Measurement of Intermediate Frequency Bandwidth of Hot Electron Bolometer Mixers atTerahertz Frequency Range

Denis Meledin, C.-Y. Edward Tong, *Member, IEEE*, Raymond Blundell, and Gregory Goltsman

***Abstract*—We have developed a new experimental setup for measuring the IF bandwidth of superconducting hot electron bolometer mixers. In our measurement system we use a chopped hot filament as a broadband signal source, and can perform a high-speed IF scan with no loss of accuracy when compared to coherent methods. Using this technique we have measured the 3 dB IF bandwidth of hot electron bolometer mixers, designed for THz frequency operation, and made from 3–4 nm thick NbN film deposited on an MgO buffer layer over crystalline quartz.**

***Index Terms*—Hot-electron bolometer, intermediate frequency bandwidth, submillimeter waves.**

I. INTRODUCTION

SUBMILLIMETER wavelength heterodyne receivers with large intermediate frequency (IF) gain bandwidth are particularly suited to the observation of distant galaxies, where spectral line widths are large. Furthermore, when a low power solid-state local oscillator (LO) source is used in conjunction with a Martin-Puplett interferometer (MPI) to combine signal and LO, it is desirable to operate at a relatively high IF to maximize the usable instantaneous bandwidth. Above 1 THz, the superconducting Hot-Electron Bolometer (HEB) mixer has become the element of choice in low-noise receiver design [1]. However, HEB mixers generally offer a limited IF bandwidth. For HEB mixers based on Niobium Nitride (NbN) thin film, the IF bandwidth is largely dictated by the acoustic match between the film and its underlying substrate, and the thickness, purity, and critical temperature (T_c) of the film. Given that these parameters are not sufficiently well controlled, it is important to measure the IF bandwidth of candidate mixer chips using a reliable procedure that is simple, yet produces accurate results.

It is a nontrivial task to accurately measure the IF bandwidth of mixers designed to operate in the THz frequency range. The conventional method requires both a frequency-stable LO source and an equally stable signal source that also produces a constant output level. Ideally, both sources would be phase-locked to a lower frequency microwave reference, and the LO source would be swept in frequency so as to provide a monochromatic output that can be measured using a spectrum analyzer. [2], [3]. This measurement method tends to be slow and the accuracy of each data point is typically only ± 0.5 dB.

Here, we propose an alternate method to measure the IF bandwidth, which utilizes a thermal noise source. This technique is similar to swept IF measurements usually employed in microwave noise figure meters [4]. A similar modulation technique has also been used in Y-factor measurements of HEB mixers [5], [6]. However, we have focused our attention to the measurement of the IF gain bandwidth of HEB mixers and have demonstrated that this technique is highly effective in the THz frequency range.

II. EXPERIMENTAL SETUP

A block diagram of our measurement setup is shown in Fig. 1. Referring to the figure, the waveguide mixer block is bolted directly to the cold plate of liquid helium filled cryostat and is connected to a room temperature amplifier through a small section of microstrip line and a length of stainless steel coaxial cable. DC bias is applied to the mixer via a broad-band bias tee inside the cryostat.

In our experiments, LO power at 0.81 THz is provided via a solid-state LO unit consisting of a 135 GHz Gunn oscillator, followed by two stages of diode frequency multiplication. The beam emerging from the LO assembly is collimated using a 90° off-axis parabolic mirror; and a wire grid beam-splitter, positioned in front of the 0.5 mm thick Teflon cryostat vacuum window, is used to combine signal and LO. In this setup it is not necessary to phase-lock the Gunn oscillator, as frequency drifts due to room temperature fluctuations are small. We use a heated filament, focused by a 90° off-axis parabolic mirror, as a signal source. The filament, a ceramic infrared element [7], consumes about 10 W of dc input power and generates unpolarized thermal radiation. In a separate series of experiments we have determined that the equivalent blackbody radiation temperature of the filament is 950 (± 60) K, which is equivalent to a noise source with an Excess Noise Ratio of about 5 dB. Since the emissivity of the ceramic filament is fairly constant over our small measurement bandwidth (< 20 GHz), the radiated power spectrum is flat.

A mechanical chopper whose blades are covered by AN-72 absorber to prevent unwanted reflections chops the radiated power from the filament. Absorber material is also placed behind the filament to limit the possibility of standing waves

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D. Meledin, C.-Y. E. Tong, and R. Blundell are with the Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138 USA (e-mail: dmeledin@cfa.harvard.edu).

G. Goltsman is with Moscow State Pedagogical University, Moscow, 119891, Russia.

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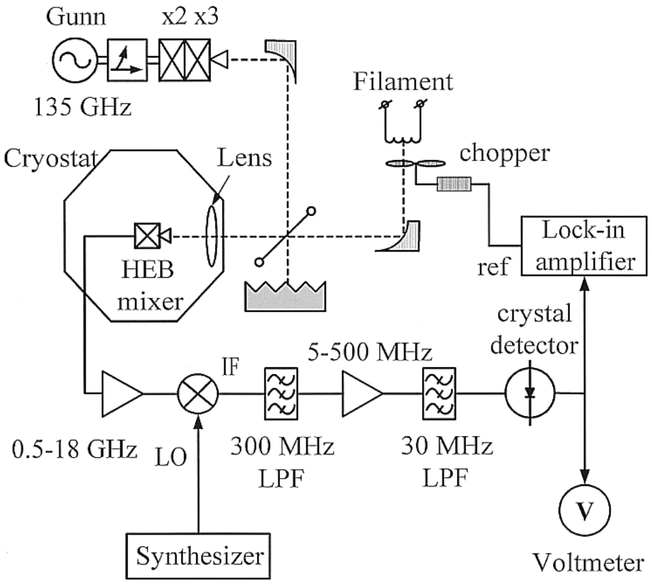

Fig. 1. Block-diagram of the setup used for IF bandwidth measurements at 0.81 THz. A computer controlled synthesizer down-convert the mixer output to base-band. A 300 MHz LPF is inserted to prevent leakage from the synthesized LO. After further amplification, the signal is passed through a 30 MHz low-pass filter before final detection by a crystal detector.

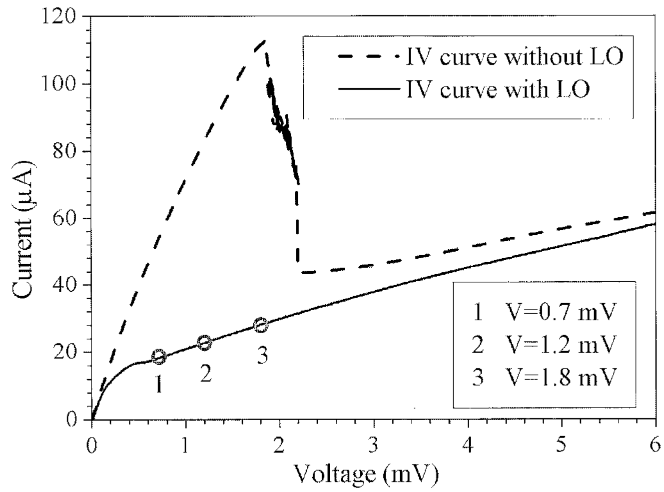

Fig. 2. The *I-V* curves of the HEB mixer at the operating points with and without applied LO power drive at 0.81 THz. Three bias points, used for IF measurements, are marked by open circles.

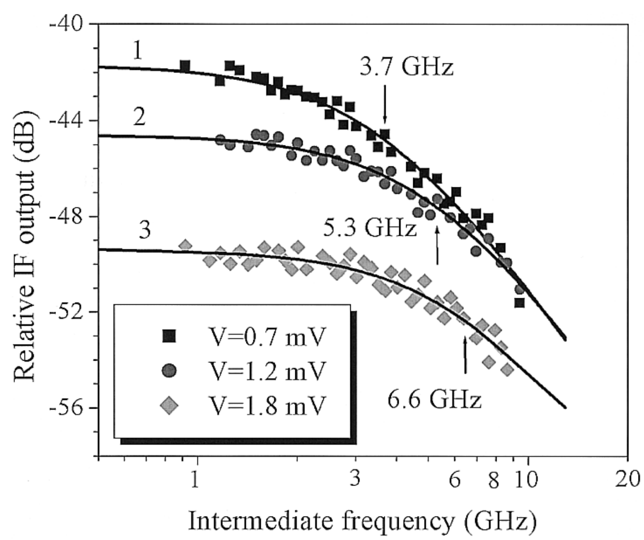

Fig. 3. IF bandwidth measurements at 0.81 THz LO frequency for three different bias voltages at constant LO power level. Optimal noise performance is obtained at 0.7 mV bias (point 1). Data points are fitted to the curve $1/[1+(f_{\mathrm{IF}}/f_{3\mathrm{dB}})^2]$. The best fit curves are displayed in solid lines. Arrows indicate $f_{3\mathrm{dB}}$ for the each curve.

influencing the result. In addition, by adjusting the optical coupling, we limit HEB mixer bias current changes arising from direct detection of the filament output to less than 0.5%.

Referring to Fig. 1, the mixer output is first amplified using a broad-band room temperature amplifier, and subsequently down-converted to base-band using a synthesized LO. After further amplification and filtering, the output passes through a 30 MHz low pass filter to a crystal detector. A voltmeter and a lock-in amplifier are then used to measure the dc and ac components of the detected output. The detected output, in a 60 MHz wide bandwidth centered about the synthesized LO, is measured as a function of IF by sweeping the frequency of the synthesizer. In a typical measurement, the synthesizer is swept from 700 MHz to 9.5 GHz, the time constant of the lock-in amplifier is set at 0.3 s, and the chopper runs at 79 Hz. With the lock-in amplifier and synthesizer under computer control, automated IF scans can be made. These can later be averaged to improve data quality. In addition, the effects of small LO drifts can be reduced by reversing the direction of the frequency sweep between successive scans.

Given that the mixer is connected directly to a room temperature IF chain with noise temperature of about 500 K, and recalling that our HEB mixer elements have a conversion loss of typically -17 dB, our system is not well suited to performing receiver noise measurements.

III. Measurement Results

Before the measurement, the gain of the entire room temperature IF chain is calibrated using a noise tube, while the loss introduced by the coaxial cable inside the cryostat is calibrated with a network analyzer. The accuracy of these calibrations is estimated to be about 0.2 dB. Care is also taken so that the crystal detector operates in a linear regime. With the lock-in amplifier time constant set to 0.3 s we achieve a dynamic range in excess of 20 dB for IFs below 1 GHz, and somewhat less at higher frequencies.

Using this method, we have measured the IF bandwidth of HEB mixers fabricated from 3–4 nm NbN film, deposited on a 200 nm thick MgO buffer layer over crystalline quartz [8]. The current-voltage characteristics of one of the mixers, with and without LO power applied at 0.81 THz, are shown in Fig. 2. Referring to the figure, IF bandwidth measurements were performed at three bias points, marked by open circles. Optimal low noise mixer performance, determined in a separate experiment [8], occurs at bias point 1 ($V = 0.7$ mV). Bias points 2 and 3 have the same LO power as at bias point 1, and have been chosen to demonstrate the variation of IF bandwidth with mixer bias. The measured relative IF output as a function of IF at these bias points is shown in Fig. 3. The experimental data are fitted to expression $1/(1+(f_{\rm IF}/f_{\rm 3dB})^2)$, where $f_{\rm 3dB}$ is the characteristic 3 dB roll-off frequency. It can be seen that the experimental data fitting is quite good. The measured IF bandwidths at bias points 1, 2, and 3 are 3.7 GHz, 5.3 GHz, and 6.6 GHz, with maximum errors of ± 0.4 GHz, 0.6 GHz and 0.8 GHz respectively. The IF scans, made using this setup, are highly repeatable. We typically make 4–6 continuous IF scans of about 50 frequency points each. It takes about 7 minutes to perform each scan, and a comparison of the data from one scan to another yields an RMS data dispersion of about 0.3 dB at bias point 1. The error increases toward higher bias due to deterioration in mixer conversion gain. The conversion efficiency at bias point 3 is lowest, and we obtain RMS data dispersion of 0.5 dB. These IF bandwidth data is very consistent with results we have reported using coherent IF bandwidth measurement method [3].

This technique is usable at even higher frequencies. We have performed IF bandwidth measurements on another NbN HEB device at an LO frequency of 1.26 THz, using an all-solid-state LO unit. In this case, the measured IF bandwidth at the bias voltage of 0.7 mV, and optimal LO power for low noise operation, was 2.5 GHz with maximum error of 0.4 GHz [9]. This demonstrates the potential usefulness of our technique in the THz frequency range where stable LO sources are in short supply.

IV. CONCLUSION

We have developed an experimental setup for measuring the IF bandwidth of HEB mixers. Our measurement system is robust and allows repeatable IF bandwidth measurements, to an accuracy of about 10% at 0.81 THz and 15% at 1.26 THz, to be made into the THz frequency regime.

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