Gain and Noise in THz MgB2 Hot-Electron Bolometer Mixers With a 30-K Critical Temperature

Gain and Noise in THz MgB_2 Hot-Electron Bolometer Mixers with a 30K Critical Temperature

Evgenii Novoselov and Sergey Cherednichenko

***Abstract*—In this paper, we study variation of the MgB_2 hot-electron bolometer mixer characteristics such as noise temperature, gain, output noise, and local oscillator (LO) power at 5K, 15K, and 20K bath temperatures, and at 0.69THz and 1.63THz Local Oscillator frequencies. The main reason for the noise temperature rising at higher temperatures is a reduction of the mixer gain, which occurs proportionally to the LO power reduction. Contrary to this, the output noise remains constant (for the same bias point).**

***Index Terms*—Hot-electron bolometer, HPCVD, magnesium diboride, mixer, superconductivity, thin film.**

I. INTRODUCTION

Superconducting hot-electron bolometer (HEB) mixers made from thin MgB_2 films have demonstrated a noise temperature of ~1000K and a noise bandwidth of 11GHz at local oscillator (LO) frequencies of 0.69THz and 1.63THz [1]. When comparing previously published results [2]-[7], this progress was made owing to advances in thin MgB_2 films deposition by Hybrid Physical Chemical Vapor Deposition (HPCVD), where films thinner than 10nm with a critical temperature (T_c) above 30K have been obtained [8]-[11]. When the mixer operation temperature was raised from 5K to 15K only a small increase of the receiver noise temperature, T_r has been observed (20%). However, when the mixer temperature was increased to 20K, the noise temperature rose by another 50%. The origin of this effect is of great importance to future HEB performance improvement. In the current paper, we study how the major HEB mixer characteristics, such as the noise temperature, the gain, the output noise, and the LO power, vary through an operation temperature range of 5K-20K. The mixer parameters most critical to mixer low noise operation up to 20K (or above) are discussed.

II. DEVICES AND SETUP

In this study, mixers from the same batch as reported in Ref. [1] were used. In brief, MgB_2 films were deposited on SiC substrates using HPCVD [11]. HEB mixers were essentially 1µm×1µm micro bridges integrated with a 270nm thick gold planar spiral antenna [3]. The MgB_2 film thickness was measured on one of the devices from this batch using Transmission Electron Microscopy (TEM). The measured film thickness of 8nm was slightly higher than the value (6nm) estimated from the deposition rate (obtained for thicker films). The critical temperature in the devices after patterning and dicing was 30K (see Fig. 1).

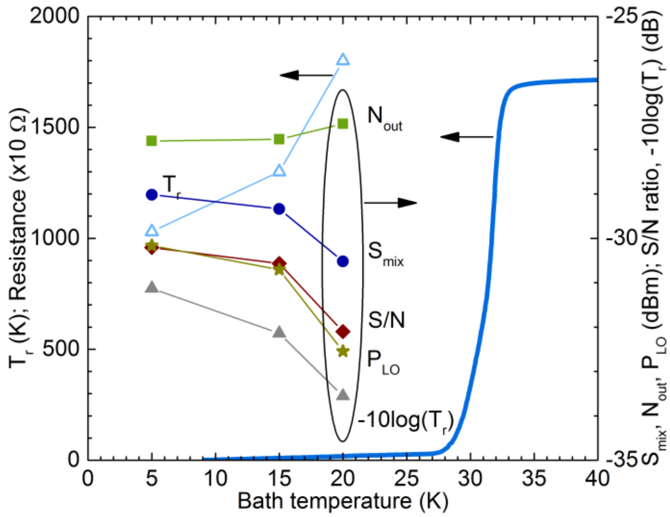

Fig. 1. The mixer output noise N_{out}dB (squares, 50MHz bandwidth), the mixing signal S_{mix}dB (circles), *signal-to-noise* ratio *S/N* dB (diamonds) (shifted by +73dB, +57dB, and -45dB, respectively), T_r (open triangles), -10log(T_r) (triangles), and LO power (P_{LO}) (shifted by +10B), versus temperature. Normalization factors were applied for fitting all curves on the single figure. Resistance (×10) versus temperature (solid line). Mixer characteristics were measured at 7mV and 0.23mA bias for all temperatures. LO frequency is 0.69THz

HEBs were tested in a quasi-optical mixer block with an uncoated 5mm elliptical Si lens. A 30mm diameter off-axis aluminum parabolic mirror collimated the THz beam prior to exit from the cryostat. A bias-T and a low noise IF amplifier (LNA) were mounted in the cryostat. The mixer temperature was varied by means of a resistive heater mounted onto the mixer block. A far infrared (FIR) gas laser was used as the LO. Previously, we have reported [1] that LO pumped current voltage (IV) curves of the discussed devices were the same for LO frequencies of 0.69THz, 1.63THz, and 2.56THz. As the LO frequency increases from 0.69THz to 1.63THz, rather

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E. Novoselov and S. Cherednichenko are with the Department of Microtechnology and Nanoscience (MC2), Chalmers University of Technology, SE-41296 Göteborg, Sweden (e-mail: evgenii@chalmers.se; serguei@chalmers.se).

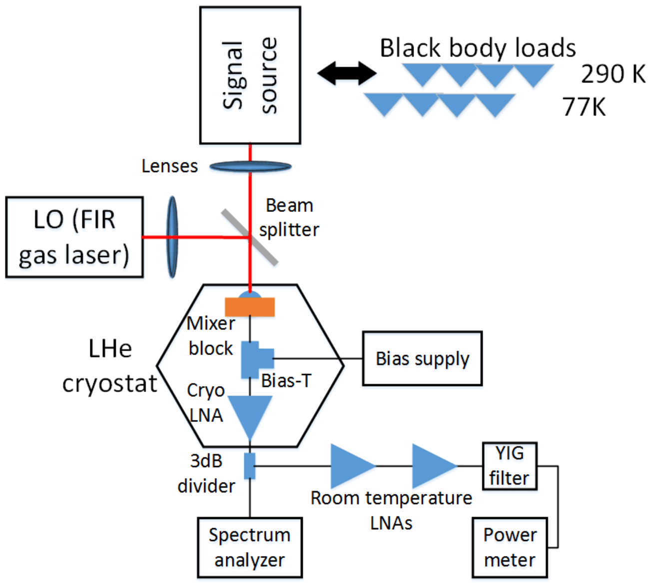

Fig. 2. Measurement setup.

small growth of the receiver noise temperature (from 830K to 930K) was observed. Therefore, experiments reported here were performed at 0.69THz LO, due to a higher output power being available as compared to e.g. 1.63THz, as well as due to the availability of another 0.69THz tunable source used for the mixing experiments. The receiver noise temperature was measured with the Y-factor technique, using a 295K and a 77K black body emitter (loads). The variation of the mixer (relative) gain was measured with a monochromatic THz signal source, based on frequency multipliers (see Fig.2) [12]. The absolute power of the signal source (including mixer-to-source beam mismatch losses) was of no importance at that stage. However, the output power of the signal source was kept constant during all experiments. Based on the measured mixer gain (see Section III.b) we estimate an incident power of 10pW. The IF signal was split into two branches outside the cryostat: 1) with an extra LNA and a tunable band-pass YIG

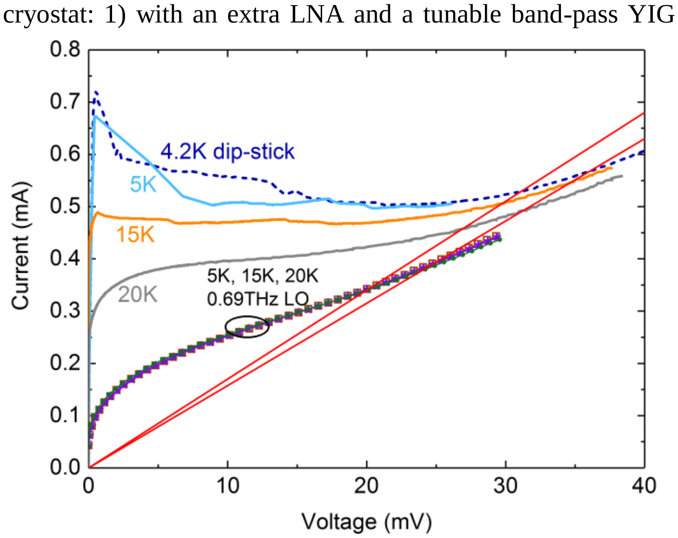

Fig. 3 The mixer IV-curves: at 4.2K (in the dip-stick, dashed); in the cryostat (≈5K, no LO, blue), at 15K (no LO, orange), at 20K (no LO, grey). Three (fully overlapping) IVs at optimal LO power at 5K, 15K; and 20K (open squares, stars, and circles). Straight lines are used for LO power calculations by the isothermal method.

filter (for the Y-factor and the output noise measurements); and 2) directly fed into a spectrum analyzer. The YIG-filter was set at a 2GHz (B_{if}=50MHz bandwidth). Both the output noise power and the mixing signal power were corrected for the gains of the corresponding amplifier chains, hence being referenced both to the output of the HEB mixer.

The test source frequency was 695.5GHz, i.e. 2.5GHz off-set from the LO, in order to exclude any effect from the test source on the reading from the black body source. For consistency, we accounted for losses in the optical path (the humid air absorption, the cryostat window, and the IR filter) in the receiver noise temperature measurements. Details on optical loss correction are given in Ref. [1]. Neither the Si lens reflection loss nor the beam splitter reflection loss are accounted for. The results for the two tested devices (#10-7 and #10-8) from the discussed batch were very similar. Therefore, we concentrated on results from device #10-7 without loss of generality.

The HEB critical current was 0.67mA at 5K, corresponding to a critical current density of 8.4×10^6A/cm^2. At both 5K and 15K, the IV had a distinct critical current (switch-type IV), whereas at 20K a smooth flux-flow type of IV has been observed (see Fig. 3). The aforementioned critical current density is of the same order of magnitude as reported before for films of the same thicknesses (≤10nm) but obtained using a thinning-down technique [9], [10]. Room temperature and residual resistances of the discussed device are 196Ohm and 170Ohm, respectively.

III. Results

A. *Bias optimization*

Receiver noise temperature was measured using the Y-factor technique at various LO power levels and in a bias voltage range up to 25mV. The corresponding set of IVs (each relates to a certain LO power) is given in Figs. 4a-6a for mixer temperatures 5K, 15K, and 20K. The receiver noise temperature measured along IV-5 (at 5K and 15K) is given in Fig. 4a and Fig.5a (filled dark cyan squares, right Y-axis). In Fig,4a, for a bias voltage of 7mV, T_r as a function of mixer current (hence, LO power) is shown in purple balls (top X-axis). The lowest noise temperature is obtained for voltages corresponding to the maximum output noise, i.e. 5-10mV. The IV-range for the lowest T_r is marked with the red-oval. At 5K, a constant T_r is obtained at a variety of LO powers corresponding to IV-3–IV-5. As the mixer temperature increases, the optimal LO power range decreases. At 20K the lowest T_r can be achieved at around IV-5 only. The lowest receiver noise temperatures obtained at 5K, 15K, and 20K are plotted in Fig. 1 (open triangles). They correspond to IV-5 (7mV, 200μA).

With the second THz source, detuned by 2.5GHz from the LO, the mixing signal P_{if} was recorded for the same IVs along with the receiver output noise power P_{out}:

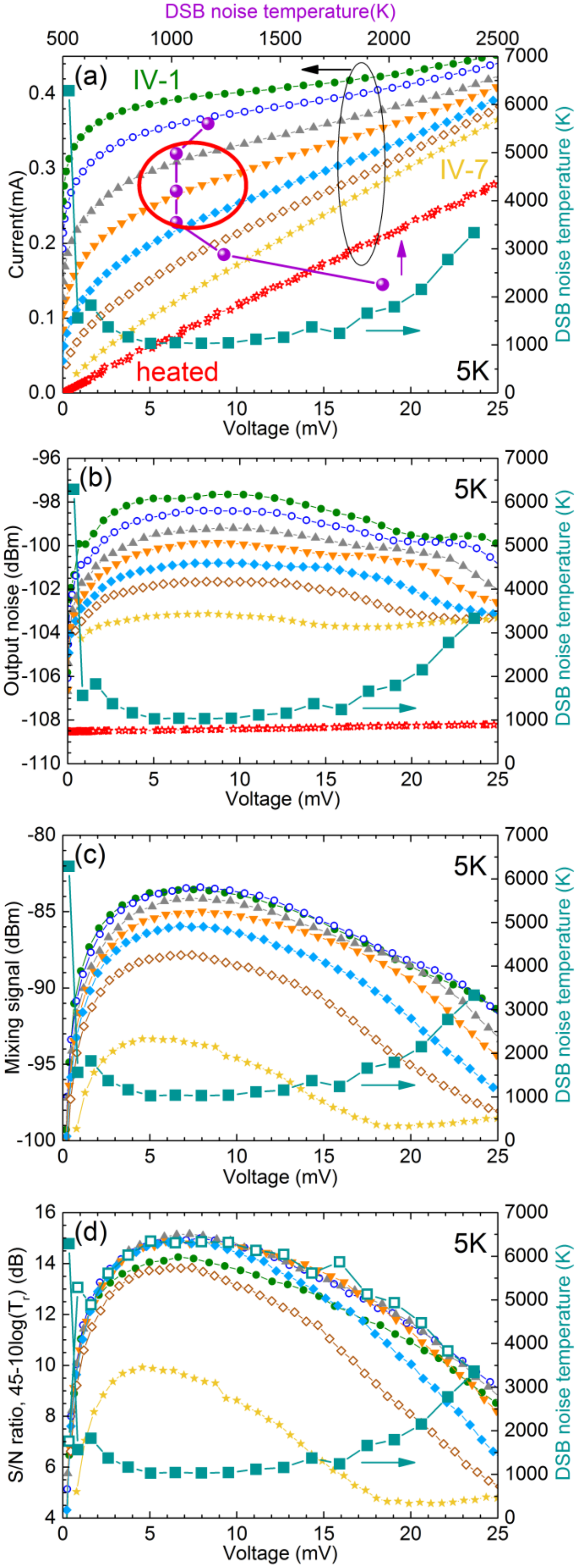

Fig. 4. LO at 0.69THz. T=5K. The area of the highest S/N ratio is marked on the I-V plane. The open squares in (d) are for 45-10log(T_r).

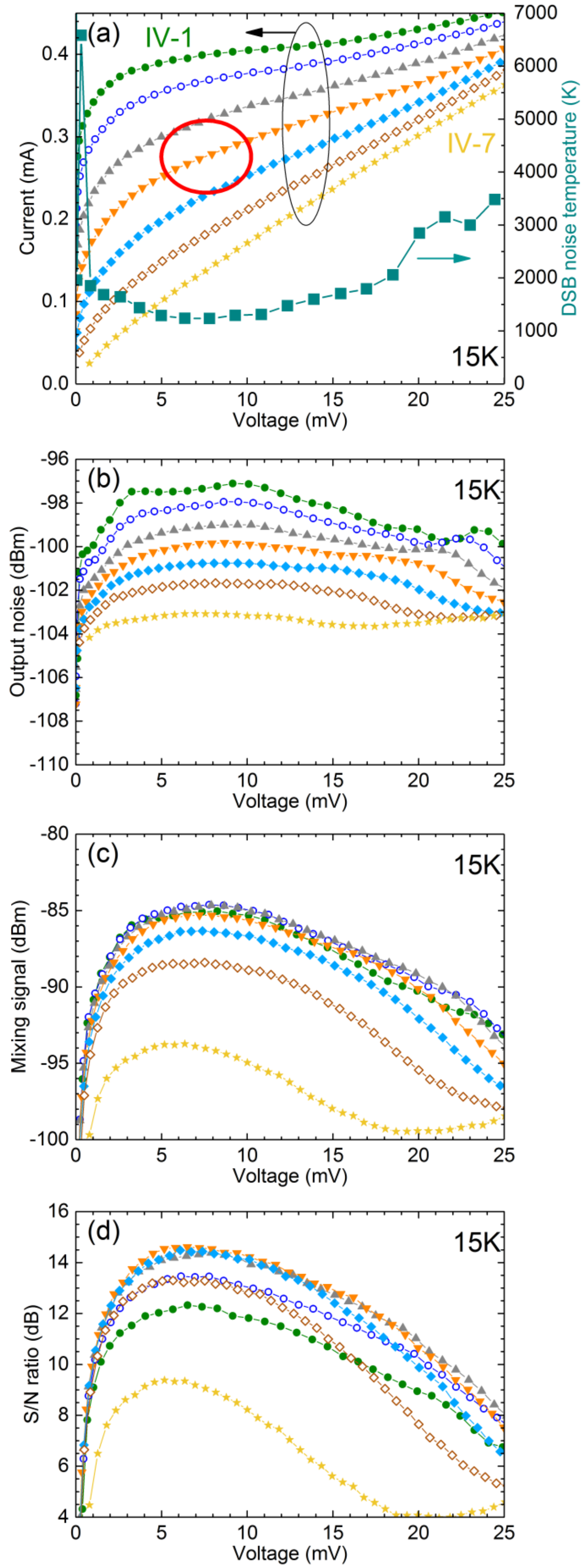

Fig. 5. LO at 0.69THz. T=15K. The area of the highest S/N ratio is marked on the I-V plane.

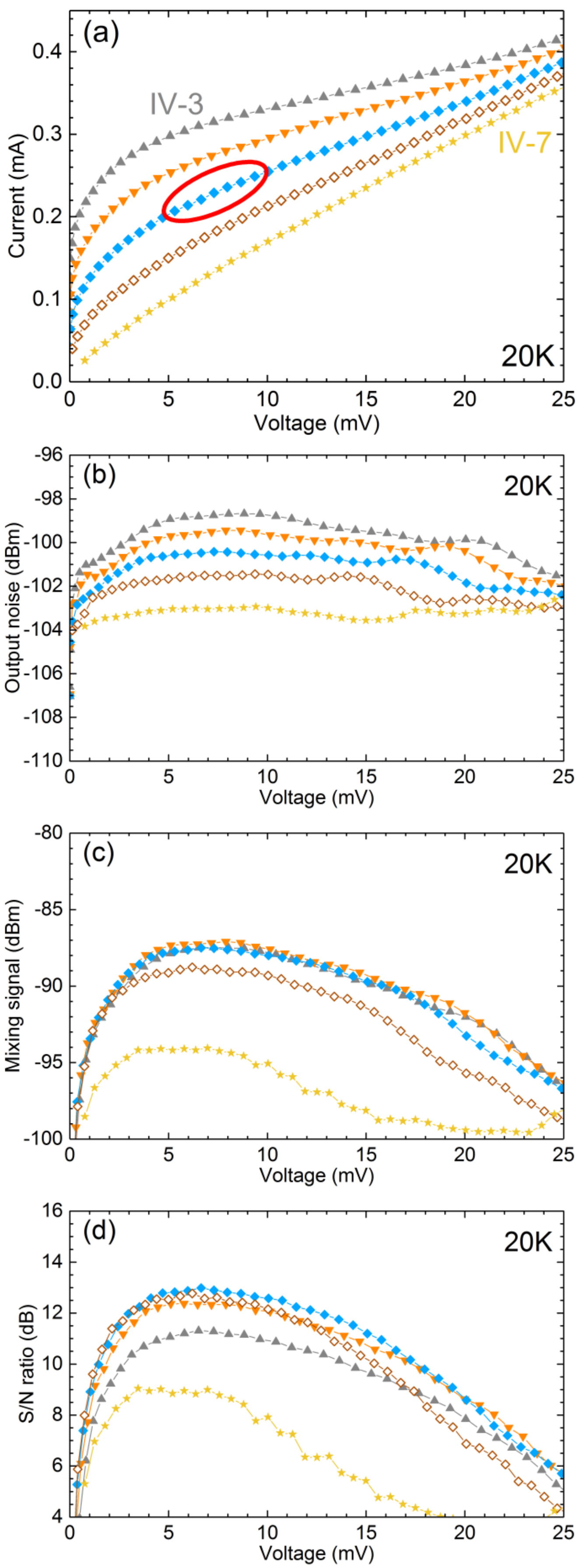

Fig. 6. LO at 0.69THz. T=20K. The area of the highest S/N ratio is marked on the I-V plane.

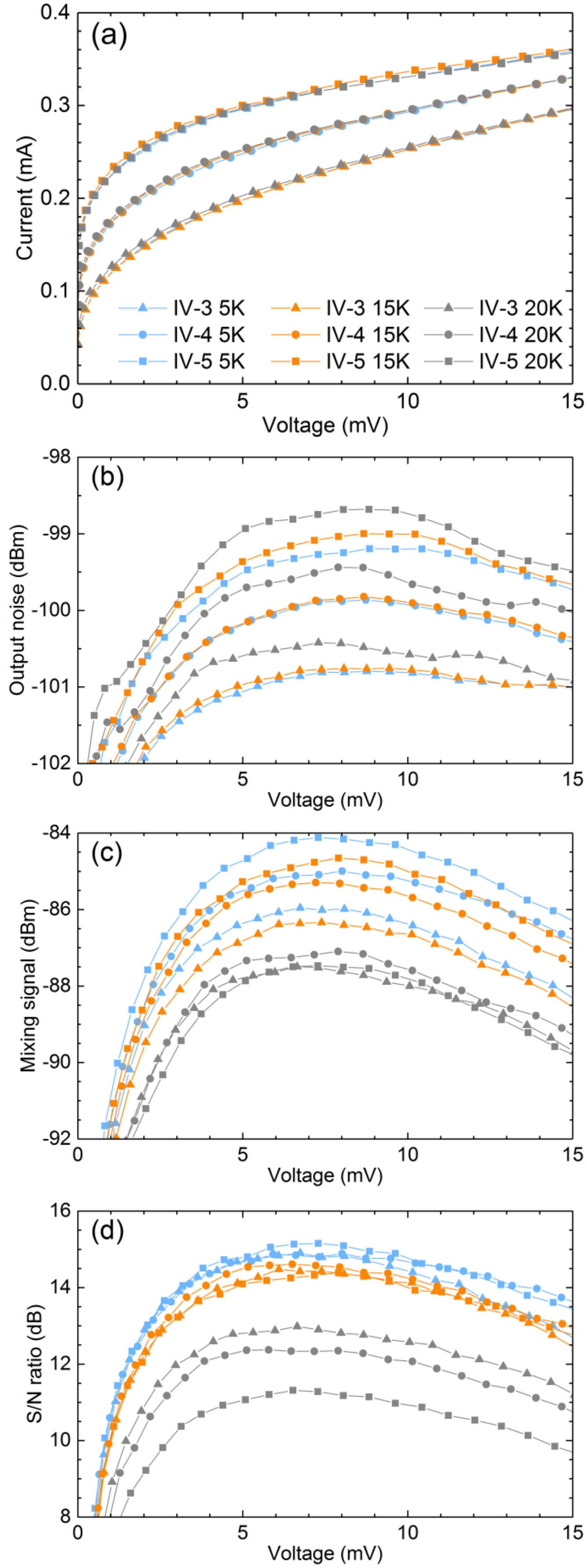

Fig. 7. LO at 0.69THz. T=5K, 15K, and 20K. Close comparison of the I-V, P-V, G-V, and S/N-V at the bias voltages and LO power levels corresponding to the highest S/N ratio.

$$P_{if} = P_s \cdot \frac{1}{L_{opt}} \cdot G_m \cdot G_{if} \quad (1)$$

$$P_{out} = \left(T_{out} + 2 \cdot 300K \cdot \frac{1}{L_{opt}} \cdot G_m + T_{if}\right) G_{if} \cdot k_B \cdot B_{if} \quad (2)$$

where L_{opt} is the optical loss, G_{if} and T_{if} are the IF chain gain and the noise, B_{if} is the YIG-filter bandwidth, k_B is the Boltzmann constant, and T_{out} is the HEB mixer output noise. Correcting for the IF chain gain, G_{if} we plot the mixer output signal $S_{mix}=P_{if}/G_{if}$ in Fig,4c-6c.

Since the incident THz signal power P_s was constant through the whole experiment, variations of the IF signal S_{mix} are due to changes of the mixer gain G_m, as shown in (1). Therefore, the mixer gain (in relative units) can be compared at different LO power levels and mixer temperatures (Figs. 4c-6c).

In order to calculate the HEB output noise T_{out} from (2), we utilized the HEB conversion gain G_m at the optimal point as described in Section III.B. Variations of G_m away from the optimal point were obtained from variation of S_{mix}. The corrected output noise, namely $N_{out}= T_{out} \times k_B \times 50MHz$, is plotted in Fig.4b-6b. Therefore, during this experiment we measure both variations of mixer gain and output noise, simultaneously.

For the given set of IVs, which more than covers the optimal LO-bias voltage range, the mixer output noise (Figs. 4b-6b) increases continuously as the LO power is reduced from IV-7 (overpumped HEB) to IV-1 (underpumped HEB). The mixer gain starts to saturate just above IV-3, hence above the optimal bias zone. The resulting signal-to-noise ratio (S/N) (Figs. 4d-6d) has a maximum at IVs-3-5. The (A-log(T_r)) for IV-5 is also plotted in Fig. 4d , where $A=45dB$ is a free coefficient used to place this curve close to the measured S/N curve. The log-function of $T_r(V)^{-1}$ closely follows the $S/N(V)$ curve, as is expected for the ideal case:

$$\log\left({}^{S}/_{N}\right) = \log\left(\frac{P_s}{T_r \cdot B_{if} \cdot k}\right) \propto -\log(T_r) \quad (3)$$

where k is the Boltzmann constant. Comparing Fig. 4a and 4d

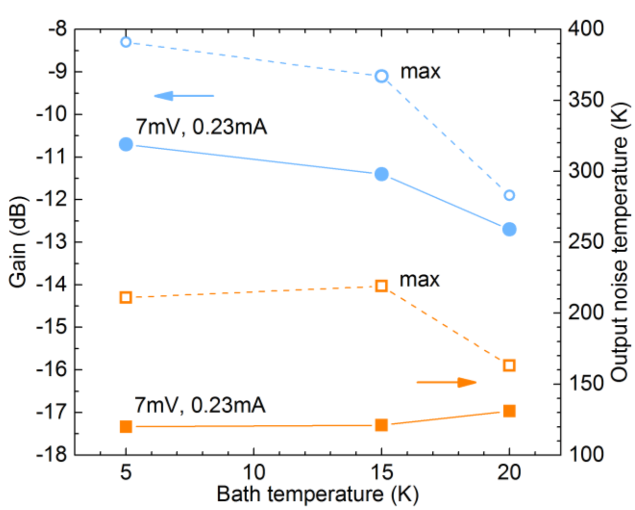

Fig. 8. The mixer gain, G_m (U-factor technique) and the output noise temperature as a function of the bath temperature. Filled symbols are at 7mV and 0.23mA bias point. Open symbols are the maximum output noise temperature and the corresponding mixer conversion gain providing the same receiver noise temperature as at the discussed bias point.

we conclude that bias voltage–LO power optimizations for both S/N and T_r coincide across the IV-plane. This fact demonstrates that, despite the broadband antenna used with the mixer, the "direct detection" effect has no impact on the choice of mixer operation point. The discussed "direct detection" effect is a shift in the HEB bias point when the receiver input load switches from 300K to 77K. In a 3THz band, a black body at 300K (77K) emits approximately 2.8nW (1.6nW) in the single spatial mode [13]. This is about 1% of the optimal LO power for NbN HEB mixers, and hence a switch of the load temperature changes the mixer bias point. For NbN HEB mixers, this effect can be detrimental, either decreasing or increasing the Y-factor, and hence the apparent receiver noise temperature. The effect has been reported to be more pronounced at smaller bias voltages. Our results show that for discussed MgB_2 HEB mixers, although integrated with a broadband antenna, the direct detection effect is negligible.

Furthermore, measurements of the S/N ratio allow for a much larger dynamic range compared to the Y-factor. Instabilities of the LO source sometimes lead to receiver output power fluctuations as large as 0.1dB. This fact limits applicability of the Y-factor technique to mixer operation points (IV-plane) corresponding to the highest sensitivity (highest Y-factor). To verify the validity of physical models, experimental data well off the sensitive points would be required. Furthermore, the Y-factor technique can be applied mostly to mixers already having quite good sensitivity, e.g. T_r<10000K (Y>0.1dB).

B. Mixer characteristics versus temperature

Two types of analyses can be performed in order to compare HEB mixer operation at different temperatures. First, the form of all corresponding I-V, N_{out}-V, and S_{mix}-V curves at 5K, 15K, and 20K is the same (Figs. 4-6). In order to perform a more precise comparison, we plotted three sets of the curves (corresponding to IVs 3-5) on the same figure (Fig. 7). For a certain temperature we find an IV totally matching an IV at another temperature by changing the LO power (Fig. 7a) (see also a discussion in Ref. [1]). For the matching IVs, N_{out}-V curves also closely overlap each other. This may only be possible if the mixer output noise temperature, T_{out} is independent of mixer temperature (for the matching IVs). In Fig.1, N_{ou} (in dBm) is plotted as a function of mixer temperature (all for 7mV and 200µA (IV-5, lowest T_r point)).

The absorbed LO was calculated using a constant resistance line, intersecting both the LO pumped and unpumped IVs (the isothermal method [14]). The isothermal method is based on an assumption that both the dc current and the THz LO have the same effect on the HEB dc resistance. This can only be true for HEBs close to the normal state both with and without LO pumping. The utilized constant resistance lines are shown in Fig.3. For those, the calculated LO power at 5K is 10.6µW and 9.6µW. Another approach, such as recording two IVs with close LO power levels with a known attenuation, also gives a value close to 10µW. Moreover, we verified that the LO power variation induced by a wire grid attenuator corresponds to the variation of the LO power calculated from the constant resistance line. A similar observation was made for LO power variations versus temperature. P_{LO} (in dBm) is plotted in Fig. 1 (stars) along with the mixer relative gain, S_{mix} (in dBm) (circles).

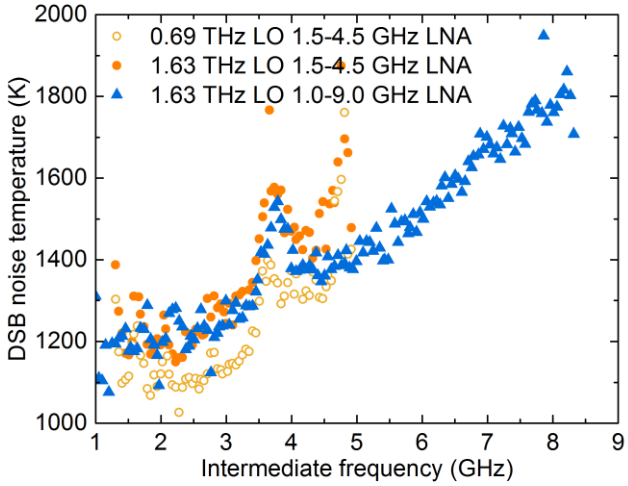

Fig. 9. The receiver noise as a function of the intermediate frequency recorded at 5K. Filled symbols: 1.63THz LO. Open symbols: 0.69THz LO. Circles: 1.5-4.5 GHz LNA. Triangles: 1.0-9.0 GHz LNA.

In contrast to N_{out}, mixer gain decreases at higher temperatures (Fig. 7c and Fig.1). It can be observed that when the bath temperature increases from 5K to 20K, reduction of mixer gain (by 2.5dB) is proportional to reduction of LO power (by 2.4dB) for the given IV, as in fact would be expected considering the classical HEB mixer model [15].

-10log(T_r) (where T_r was measured using the Y-factor approach) follows exactly the same temperature trend as the S/N ratio, measured using the mixing approach (Fig. 1, filled triangles and diamonds).

Mixer conversion gain (filled circles) and output noise temperature (filled squares), calculated using the U-factor technique with the HEB in the normal state as in the reference [3], are plotted in Fig. 8 for 5K, 15K and 20K bath temperatures (all at the same bias point of 7mV and 0.23mA). Mixer gain is inversely proportional to the temperature, whereas output noise remains almost the same. This is also confirmed by the mixing experiment, as can be seen in Fig.1.

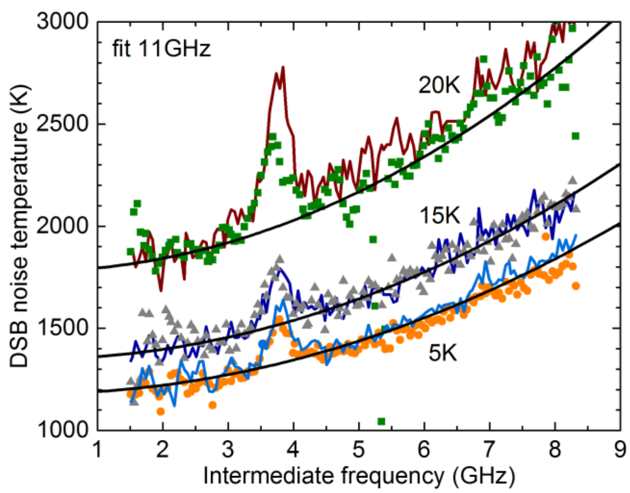

Fig. 10. The receiver noise (at 1.63 THz LO) as a function of the intermediate frequency recorded at 5K, 15K, and 20K operation temperatures. Results for mixers #10-7 (line), and #10-8 (symbols) are shown.

As follows from Figs. 4-5 (corresponding to mixer temperatures of 5K and 15K), receiver noise temperature is constant over quite a wide range of LO power levels. Across this range (IV5-IV3), both mixer gain and output noise vary by a factor of 2: from 120K to 220K and from -10.7dB to -8.3dB, respectively (Fig.8). Apart from a lower LO power, operation at IV3 has an advantage of higher output noise. With an output noise of 220K (see Fig.8), the IF LNA noise becomes much less critical to the receiver noise temperature:

$$T_r = \frac{1}{2} \cdot L_{opt} \cdot G_m \cdot \left(T_{out} + T_{if}\right) \qquad (4)$$

This is particularly important for broadband IF LNAs. LNA optimization can now be focused on input matching rather than on noise, hence eliminating a need for an isolator. In Fig.8 both the maximum output noise temperature and the corresponding mixer gain (within the minimum T_r zone) are plotted for 5K, 15K, and 20K mixer temperatures.

IV-5 (Fig.4-6) corresponds to the optimal LO power at temperatures from 5K to 20K. This the reason why T_r, P_{LO}, and relative mixer gain (S_{mix}) corresponding to this IV were selected for comparison in Fig.1. Theoretically, P_{LO} can be estimated from the steady-state heat balance equations:

$$G \cdot \left(T_e^n + T_s^n\right) = P_{LO} + P_{dc} \qquad (5)$$

where, T_e and T_p are electon and phonon temperatures, P_{dc} is the Joule heating due to dc bias current, both G and n are material parameters. G corresponds to the total heat conductance from electrons to the heat bath (the substrate, if the electron diffusion is weak, as it is the case in MgB2 HEB mixers). Coefficient n can be estimated [16] from the temperature dependence of the HEB response time and temperature dependences of the heat capacitance. E.g. if film-substrate thermal resistance dominates electron cooling process, phonon dynamics will play the major roll. In this case, n=4 [17]. On contrary, for very thin films with a negligible thermal resistance to the substrate, electron-phonon interaction will determine the constant n. In NbN HEB mixers, n of about 3.6 has been reported by several groups [18,19]. This value points on a transition for the electron cooling from being phonon-substrate limited to being electron-phonon limited. By fitting our data $P_{LO}(T)$ with (5), we obtain n=2+-0.3 and Tc=29.8+-1K. This value for n confirms conclusions made in literature [20] that MgB2 films have very low thermal resistance towards substrate, and hence, electron-phonon heat transfer to be the limiting factor in the electron cooling for very thin MgB2 films.

C. The noise bandwidth

To obtain the HEB receiver noise bandwidth (NBW), the Y-factor was measured across a wide IF band with an IF step of 50MHz. Both a 1.5-4.5GHz and a 1.0-9.0GHz IF LNA were used for these experiments. Intentions with measurements using the 1.5-4.5GHz LNA were to verify whether HEB-LNA interference might be affecting the obtained results. In Fig. 9, we show the receiver noise temperature measured with the 1.5-4.5GHz LNA at both 0.69THz and 1.63THz LOs. The noise temperature increases proportionally over the whole IF range, indicating that NBW is the same at both LOs, and hence supporting the idea of the bolometric nature of the heterodyne response in discussed devices. The noise temperature curve as measured with the 1.5-4.5 GHz LNA fully overlaps with the data obtained using the 1.0-9.0 GHz LNA at the corresponding IFs. The hump, seen at 3.7GHz, is present in both data sets, and hence originates from the bias-T, used for both experiments.

The noise temperature spectrum at 1.63THz LO was measured at 5K, 15K, and 20K for two HEBs from the same batch (Fig. 10). The fitting curves are for an 11GHz noise bandwidth. Curves for both devices totally overlap, hence indicating good reproducibility of results.

IV. Conclusions

Using both mixing experiments at 0.69THz and the U-factor technique, we demonstrate that MgB_2 HEB mixers gain variation vs temperature is proportional to LO power. Simultaneously, output mixer noise temperature is nearly constant from 5K up to 20K. In order to improve mixer gain at 20K (and, hence, receiver noise temperature), utilization of devices with a higher T_c seems to be a clear direction.

A high value of the output noise (~200K) reduces requirements for the IF LNA noise. This property might appear very useful for reduction of the IF ripples, which occur between the HEB and the LNA due to impedance mismatch. For example, for broadband LNAs, input matching (S11) could be >-3dB. In this case, even a simple 3dB attenuator would increase the IF chain noise temperature from 5K till 15K without a noticeable degradation of T_r, but will improve the HEB-LNA matching by 6dB. In general, the high output noise of MgB_2 HEBs allows for LNA optimization aiming at a low S11 rather than at a low noise temperature.

Experimental verification of MgB_2 HEB mixers with both the Y-factor and mixing techniques coincide fully, thus dismissing the issue of direct detection effect on the measured Y-factor. Furthermore, mixer sensitivity data for a much broader bias voltage, operation temperatures, and LO power ranges can be obtained compared to the Y-factor technique.

Our preliminary data indicate that MgB_2 HEB mixers can be fabricated with a T_c of 33-34K (quite feasible with an improved fabrication procedure). In this case, receiver noise temperature at 20K will greatly improve. This feature is of particular interest for systems where compact mechanical cryocoolers are required (e.g. for space borne instruments).

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Evgenii Novoselov, was born in 1988 in Saint-Petersburg, Russia. He received his B.Sc. and M.Sc. (summs cum laude) in 2009 and 2011, respectively, from The Saint-Petersburg National Research University of Information Technologies, Mechanics and Optics (NRU ITMO).

During his studies at the university, he worked at the research center “Femtosecond optics and femtotechnology” (NRU ITMO) (2007-2011). There he participated in a number of projects on the development of terahertz spectrography and reflectometry using TDS. After compliting his master degree, he joined LLC “TELROS Integration” (Saint-Petersburg, Russia) as a communication systems design engineer (2011-2013).

Currently, he is a PhD student at the Terahertz Millimetre Wave Laboratory at Chalmers University of Technology, working on MgB_2 Hot Electron Bolometers.

Sergey Cherednichenko, was born in 1970 in Mariupol, Ukraine. He received his Diploma with Honours in Physics in 1993 from Taganrog State Pedagogical Institute, and Ph.D. in physics in 1999 from Moscow State Pedagogical University.
He is working at the Department of Microtechnology and Nanoscience at Chalmers University of Technology (Gothenburg, Sweden). From 2000-2006 he was involved in development of terahertz band superconducting mixers for the Herschel Space Observatory; and from 2008 till 2009 in the water vapour radiometer for ALMA. As from 2007 he has been an Associate Professor at the department of Microtechnology and Nanoscience at Chalmers University of Technology. His research interests include terahertz heterodyne receivers and mixers, photon detectors; THz antennas and optics; thin superconducting films and their application for THz and photonics; and material properties at THz frequencies.