Analysis of the Broad IF-Band Performance of MgB_2 HEB Mixers

Narendra Acharya, Evgenii Novoselov, and Sergey Cherednichenko

***Abstract*—We present an experimental study of gain and noise bandwidths in superconducting MgB_2 hot-electron bolometer (HEB) terahertz mixers in a 0.1–20 GHz intermediate frequency (IF) range. At an elevated temperature and with a 90-GHz local oscillator (LO), we measure a gain bandwidth of 13–14 GHz, which is the first accurate data for ultrathin MgB_2 films. The output noise spectrum has its maximum in the 100–200 K range, depending on the temperature (or the LO power) and the bias point, and its spectrum also confirms the gain bandwidth data obtained with the mixing experiment. Using both the gain and the output noise spectra, we obtain the mixer input noise temperature, which is nearly constant up to 20 GHz. Using the measured data and the HEB mixer theory, we argue that noise bandwidth in the current MgB_2 HEB mixers is $\sim$30 GHz.**

***Index Terms*—Gain bandwidth (GBW), hot-electron bolometer (HEB) mixer, hybrid physical chemical vapor deposition (HPCVD), intermediate frequency, magnesium diboride (MgB_2) thin films, MgB_2, noise bandwidth (NBW), terahertz (THz) mixer.**

I. Introduction

During the last two decades, superconducting hot-electron bolometer (HEB) mixers have proven to be a successful technology for extremely low-intensity molecular line observations at frequencies above 1 THz [1]–[3]. This is because, unlike superconductor–insulator–superconductor mixers, the highest operation frequency of HEBs is not limited by the superconducting gap, and, compared to Schottky diode mixers, their noise temperature is much lower. The most extensively studied and used HEB mixers are those based on phonon-cooling mechanism of nonequilibrium electrons created by the incident terahertz (THz) radiation [4], [5]. Among them, NbN HEB mixers are the most sensitive heterodyne detectors, with a minimum noise temperature of $\sim$500–1000 K [6]–[9]. Despite of being state of the art, the gain bandwidth (GBW) of NbN-based phonon-cooled HEB mixers is limited to 2–4 GHz due to about 12 ps of electron–phonon interaction time (τ_{eph}) and 30–40 ps of phonon escape time into the substrate [10], [11]. Although for many astronomical tasks such instantaneous bandwidth is sufficient, for observations of broad spectral lines toward the Galactic Center, extragalactic observations, and heterodyne lines surveys, a bandwidth in excess of at least 8 GHz is required in order to use a single (or reduced in numbers) local oscillator (LO) settings [12], [13].

There have been some efforts to enhance the GBW of NbN HEBs by initiating a faster phonon escape through an improved film–substrate interface system in various substrate materials [14], [15]. Despite some improvements in the noise temperature, the enhanced IF bandwidth in NbN HEBs has only been reported up to 5–6 GHz. Alternatively, bolometric mixing in chemically doped graphene was recently presented with a demonstrated GBW of 8 GHz, determined by electron diffusion [16]. However, high sensitivity in graphene HEB mixers, predicted theoretically, is still to be confirmed experimentally.

Due to the advancement in ultrathin superconducting MgB_2 film fabrication technology [17], [18], in recent years, MgB_2-based HEBs have become a center of interest due to their very fast inelastic electron–phonon interaction ($\tau_{\text{eph}} \sim$ 1–2 ps at 40 K) and efficient acoustic matching to both sapphire and SiC substrates [19]–[21]. A receiver noise temperature of 1000 K and a noise bandwidth (NBW) of 11 GHz have been reported for MgB_2 HEBs using the Y-factor technique at both 700 GHz and 1.63 THz LO frequencies, with an optimal LO power of about 10 μW [22]. With a critical temperature of 30 K, the mixer showed only a minor reduction of sensitivity for operation temperatures up to 20 K.

Earlier GBW measurements showed that for MgB_2 thin films the gain is almost constant up to 10 GHz (no roll-off), which is a huge improvement compared to any existing state-of-the-art HEBs. Such GBW does not match the 11-GHz NBW [22], because for HEBs an NBW/GBW ratio of $\sim$2 is to be expected [23], [24]. The obvious reason for this discrepancy is the imperfection of the utilized receiver layout, involving the mixer block, the IF amplifier and the interaction between those. In this article, we study the intrinsic performance of MgB_2 HEB mixers, namely the gain and noise temperature bandwidths, without the influence of the IF chain. In order to be able to do this, we placed the coplanar waveguide (CPW) integrated MgB_2 microbridges into a cryogenic millimeter wave probe station with an optical signal path and a readout bandwidth of 67 GHz. We measured the GBW and the output noise spectrum up to 20 GHz, and then calculated the spectrum of the input noise temperature. A similar approach was utilized earlier for the MgB_2 HEB mixer study versus the bias and temperature variations [25]. In order to benchmark the

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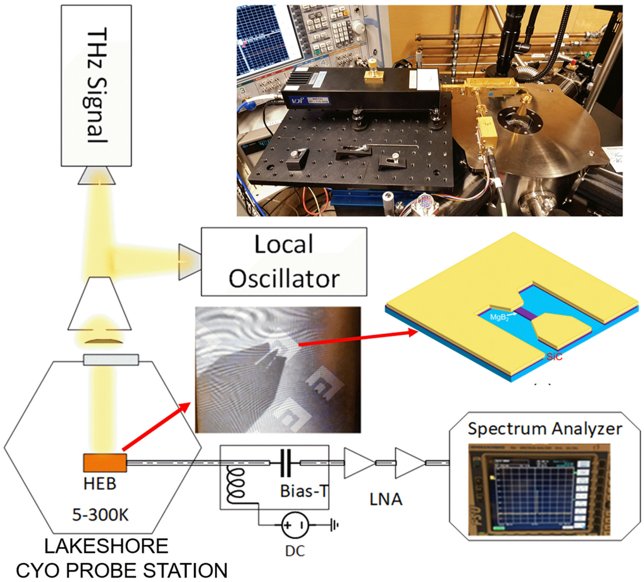


Fig. 1. Experimental setup for both the noise and the GBWs of NbN and MgB_2 HEB mixers. The microwave probe with GSG contacts and schematic of CPW contact pad along with HEB are shown in the middle. The photograph of the actual setup and the Lakeshore cryo-probe station is shown on the top.

obtained results, we fabricated and tested NbN HEB mixers in the same setup.

II. Device Fabrication and Measurement Setup

A. HEB Mixer Fabrication

Our device fabrication process starts with the deposition of ultrathin MgB_2 films (∼5–8 nm) on SiC substrates using a custom-built hybrid physical chemical vapor deposition (HPCVD) system. Details about our HPCVD system and ultrathin film growth conditions have been described in our previous reports [17], [26] and this process is based on that reported by Zeng *et al*. [27]. MgB_2 film growth occurred at a substrate temperature of 730 °C and at a chamber pressure of 20 Torr (maintained by the 400 sccm flow of hydrogen (H_2) carrier gas). Magnesium was supplied through the evaporation of Mg slugs placed around the substrate on a resistively heated substrate holder, while boron is provided through the decomposition of diborane gas (5% B_2H_6 in H_2), which is introduced into the vacuum chamber at 2 sccm only during growth. Subsequently, MgB_2 films were transferred to a dc-magnetron sputtering system where plasma cleaning of the film surface (from MgO_x) was carried out, followed by *in situ* sputtering of a 20-nm-thick Au film. Similarly, NbN films were deposited on 330-μm-thick, C-plane (0001), double-side polished, sapphire substrates by dc reactive magnetron sputtering. The films were deposited from the 2-in Nb (99.95%) target in an Ar and N_2 environment at 800 °C substrate temperature. For this study, approximately 5-nm-thick NbN films were utilized and the thickness was estimated based on the deposition rate.

Both MgB_2 and NbN HEB devices were fabricated by electron beam lithography. First, we defined the CPW contact pads and alignment marks on the films (see Fig. 1). Polymethyl methacrylate (70 nm) on top of copolymer (methyl methacrylate—470 nm) was utilized as a positive-tone two-layer resist system for electron beam lithography. The subsequent development in mixture of isopropanol and deionized (DI) water (10:1), electron beam physical vapor deposition of Ti—Au–Ti (10–200–40 nm), and lift-off in acetone, leaves the desired patterns on the substrate. The first 10-nm titanium layer promotes the adhesion of Au whereas the final 40-nm layer serves as a mask for gold contact pads later on during the Ar ion milling. The HEB bridges were defined via another electron beam lithography step, with a negative-tone resist (ma-N 2401-100 nm), and developed in tetramethylammonium hydroxide aqueous solution (ma-D 525) followed by rinse in DI water. In the final step, the remaining MgB_2 and NbN were removed by Ar ion milling.

B. Noise and Gain Characterization

In order to characterize the gain and the noise spectra, two wafers (one with MgB_2 and another with NbN HEB mixers) were mounted onto the sample holder inside the Lakeshore cryo-probe station (CRX-4 K) chamber (see Fig. 1), which we operated from 40 K (above the T_c of MgB_2) down to 5 K (the base temperature). The measurement setup diagram, the contact probe, the device layout, and the photograph of the Lakeshore probe station are shown in Fig. 1. We have presented data for a 0.5 μm wide × 2 μm long MgB_2 and a 2 μm wide × 0.3 μm long NbN HEBs. In order to be able to contact the samples with the high frequency ground–signal–ground (GSG) probe (100 μm pitch), the samples have to face upwards, without any Si lens or horn antenna, i.e., with an effective detector area of ∼20–30 μm (center contact length of the CPW line; Fig. 1). The sample-to-quartz window distance is ∼15 cm, which makes optical coupling quite poor, even for a large focusing lens/mirror above the window. Therefore, in order to make measurements possible, we chose to employ high-power WR-10 band sources.

A 90-GHz LO (Omnisys Instruments AB, 20–30 mW output power) and 90–110 GHz signal (Virginia Diodes, Inc., WR10 TxRx modul, ∼mW output power) sources were combined with a 10-dB waveguide directional coupler with a 90° waveguide bend and a smooth conical horn facing down toward the window. Two Teflon lenses with focal lengths of 75 and 100 mm (not shown in the photograph) refocused the beam onto the sample.

Both the dc bias and the IF readout were arranged via a CPW probe with the GSG contact geometry. Low thermal conductivity semirigid coaxial cables lead to a stable sample temperature and microwave readout up to 67 GHz without an appreciable loss. At room temperature, the IF chain consisted of a 40-GHz bias tee (SHF BT45B, SHF AG) and two broadband LNAs (SHF 810, SHF AG and AFS4-0012000 Miteq). The IF chain noise temperature (600–700 K) across the 0.1–20 GHz band (100 MHz step) was measured using a Y-factor technique with a microwave noise diode. Both the mixing signal and mixer output noise were recorded using a spectrum analyzer. For the noise measurements, the maximum resolution bandwidth of $B = 50$ MHz was utilized to increase measurements accuracy. The output noise of the HEB mixers was obtained from the following equations:

$$P_N = (T_{\text{out}} + T_{\text{LNA}})\, k_B B G_{\text{LNA}} \quad (1a)$$

$$P_{\text{ref}} = (T_{\text{ref}} + T_{\text{LNA}})\, k_B B G_{\text{LNA}}. \quad (1b)$$

Here, P_N is the measured noise (the HEB and the LNA) with the HEB at the desired operation point; G_{LNA} is the IF chain gain; P_{ref} is the measured noise when the HEB was biased at 100 mV, i.e., in the normal state [see Fig. 3(a) and (b)]; $T_{\text{ref}} =$ 35 K is the HEB temperature in the normal state (a linear $I(V)$). In a separate set of measurements, we observed that the equivalent noise temperature of the HEB bridge at a physical temperature of 35 K (zero bias) is the same as when the HEB is biased at 100 mV being at $<T_c$. It was essential to keep the device at the same physical temperature for both P_N and P_{ref} in order to avoid thermal expansion of the coax cable, which otherwise would lead to standing waves in the T_{out} spectrum.

As is known [4], the HEB mixer gain (at a particular bias point and LO power) follows the dependence:

$$G(f) = \frac{G(0)}{1 + (f/f_0)^2} \quad (2)$$

where $G(0)$ is the gain at zero IF, f is the intermediate frequency, and f_0 is the 3-dB gain roll-off frequency, determined approximately by the electron cooling time τ (this being slightly modified by the bias current effect) as $f_0 = 1/\tau$. Although the absolute mixer gain could not be measured in our experiments, its IF dependence was obtained by recording the power of the mixing signal from the LO and the signal source, $P_{\text{if}}(f) \propto G(f)$, when the signal frequency is tuned from 90 to 110 GHz. Fitting the measured $P_{\text{if}}(f)$ with (2) provides the GBW (f_0) of the mixer.

Samples with CPW contacts did not have antennas, and the coupling of both the LO and the signal to MgB_2 and NbN microbridges occurred via the CPW contacts (see Fig. 1). The coupling factor varied significantly across the frequency tuning range of the signal source. In order to calibrate for the signal coupling variation, amplitude modulation at 10 kHz was applied to the signal source, and the coupled power was measured as the HEB direct detection response using a lock-in amplifier. The measured $P_{\text{if}}(f)$ data were also corrected for the gain in the IF chain (G_{LNA}).

At 5 K, the photon energy of the 90 GHz LO is much lower than the superconducting energy gaps in both MgB_2 and NbN. Therefore, the samples temperature was set close to T_c in order to reduce the energy gap, hence bringing the devices to the conditions in which the $I(V)$ has to correspond to that where the lowest mixer noise temperatures are typically measured with THz LOs. This approach was frequently utilized for HEB mixer studies, and its validity has been confirmed for NbN HEB mixers [14]. For MgB_2 HEBs, the $I(V)$ curves under the optimal power 700 GHz, 1.6 THz, and 2.6 THz LOs have been confirmed to correspond well to the $I(V)$ without an LO, but at a temperature close to T_c [22]. The same being valid also for the output noise [25].

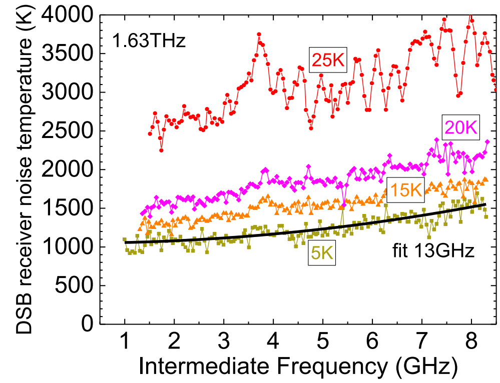


Fig. 2. DSB receiver noise temperature of MgB_2 HEB measured at a 1.63-THz LO, at various temperatures from 5 to 25 K. The solid curve at 5 K represents the fit for $f_N = 13$ GHz NBW.

Additionally, a batch of MgB_2 devices was fabricated with THz spiral antennas using MgB_2 films similar to those for the devices described above. Packaged into a mixer block with a Si lens, the noise temperature was measured with a Y-factor technique at a 1.63-THz LO at 5-, 15-, 20-, and 25-K operation temperatures (see Fig. 2) as a reference (see [22]). The measured minimum noise temperature is about 1000 K, i.e., close to that published previously. The fit to the noise temperature spectrum (9) reveals a NBW of 13 GHz, which is larger than the previously published 11 GHz. We explain this difference by a higher critical temperature and a slightly smaller film thickness for the current batch (32–33 K), which leads to a shorter electron cooling time [21]. An important note is that the NBW is the same from 5 K up to at least 25 K. This fact could be used to justify our further experiments at the 28–30 K range using the 90-GHz LO.

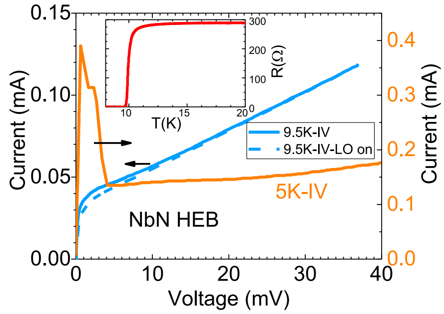
III. Results and Discussion

A. *I(V) Characteristics*

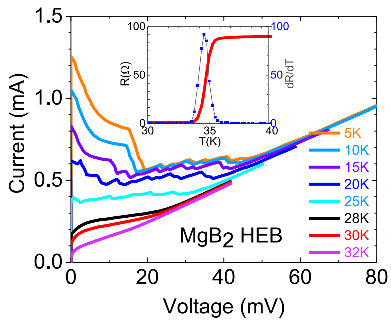
$I(V)$ characteristics of the NbN HEB at both 5 and 9.5 K, and that for the MgB_2 HEB at various temperatures from 5 to 32 K, are shown in Fig. 3(a) and (b), respectively. At 5 K, the critical current (I_c) of this MgB_2 HEB sample is 1.25 mA, corresponding to a rather high critical current density of 3×10^7 A/cm^2. Similarly, the normal state resistance of the tested device was 90 Ω (>40 mV), which is consistent with the resistance obtained from the resistance versus temperature $R(T)$ measurement (>35 K). The critical temperatures T_c of both NbN and MgB_2 HEBs were deduced from the $R(T)$ measurement and come in at 10 K (a typical T_c for thin NbN films) and 33–34 K, respectively [see Fig. 3(a) and (b), insets]. In both samples, narrow transition widths were observed, indicating that the high quality of films was preserved through the HEB fabrication.

B. *GBW of NbN HEB Mixers*

In order to benchmark MgB_2 HEB mixers against the well-established technology of NbN HEB mixers, the GBW of NbN HEBs, integrated with the same CPW contacts as for MgB_2 HEBs, was measured in the same setup. The critical current of the tested NbN sample ($w = 2\,\mu$m $\times L = 0.3\,\mu$m) was $I_c(5\,\text{K}) =$

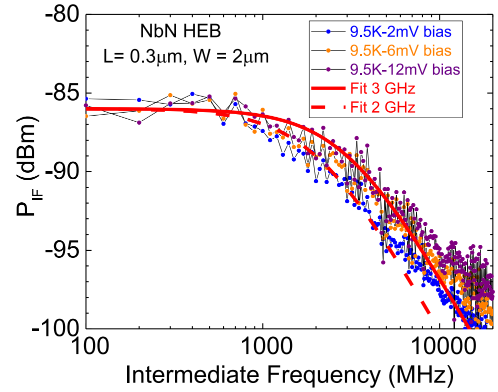


(a)

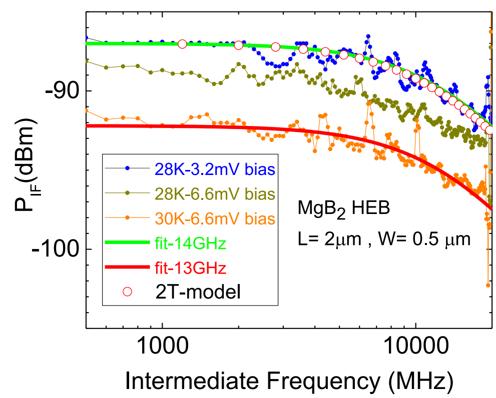


(b)

Fig. 3. (a) Current–voltage, $I(V)$, characteristics of the NbN HEB (2 μm $\times$ 0.3 μm), at 5 and 9.5 K. The blue dash line shows the $I(V)$ at 9.5 K with LO switched ON. The inset red curve represents the $R(T)$ of NbN HEB; (b) $I(V)$ characteristics of the MgB_2 HEB (0.5 μm $\times$ 2 μm) measured at various temperatures from 5 to 32 K. Inset shows the $R(T)$ and the dR/dT of the same HEB device.



(a)



(b)

Fig. 4. Mixing signal power versus IF at various bias points. (a) NbN HEB with a 3-dB IF power roll-off (GBW) at 2–3 GHz and (b) MgB_2 HEB with a GBW of 14 GHz at 28 K and 13 GHz at 30 K: symbols+lines (measured), solid lines (single-pole Lorentzian fits), open circles (two-temperature modeling).

0.39 mA [see Fig. 3(a)]. At 9.5 K, the $I(V)$ curve is very similar to that pumped to the optimal performance, with a high frequency LO ($f > 2\Delta$) from 4 K [28]. The best fit for the measured (from 100 MHz to 20 GHz) IF response ($P_{\text{if}}(f)$) to (2) shows a 3-dB roll-off at 2–3 GHz [see Fig. 4(a)], i.e., similar to that previously reported [10], [24].

C. GBW and the Output Noise Spectrum of MgB_2 HEB Mixers

Based on previous experience [22], [25], as well as on the sample presented in Fig. 2, the best fits to $I(V)$ curves optimally pumped with $f_{\text{LO}} > 2\Delta$ $I(V)$ are those taken in the range 28–30 K. Consequently, GBW was measured at these temperatures, with a small LO power at 90 GHz. The measured GBW is ∼13–14 GHz [see Fig. 4(b)], which is the same as for both 28 and 30 K, and is independent on the bias point along the $I(V)$.

Measured output noise [see Fig. 5(a)] at low IF is in the range 100–200 K, as has been previously reported for both 0.7- and 1.63-THz LOs [22]. The noise rolls off as the IF increases, reaching a frequency-independent value at IF > 10 GHz. Despite the IF chain noise temperature being much higher than the mixer output noise T_{out}, we managed to conduct quite reproducible measurements of $T_{\text{out}}(f)$. This fact is confirmed by two curves presented for the 28 K–$I(V)$ [see Fig. 5(a)].

D. Discussion

The output noise in HEBs (as well as in any other thermal detector) is composed of two constituents: the thermal (Johnson) noise T_J, and the temperature fluctuation noise T_{FL}: $T_{\text{out}} = T_J + T_{\text{FL}}$. [29]

The thermal fluctuation noise is a strong function of the electron temperature T_e (in superconducting HEBs at the optimal LO and dc drive $T_e \approx T_c$) and dR/dT. Following the lumped element HEB model [30], [31]:

$$T_{\text{FL}}\left(T_e\right) = \frac{4 I_0^2 \frac{dR}{dT} T_e^2 R_L C_0 \left(1 - C_0 I_0^2\right)^2}{\left(R_0 - R_L\right)^2 \left(1 + C_0 I_0^2 \frac{R_0 - R_L}{R_0 + R_L}\right)^2} \tag{3}$$

$$C_0 \equiv \frac{dR}{dP} = \frac{1}{I_0^2} \times \left[\frac{\frac{dV}{dI} - R_0}{\frac{dV}{dI} + R_0}\right] \tag{4}$$

where the differential resistance dV/dI, the dc resistance $R_0 = V_0/I_0$, and the bias voltage and current V_0 *and* I_0 can be obtained from the $I(V)$ characteristics, and R_L is the input impedance of the mixer load (the IF amplifier). Equations (3) and (4) are from the lumped HEB model, which is rather simplified and does consider the microscopic physics in superconducting microbridges. However, being combined with empirically obtained C_0, they have shown to describe well experimental results for low-T_c HEB mixers (Nb and NbN).

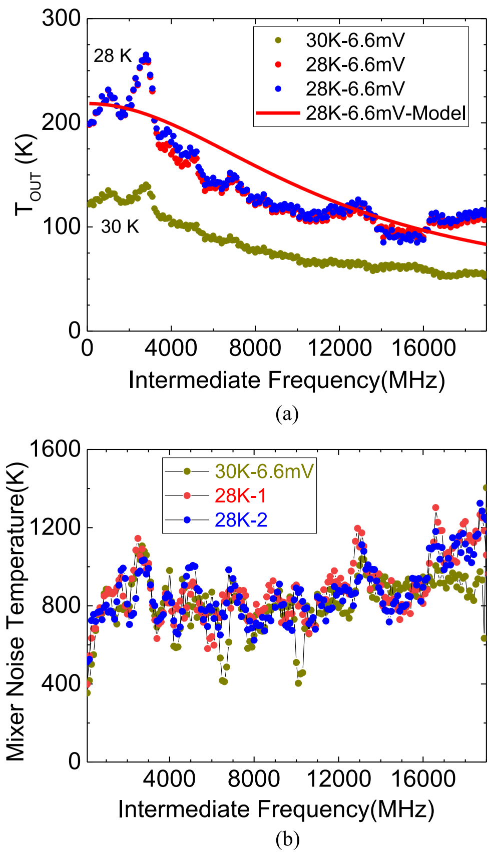


Fig. 5. (a) Output noise of the MgB_2 mixer [T_{out}, see (2)] versus IF, measured at the same bias points as P_{if},(*f*) in Fig. 4(b). The solid line represents the output noise $T_{\mathrm{out}} = T_J + T_{\mathrm{FL}}$, calculated using $T_J = T_c$ and T_{FL} according to (2). (b) Normalized mixer noise temperature T_m of the MgB_2 HEB at 30 and 28 K, obtained as $T_{\mathrm{mix}}(f)$=[T_{out} (*f*)/P_{if},(*f*) +normalization factor]. In this case, P_{if},(*f*) was converted to the linear scale.

The fluctuation noise spectral dependence is similar to the mixer gain spectrum, i.e.,

$$T_{\mathrm{FL}}(f) = \frac{T_{\mathrm{FL}}(0)}{1 + (f/f_0)^2}. \qquad (5)$$

The Johnson noise is, to the contrary, frequency independent

$$T_J = T_c. \qquad (6)$$

Following [4], the ratio of output noise and gain provides the spectrum of the mixer (input) noise temperature

$$T_m(f) = \frac{T_{\mathrm{out}}(f)}{G(f)}\, T_m(f) = \frac{1}{G(f)} \times \left[\frac{T_{\mathrm{FL}}(0)}{1 + \left(\frac{f}{f_0}\right)^2} + T_J\right]$$

$$= \frac{T_{\mathrm{out}}(0)}{G(0)} \times \left[1 + \frac{T_J}{T_{\mathrm{out}}(f)}(f/f_0)^2\right] \qquad (7)$$

$$T_m(f) = \frac{T_{\mathrm{out}}(0)}{G(0)} \times \left[1 + (f/f_N)^2\right] \qquad (8)$$

where

$$f_N = f_0 \sqrt{\frac{T_{\mathrm{out}}(0)}{T_J}} \qquad (9)$$

is called the NBW (the IF at which the mixer input noise temperature increases by a factor of 2 from its value at zero IF). It is clear that the higher the $T_{\mathrm{out}}(0)/T_J$ ratio, the larger the f_N versus f_0 becomes. Noise temperature is the main figure of merit of the mixer, and the fact that $f_N > f_0$ is indeed a nice feature in superconducting HEBs where $\frac{T_{\mathrm{out}}(0)}{T_J} > 2$ is fairly common.

In practice, HEB mixers operate with (cryogenic) IF amplifiers (LNA), where the system noise temperature (the receiver noise temperature) can be expressed as

$$T_{\mathrm{rec}}(f) = \frac{T_{\mathrm{out}}(0) + T_{\mathrm{LNA}}}{G(0)} \times \left[1 + (f/f_N^*)^2\right] \qquad (10)$$

where

$$f_N^* = f_0 \sqrt{\frac{T_{\mathrm{out}}(0) + T_{\mathrm{LNA}}}{T_J + T_{\mathrm{LNA}}}} \qquad (11)$$

is the system (or the receiver) NBW. In a THz astronomical receiver, it is f_N^* which matters, hence the lower the T_{LNA} versus (T_J, T_{out}), the better.

Using device parameters (see Fig. 3), the measured GBW of 13 GHz and (3)–(6), we calculated the output noise spectrum for the MgB_2 HEB (Fig. 5(a)—solid line). No fitting parameters were utilized in these calculations however, and as can be seen, the calculated curve matches the measured data rather well. Measured T_{out}(*f*) data can be considered as an independent verification for the mixer GBW.

Nearly linear scaling of the GBW with the film thickness, observed for both MBE-grown MgB_2 films on sapphire [21] and HPCVD-grown films on SiC [26], suggests that the process of electron energy relaxation occurs mainly due to inelastic electron–phonon collisions and consequent phonon energy transfer to the substrate [4], [32]

$$G(f) = 20\lg\left[\left|\frac{C_0}{\xi(f,d,Tc) + C_0\frac{R_0 - R_L}{R_0 + R_L}}\right|\right] \qquad (12)$$

where

$$\xi(f,d,Tc) = \frac{(1 + j2\pi f\tau_1)(1 + j2\pi f\tau_2)}{(1 + j2\pi f\tau_3)}$$

$$\tau_{1,2}^{-1} = \frac{\tau_3^{-1} + \tau_{\mathrm{eph}}^{-1}}{2}\left[1 \pm \sqrt{1 - 4\frac{\left(\tau_3^{-1} - \tau_{\mathrm{eph}}^{-1}\right)^{-2}}{\tau_{\mathrm{eph}}\tau_{\mathrm{esc}}}}\right]$$

$$\tau_3^{-1} = \tau_{\mathrm{esc}}^{-1} + \tau_{\mathrm{eph}}^{-1}\frac{c_e}{c_{\mathrm{ph}}}.$$

Here, τ_{eph} and τ_{esc} are electron–phonon interaction time and phonon escape (from the film into the substrate) time. Electron and phonon specific heats c_e and c_{ph} in MgB_2 as well as electron–phonon interaction time and phonon escape $(\tau_{\mathrm{eph}}, \tau_{\mathrm{esc}})$ time have been discussed in previous publications [21], [33]. Both mass density and sound velocity in SiC are close to those in sapphire. Therefore, we assume that the phonon escape time from MgB_2 into SiC is the same as into sapphire. With the other relevant parameters in hand (see Table I), we simulate the IF spectrum of the conversion gain for the studied

TABLE I
MgB_2 THICKNESS (d), CRITICAL TEMPERATURE (Tc), ELECTRON–PHONON INTERACTION TIME, PHONON ESCAPE TIME, DEBYE TEMPERATURE AND SOMMERFELD CONSTANT

d(nm)	Tc(K)	$\tau_{e\text{-}ph}$(ps)	τ_{esc}(ps)	T_D(K)	$\gamma\left(\frac{mJ}{mol\cdot K^2}\right)$
5	34	4.2	5.5	750	3.8
		[21]	[21]	[33]	[33]

MgB_2 HEB mixer [see Fig. 4(b), open circles]. The resulting 3-dB roll-off frequency is 13.5 GHz, i.e., very close to the experimental value. For the modeling, the electron temperature T_e is assumed to be equal to T_c [14], [21]. The phonon temperature $(T_{\text{ph}} = 0.8 \times T_e)$ was calculated using the system of two heat balance equations: electron–phonon and phonon–substrate [32].

Finally, using the measured gain and the output noise spectra, we can calculate [using (7)] the spectrum of the mixer input noise temperature [see Fig. 5(b)]. The absolute value of the mixer gain is not known; therefore, it is the IF dependence of T_m that we consider. However, we normalized T_m in Fig. 5(b) in order to fit the low IF T_m data obtained with the Y-factor approach (see Fig. 2). The obtained T_m(20 GHz) is only 20–25% higher than T_m (1 GHz), which suggests that the NBW is >20 GHz. On the other hand, using (9), $f_0 = 14$ GHz [see Fig. 4(b)], $T_{\text{out}}(0)\sim 150$ K [see Fig. 5(a)], and $T_J \sim 33$ K $(T_J \sim T_c)$, we obtain $f_N \sim 30$ GHz, which should be achievable with a well-designed IF readout.

MgB_2 HEB mixers have much larger T_{out} (100–200 K) compared to NbN HEBs (20–40 K) [34], and the fact that LNA performance is far less critical to MgB_2 HEBs compared to NbN HEBs has been previously emphasized. Indeed, with a noise temperature of 3–6 K for cryogenic broadband microwave amplifiers being quite common, the effect of the IF LNA noise on the MgB_2 HEB receiver sensitivity is not expected to be significant.

However, so far, we have been neglecting the impedance matching and interference between mixer and LNA, the importance of which has been pointed out in previous publications [35], [36]. Therefore, understanding each and every single component in the THz receiver (the mixer, the LNA, and the interaction between these) is crucial to obtaining top receiver performance, as is required for astronomy.

IV. CONCLUSION

In summary, we have characterized MgB_2 HEB mixer gain and noise spectra in a broad IF band (from 100 MHz to 20 GHz) utilizing a high-quality readout setup at the Lakeshore cryo probe station CRX-4K. We have demonstrated that HEB mixers made from thin (5 nm) MgB_2 films have a GBW of 13–14 GHz, which was also confirmed by the output noise spectrum. This experimental result is in agreement with modeling, which presumes electron cooling via electron–phonon interaction. Mixer noise temperature (excluding the LNA) is nearly constant up to 20 GHz, with NBW of $f_N \sim 30$ GHz, calculated based on GBW and output noise. On the other hand, a Si-lens-integrated MgB_2 HEB mixer shows a minimum noise temperature of 1000 K and an NBW of 13 GHz when a standard IF LNA (2–8 GHz) is used. This confirms that in order to make use of the full potential of MgB_2 HEB mixers, all parts of the receiver (mainly, the mixer and the LNA) have to be carefully designed.

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