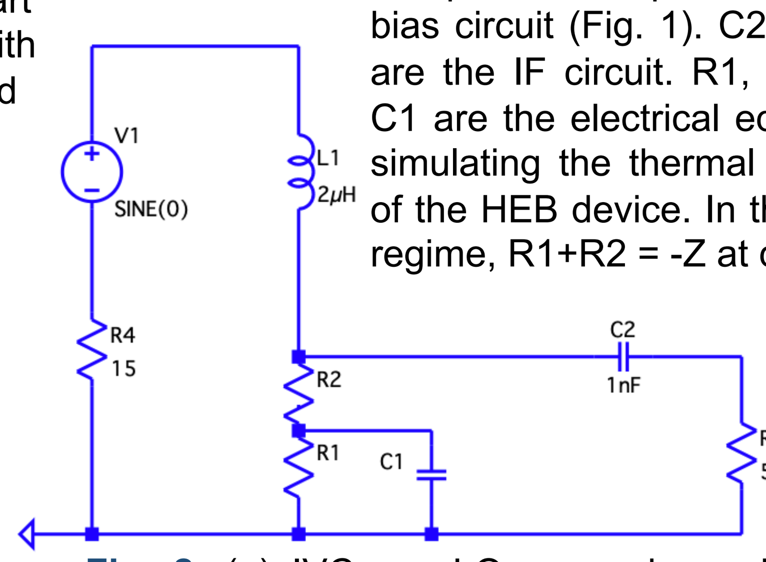


**Fig. 3.** LTSpice model of the HEB mixer. R4=15 Ohm and L1 = 2 μH are the parts of the dc bias circuit (Fig. 1). C2 and R3 are the IF circuit. R1, R2, and C1 are the electrical equivalent simulating the thermal reaction of the HEB device. In the nETF regime, R1+R2 = -Z at dc.

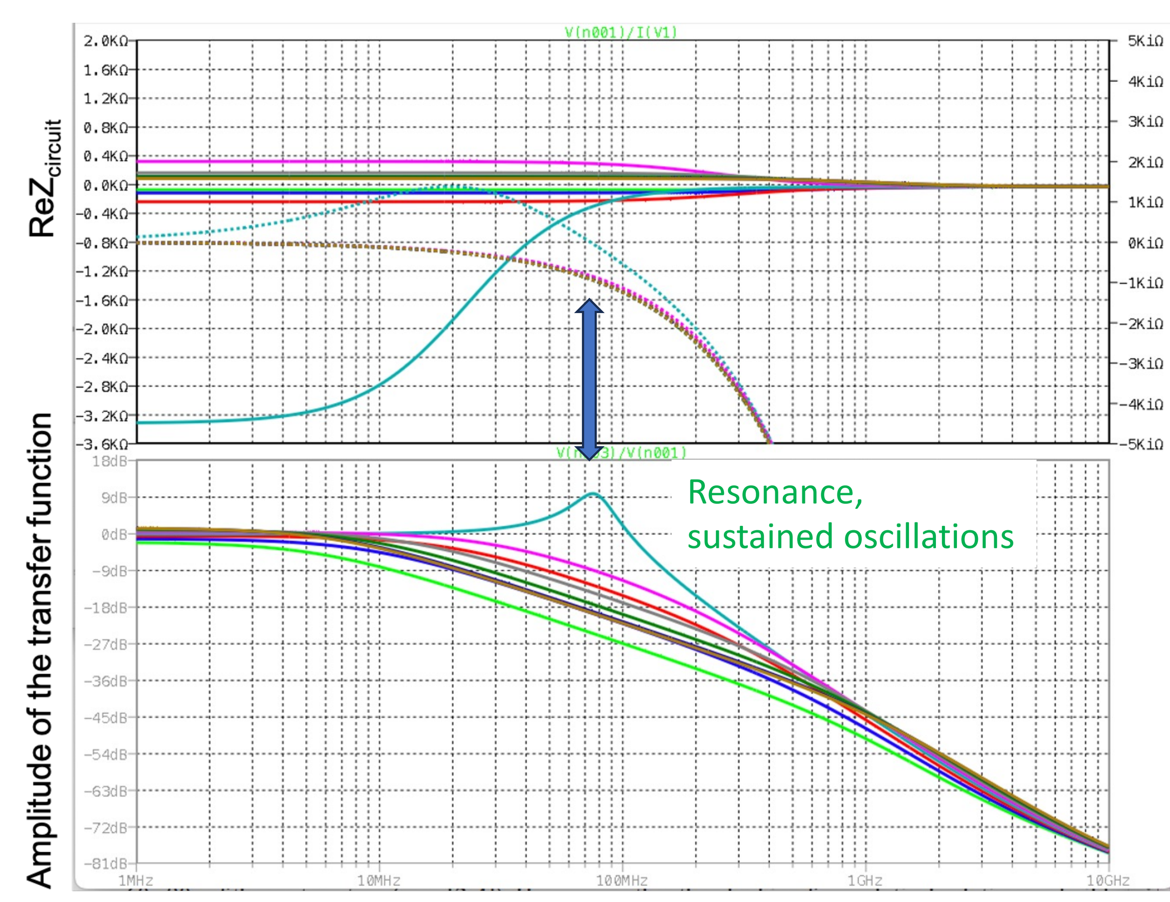


**Fig. 4.** Top: Circuit impedance presented to the source V1 (see Fig. 2). At the point of the resonance (~ 7.5 MHz), $ImZ_{circuit}$ = 0 (dotted green line) and $Re_{Zcircuit}$ < 0 (solid green line). Bottom: The transfer function exhibits a resonant peak in agreement with the impedance behavior. Multiple lines correspond to the different bias conditions.

**Significance/Benefits to JPL and NASA:** This work is highly beneficial to NASA & JPL as it targets a dramatic improvement of the SOA for the THz heterodyne receivers. The sensitivity gap between the current SOA HEB mixers and the quantum limit is real and our way of biasing the HEB mixer can reduce this gap significantly. The solution can be quite universal and result just in an augmented circuit that could be inserted in the IF lines of the existing HEB receivers. The reduction of the noise temperature will result directly in an increase of the mapping speed and science return of a heterodyne space mission.

**Publication:**

B. S. Karasik, C. Yoo, "On the sensitivity limitation in the HEB mixers," presented at the *33nd IEEE Int. Symp. Spc. THz Technol. (ISSTT 2024)*, Charlottesville, VA, USA, April 7-11, 2024.

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