Effect of the critical and operational temperatures on the sensitivity of MgB_2 HEB mixers

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***Abstract*—We present a study of the noise and the gain of MgB_2 hot-electron bolometer mixers with different critical temperatures (T_c) and at various operation temperatures. At a Local Oscillator (LO) frequency of 1.63THz the minimum input receiver noise temperature (T_r) was 700K with a gain of -18dB for a device with a T_c of 8.5K. For a device with a T_c of 22.5K the corresponding values were 1700K and -19dB. For the latter device the T_r was 2150K at a bath temperature of 12K, which is not achievable with Nb-compound based HEB mixers. We present and compare different methods for measurements of the HEB mixer gain and the output noise.**

***Index Terms*—HEB, THz mixer, sub-mm astronomy, bolometer, conversion gain, noise temperature, MgB_2.**

I. Introduction and Background

Hot-electron bolometer (HEB) mixers have been proven to be a class of highly sensitive terahertz (THz) detection elements (from 1.3THz to 5.3THz) employed in many receivers for astronomical and atmospheric science observation programs launched in recent years, including RLT [1], APEX [2], [3], Herschel [4], [5], TELIS [6], [7], SOFIA [8], [9]. They are also chosen for different programs under development, such as ASTE [10], DATE5 [11].

Until recently, the state-of-the-art phonon-cooled HEBs were fabricated using either NbN or NbTiN superconducting ultrathin films providing a low Double Sideband (DSB) receiver noise temperature (T_r) at Intermediate Frequencies (IF) less than 2 GHz: from 300K (corrected for optical losses) at 1.3THz local oscillator (LO) [11] to 1150K (in a vacuum setup) at 5.3THz LO [12]. It has been shown that at frequencies over 3THz the quantum noise term starts "to take over" other terms and becomes dominant at higher frequencies [13], [14].

Due to a limited electron temperature relaxation rate in thin NbN and NbTiN films, HEB mixers have a gain bandwidth (GBW) <4GHz. As a result, a T_r increases towards higher IFs and doubles already at IF of 4-5GHz. Therefore, the number of scientific tasks in radio astronomy that can be performed with HEB mixers becomes limited. Furthermore, a superconducting critical temperature (T_c) of 8-11K limits the NbN and NbTiN HEB mixer operation to liquid helium (LHe) temperatures (≤4.2K). 4K cryocoolers qualified for space application are *rarae aves*, which necessitates utilization of LHe and leads to the reduction of the spaceborn mission lifetime. The discovery of superconductivity in MgB_2 [15] with the highest T_c among intermetallic compounds (bulk T_c = 39K) and recent progress in ultrathin film deposition [16], [17] opened new opportunities in HEB development [18]–[23].

In previously published work there have been two main goals in MgB_2 HEB mixer development: a large GBW and a low T_r. A GBW of 2-3 GHz was reported both for thicker films with a higher T_c (20nm, 20K) and for thin films with a much lower T_c (10nm, 9K) [18], [19]. A possibility of achieving a GBW of 8-10GHz with HEB mixers made from thin films with a high T_c was also suggested in [20], which was recently confirmed in experimental work by Cunnane et al. [22]. In that paper a GBW of 7 GHz (at 9K) and 8GHz (at 25K) was demonstrated for a device made from a 15nm thick MgB_2 film with a T_c of 33 K. A feasibility of achievement of a low T_r was already demonstrated in the first publications on the MgB_2 HEB mixers, which allowed for measurements of the mixer noise bandwidth (NBW), as a more appropriate criterion for the HEB mixer performance assessment. At the moment the state-of-the-art T_r for MgB_2 devices is 600K at a 600GHz LO [19], and 1150K at a 1.63THz LO [21]. Both figures were reported for devices made from 10nm films with a T_c of 9K and a NBW of 3GHz. For devices with a higher T_c, a higher T_r was observed (e.g. 1800K in [20]), but a NBW was more superior (6-7GHz). For the device with a T_c of 33K a T_r of 3900K was measured [22].

So far very few studies have been performed to understand how HEB mixers would operate at temperatures higher than LHe or how mixer performance depends on the bath temperature. A low T_c for NbN thin films (8-10K for 3-10nm films) does not facilitate studying HEB mixer operation at higher temperatures [24]. However, MgB_2 HEB mixers offer such a possibility. In [20], it was shown at a 600GHz LO that for MgB_2 HEB mixers the T_r remained constant up to 11K (T_c

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= 15K). However, no further details were provided.

Currently, the highest T_c of our MgB_2 films is about 22-24K for 20nm. In this paper, we present an experimental investigation and analysis of the noise temperature, the NBW, and the conversion gain at a 1.63THz LO with different bath temperatures for devices made from two films with either a 8.5K or a 22.5K T_c. We used three methods to obtain the mixer gain, which gave very similar results. Moreover, we present a study of how the most important mixer characteristics, such as the noise temperature and the conversion gain, vary when both the T_c and the film thickness alter over a wide range.

II. Device Fabrication and DC Characterization

Two batches of the HEBs were fabricated using MgB_2 films that are 10nm and 20nm thick. Films were deposited on a c-cut sapphire substrate by molecular-beam epitaxy (MBE) and covered *in-situ* with a 20nm gold layer to prevent film degradation and to reduce contact resistance between the MgB_2 film and the metal layers deposited later. The HEBs were fabricated using e-beam lithography and argon ion beam milling in several steps. Each substrate held 8 HEBs of various dimensions. For the 20nm film all devices survived during the processing and the dicing, but for the 10nm film the yield was quite low and only several devices were usable. For radiation coupling into the bolometer, a broadband planar spiral antenna was made from 270nm gold film in the same process. Devices were passivated with a 40nm SiN_x for protection from degradation due to both oxidation and exposure to water [25]. One device from the each batch was chosen for tests. The criteria for device selection were: the small size and low critical current density (to fulfil LO power requirement with the available source), and a DC resistance close to 100Ω (the designed impedance of spiral antenna). HEB#1 discussed below, was 10nm thick and 1x1μm² in size, with a T_c of 8.5K, a transition width of 2.5K, and a room temperature resistance of 160Ω. HEB#2 was 20nm thick and 1x0.2μm² in size, with a T_c of 22.5K, a transition width of 0.6K, and a room temperature resistance of 330Ω. R-T curves measured in a dip-stick for both HEBs are presented in Fig. 1. The presence of the double transition in the R-T curve for HEB#2 (Fig. 1) suggests that the electrical contact between MgB_2 and Au was quite good.

I-V curves of HEB#1 at 4.2K (with and without LO pumping) and the corresponding IF response versus the bias voltage (at a 295K load) are presented in Fig. 2. An LO power required to reach the minimum T_r (LO3 curve in Fig. 2a) was 70nW as was calculated using an isothermal method with an assumption that both the direct current (DC) and the LO power have the same effect on the bolometer resistance [26]. The optimal LO power is in the same order of magnitude as that reported for NbN HEB mixers.

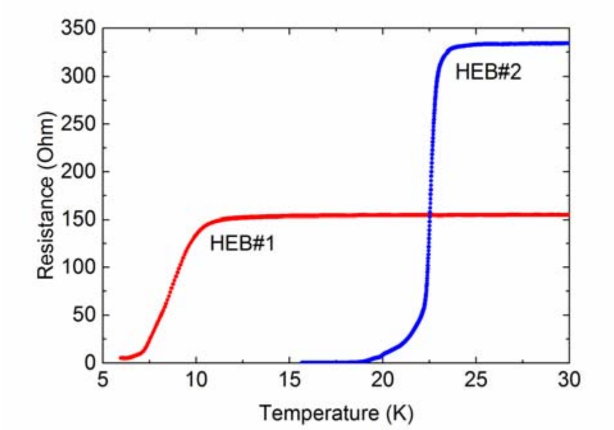

Fig. 1. Resistance versus temperature dependence for the tested devices.

TABLE I
MgB_2 HEB SIZE (WxL), THICKNESS (D), CRITICAL TEMPERATURE (T_C), TRANSITION WIDTH (ΔT_C), RESISTANCE AT 300K (R_{300K}), SHEET RESISTANCE (R_S), RESISTIVITY (ρ), CRITICAL CURRENT AT 4.2K (I_C) AND CRITICAL CURRENT DENSITY (J_C).

#	WxL(μm²)	D(nm)	T_c(K)	ΔT_c(K)	R_{300K}(Ω)
1	1x1	10	8.5	2.5	160
2	1x0.2	20	22.5	0.6	330

#	R_S(Ω/□)	ρ (10^{-6}Ω cm)	I_c(10^{-6}A) @4.2K	J_c (10^6A/cm²)
1	160	160	70	0.7
2	1650	3300	1000	5

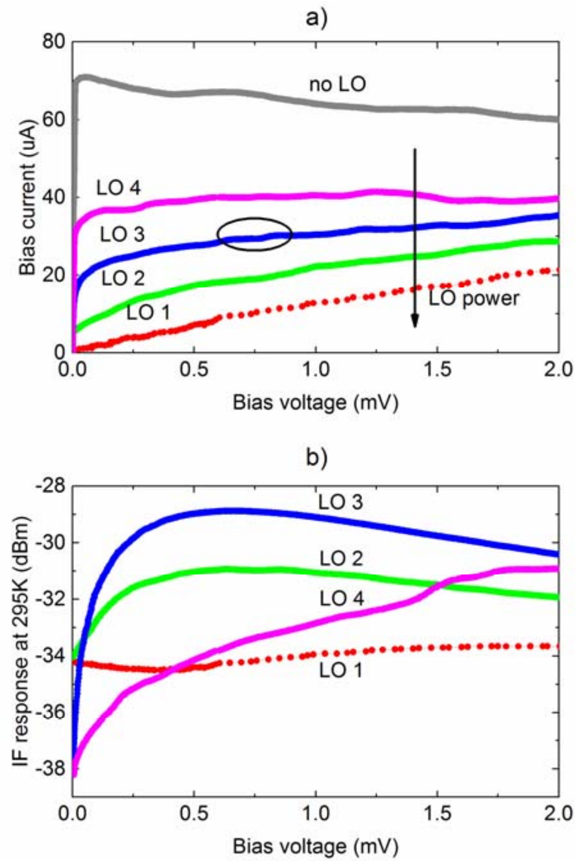

Fig. 2. (a) I-V curves for HEB#1 under different LO (1.63THz) power at 4.2K bath temperature, optimal operation points marked with a black ellipse and (b) the corresponding IF response at 295K load at 1.8GHz IF.

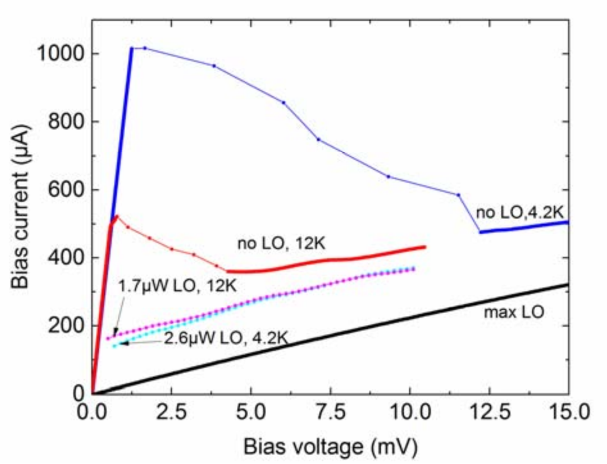

Fig. 3. I-V curves for HEB#2 with and without LO power (1.63THz) at 12K and 4.2K bath temperatures.

I-V curves of HEB#2 at 4.2K and 12K (with and without LO pumping) are presented in Fig. 3. At a bath temperature of about 12K the HEB critical current (0.5mA) was around half of its value at 4.2K (1mA). The LO power calculated using the isothermal method was either 2.6μW for 4.2K bath temperature or 1.7μW for 12K. DC parameters of HEB#1 and HEB#2 are summarized in Table I.

III. Measurement Setup and Experimental Technique

The HEBs were mounted in mixer blocks with Si lenses and placed on the cold plate of a LHe cryostat sealed with a HDPE window. A Zitex™ IR filter was placed on the 4K shield of the cryostat. Losses in the optical path from the hot/cold loads to the mixer and equivalent noise temperatures of the corresponding elements are presented in Table II. Reflection loss of the Si lens (1dB) was not included in the list and it was not accounted for. Therefore, for a specific frequency, both the T_r and conversion gain can be further reduced/increased by application of a proper designed AR layer for the Si lens [27]. In our case, Si lens reflection loss was treated as a part of the mixer conversion gain (G_m). A bias-T followed the mixer block to apply the voltage bias to the device and to separate the intermediate frequency (IF) response. Three cascaded amplifiers were used in the IF chain to measure the IF response: a 2-4GHz InP low-noise amplifier mounted on the cryostats' cold plate, a 2-4GHz GaAs low-noise amplifier at room temperature outside the cryostat, and a broadband (0.1-10GHz) amplifier at the end. A 3dB attenuator was placed between the cryostat and the first room temperature LNA to reduce standing waves in the long IF cable. The amplified signal was measured through a tunable (1-9 GHz) YIG-filter (50MHz bandwidth) with a power meter. Mylar® beam splitters (BS) (of either 12μm or 3μm thick) were used to combine the LO and the signal (from the hot/cold loads) beams. Noise measurements were performed with a 1.6THz LO (a far-infrared (FIR) gas laser) at bath temperatures of 4.2K, 2.7K (achieved by helium vapour pumping) and 12K (achieved by use of a resistive heater mounted on the mixer block). A Golay cell connected to the oscilloscope was placed behind the beam splitter to monitor the FIR gas laser emission power during experiments.

TABLE II
LOSSES (L) AND EQUIVALENT NOISE TEMPERATURES (T_{EQ}) OF OPTICAL COMPONENTS ALONG THE BEAM PATH AT 1.63THZ REFERED TO THE INPUT OF THE CORRESPONDING COMPONENT. T IS THE PHYSICAL TEMPERATURE OF THE COMPONENT.

Component	T (K)	L (dB)	T_{eq} (K)
Air path (40 cm)	295	1	76.4
Beam splitter (Mylar®)	295	0.1	7.0
Cryostat's window (1mm HDPE)	295	0.7	52.5
IR filter (2 Zitex™ sheets)	4.2	0.6	0.6
Total	-	2.4	137

For measurements of the T_r the standard Y-factor technique (295K/77K loads) was used. In order to obtain the mixer conversion gain and the mixer output noise temperature, a U-factor technique was applied as described in [21], [29]. In this case, the receiver conversion gain can be calculated as:

$$G_{tot} \equiv G_m / L_{opt} = \frac{U(T_{LNA} + T_{REF})}{2(T_{rec} + T(295))} \quad (1)$$

where L_{opt} is the optical loss (2.4dB in our case), T_{LNA} is the IF chain noise temperature. T_{REF} is the reference temperature that depends on the state chosen as the reference to measure the U-factor. For the superconducting state T_{REF} is equal to T_{LNA}, because in this state the HEB acts as a microwave short and hence it reflects the power coming from the IF chain. For the normal state, achieved by pumping with all available LO power (e.g. using a mirror instead of a BS), the noise does not depend on the bias point (LO1 curve on Fig. 2) and it is defined by the Johnson noise of the HEB, so T_{REF} is equal to the HEB electron temperature determined from the R-T curve by DC resistance. The factor "2" in the equation comes from the DSB operation of the mixer with an assumption that the sideband ratio is 1. As follows from (1), the mixer output noise temperature T_{out} can be calculated as:

$$T_{out} = U(T_{LNA} + T_{REF}) - T_{LNA} - 2G_{tot}T(295K) - 2G_{tot}T_{RF} \quad (2)$$

where T_{RF} is the noise contribution of optical components (137K in our case, see Table II).

Another method to obtain the mixer conversion gain and the mixer output noise temperature is from the output noise of the HEB mixer (P_{IF}) at the operation point and an accurate measurements of the IF chain gain, G_{IF} :

$$G_{tot} = P_{IF} / 2G_{IF}k_B B(T_{rec} + T(295)) \quad (3)$$

$$T_{out} = P_{IF} / 2G_{IF}k_B B - T_{LNA} - 2G_{tot}T(295K) - 2G_{tot}T_{RF} \quad (4)$$

where k_B is Boltzmann constant, and B is the bandwidth of the IF filter (see above in this Section).

IV. Experimental Results and Discussion

For HEB#1, the T_r (corrected for optical losses, as in Table II) versus the intermediate frequency at the 4.2K bath temperature is presented in Fig. 4 (circles).

Equation (5) is usually used to define the receiver NBW [28]:

$$T_m = T_m(0)\left[1 + \left(f_{IF}/f_N\right)^2\right] \quad (5)$$

where $T_m(0)$ is the noise temperature at zero IF, and f_N is the NBW. Fitting the measured T_r for HEB#1 to (5), both $T_m(0)$ of 1150 K and f_N of 3.5 GHz were obtained.

The T_r was also measured at a bath temperature of 2.7K. This resulted in a 30% increase in the HEB critical current (90μA) and a 40% reduction of the T_r (Fig. 4). The optimal operation region moved to slightly higher bias voltages. The required LO power calculated with the isothermal method was 80nW. The T_r corrected for optical losses versus the IF for the optimal operation point at 2.7K is presented in Fig. 4 (diamonds). Experimental points are fitted to (5) as was done for the data obtained at 4.2K. It provides the zero IF noise temperature of 700K and the NBW of 3.2GHz.

The mixer conversion gain and the mixer output noise temperature were calculated as discussed in Section III using experimental data from Fig. 4 and Fig. 2b. The noise temperature of the IF chain is determined mostly by the noise temperature of the first amplifier in the chain i.e. by the cold LNA, which is mounted on the cryostat's 4.2K plate. It has a gain of 30dB and a noise temperature of 2K. Therefore, the noise temperature of the whole IF chain was estimated as not to exceed 3K. The total gain of the entire IF chain, G_{IF} was measured to be 77dB at 1.8GHz. Using an IF response at the optimal operation point (U_0 = 0.8mV and I_0 = 28μA) of -29.4dBm, a U-factor of either 8.2dB (reference state is the superconducting state) or 4.7dB (reference state is the normal state), the T_r = 2500K, and the HEB temperature of T_{REF} = 9K in the normal state, both the mixer conversion gain and the mixer output noise temperature were calculated at 4.2K with all three methods presented in Section III.

At 2.7K, the input data for the calculation of the mixer conversion gain and the mixer output noise temperature (at an operation point of U_0 = 1.3mV and I_0 = 23μA) for HEB#1 were: the IF response P_{IF} = -30.4dBm, the U-factor was either 7.2dB (reference state is the superconducting state) or 4.2dB (reference state is the normal state), the T_r = 1500K, and the HEB temperature T_{REF} = 9.3K.

As one can see from TABLE III the mixer conversion gain and the mixer output noise temperature obtained using three methods are quite close to each other, which we interpret as a confirmation that the methods are correct. As the mixer temperature is reduced from 4.2K to 2.7K, the mixer conversion gain is increased by approximately 1dB, whereas the output mixer noise temperature is decreased by 5-10K. It is of interest to compare these experimental data with physical modelling of the devices, however this will be a subject for a further publication. It is also interesting to compare results of HEB#1 with published data for NbN HEB mixers, since a T_c of NbN thin films (8-10K) is very close to the T_c of the MgB_2 film used for HEB#1. The reported conversion gain of NbN HEBs is approximately -12dB [29] with the mixer output noise temperature of approximately 40K at a 1.63THz LO. A lower gain and a lower output noise for the MgB_2 HEB mixer (HEB #1) can be a result of a quite large superconducting transition width (see Fig. 1). The GBW of MgB_2 HEB [20] also shows to be a factor of 1.5 smaller, as compared to the NbN HEB mixer from [28]. Therefore, for comparison of the gain and the output noise at 1.8GHz (approximately the 3dB gain roll-off frequency for HEB#1) about a +2dB correction has to be applied for the MgB_2 mixer. Despite this, the T_r for both NbN and MgB_2 HEB mixers falls within the same ball park.

HEB#2 was tested using the same setup, except that it was mounted in a mixer block with a 5mm Si lens. The measured T_r spectrum across the 1-4GHz IF band for the bath temperature of 4.2K and a fit with (5) are presented in Fig. 5. At certain IFs the mixer response to the hot/cold loads was unstable which resulted in errors in the noise temperature measurements (e.g. at 1.9GHz and 2.9GHz). The fitted line corresponds to the zero IF noise temperature of 1700K and the NBW of 5GHz.

The mixer conversion gain and the mixer output noise temperature were calculated using the U-factor technique with the normal state as a reference state. Results are shown in Fig. 6. Higher ripples for IF < 1.8GHz correspond to the IFs with a high LNA return loss. The mixer conversion gain was fitted with a single-pole Lorentzian $G_m(f_{IF})=G_m(0)/[1+(f_{IF}/f_g)^2]$, where $G_m(0)$ is the mixer conversion gain at zero IF and f_g is the mixer GBW (3dB gain roll-off frequency). The fit in Fig. 6a corresponds to the zero IF mixer gain of -15.1dB and a GBW of 3.5 GHz. The same noise and gain measurements as

TABLE III
THE MIXER CONVERSION GAIN (G_m) AND THE OUTPUT NOISE TEMPERATURE (T_{out}) FOR HEB#1 CALCULATED: USING (1) AND (2) EITHER WITH THE SUPERCONDUCTING (i) OR THE NORMAL (ii) STATES AS THE REFERENCE STATE; USING (3) AND (4) (iii). MEASUREMENTS WERE PERFORMED BOTH AT 4.2K AND 2.7K BATH TEMPERATURES (T_{bath}). f_{IF} = 1.8GHz.

	i		ii		iii	
T_{bath} (K)	G_m (dB)	T_{out} (K)	G_m (dB)	T_{out} (K)	G_m (dB)	T_{out} (K)
4.2	-19.1	31	-19.6	27	-19.9	26
2.7	-18.2	21	-18.1	22	-18.9	18

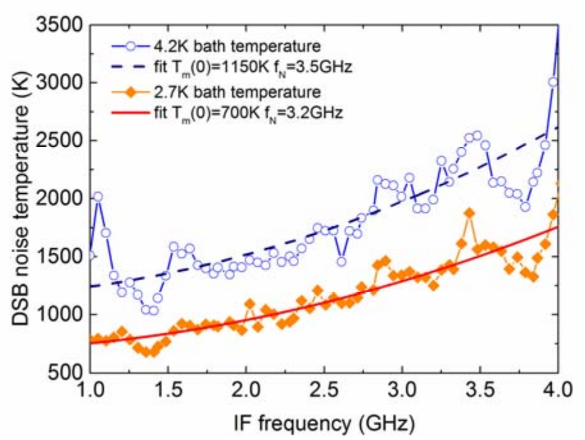

Fig. 4. The DSB receiver noise temperatures (corrected for optical losses) for the HEB#1. The bias points are U_0 = 0.8mV I_0 = 28μA and U_0 = 1.3mV I_0 = 23μA at 4.2K and 2.7K bath temperatures, respectively.

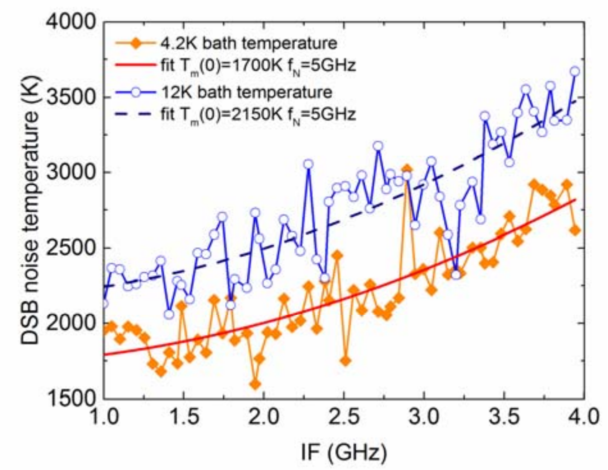

Fig. 5. The DSB receiver noise temperatures (corrected for optical losses) at 4.2K (diamonds) and 12K (circles) bath temperatures at a 1.63THz LO for HEB#2. The bias points are U_0=1.8mV I_0=200μA and U_0=1.6mV I_0=180μA, respectively.

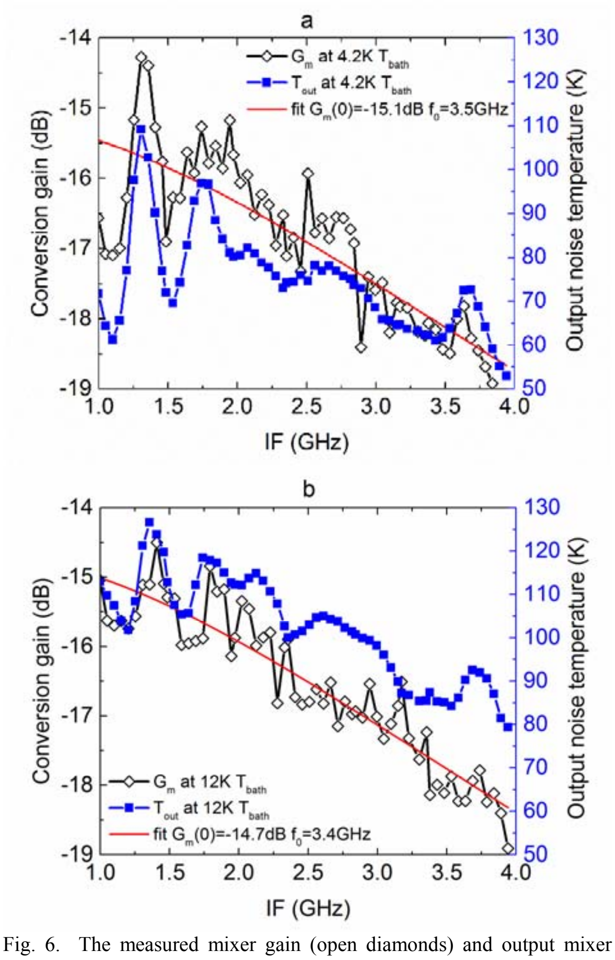

Fig. 6. The measured mixer gain (open diamonds) and output mixer noise temperature (squares) of HEB#2 versus IF at a 1.63THz LO at (a) 4.2K, U_0 = 1.6mV I_0 = 180uA and (b) 12K, U_0 = 1.8mV, I_0 = 200μA.

at 4.2K were conducted at 12K. Results are shown in Fig. 5 and Fig. 6. The fitted zero IF noise temperature, the NBW, the mixer conversion gain and the GBW are 2150K, 5GHz, -14.7dB and 3.4GHz, respectively. These data show that both the conversion gain and the GBW stays almost the same at both bath temperatures, but the output noise at a higher bath temperature is higher, similar to the behaviour observed for the "low" T_c HEB mixer, which results in a higher T_r. The acquired parameters of both HEBs are summarised in Table IV together with values for an NbN HEB mixer [29] for comparison.

TABLE IV
THE DSB RECEIVER NOISE TEMPERATURE (T_R), THE NOISE BANDWIDTH (F_N), THE MIXER CONVERSION GAIN (G_M), THE GAIN BANDWIDTH (F_G) AND THE OUTPUT MIXER NOISE TEMPERATURE (T_{OUT}) FOR MIXERS HEB#1, HEB#2 AND NBN HEB MIXER[29]

	HEB#1		*HEB#2*		*NbN HEB[29]*
	@2.7K	*@4.2K*	*@4.2K*	*@12K*	*@4.2K*
T_r, K	700	1150	1700	2150	800
f_N, GHz	3.2	3.5	5	5	-
G_m, dB	-18	-19	-15	-15	-12.3
f_g, GHz	-	-	3.5	3.4	-
T_{out},K	22	27	80	115	40

Two tested HEB mixers differed, not only in terms of the critical temperature, but also MgB_2 film thickness. As it follows from the HEB mixer theory, and some experiments with NbTiN HEB mixers [10], the film thickness affects the GBW and NBW of the device due to a longer phonon escape time. However, it should not affect the noise temperature (at IF << GBW) unduly. Our experimental data shows that this is also the case for MgB_2 HEB mixers.

V. CONCLUSION

This study shows that for superconducting films with a higher T_c both the output noise temperature and the conversion gain of HEB mixers increase as compared to the films with a lower T_c. This is valid for the optimal operation conditions. At the same time films with a higher T_c provide a broader NBW, as has been discussed in previous works. Already having reached a T_c of 22K, the HEB mixer can operate above 12K with only a 25% increase of the receiver noise temperature, compared to that at 4.2K. Achieving the HEB mixers with a T_c > 30-35K will push the HEB operation temperature above 20K with no or very small sensitivity reduction. In addition, we have demonstrated that the quality of MgB_2 is not critically important to achieving low noise temperature in the 2-4K temperature range and IF < 2GHz.

In this work we achieved a mixer noise temperature and a noise bandwidth comparable to NbN HEBs using quite low quality MgB_2 thin films with a "low" T_c (compared to a T_c of 39K for the bulk MgB_2 or 33-38K for the high quality MgB_2 films). The required LO power in this case is approximately 100nW, which can be easily realized with the available source technologies for frequencies, even above 2THz. Fabricated devices demonstrated high robustness and did not lose their properties after 1.5 years of storage in a nitrogen atmosphere. However, more specific tests would be required for space application.

Three different methods were applied to estimate the mixer conversion gain of the same HEB mixer. Good agreement with an error margin of ±0.5dB (which is within the accuracy of these measurements) between methods, indicates that the obtained mixer gain values are correct.

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