Wideband MgB_2 Hot-Electron Bolometer Mixers: IF Impedance Characterisation and Modeling

Stella Bevilacqua, Evgenii Novoselov, Sergey Cherednichenko, Hiroyuki Shibata and Yasuhiro Tokura

Abstract—**In this paper we present a method for low signal S11 parameter vector measurements of a cryogenic device in the microwave frequency range. In particularly, the intermediate frequency (IF) impedance of MgB_2 Hot-electron Bolometer (HEB) mixers was investigated over a frequency range of 100 MHz to 10 GHz. A new cryogenic calibration technique which employs the HEB as a calibration kit and two consecutive thermal cycles was developed for this purpose. The real part of measured IF impedance showed a strong correlation with the differential resistance (dV/dI) obtained from the dc I-V curves while the imaginary part was capacitive for almost the entire frequency range.**

Index Terms—**Heterodyne receiver, Hot-electron bolometers (HEBs), IF impedance, MgB_2, THz detectors.**

I. Introduction

High spectral resolution (>10^7) radio-astronomy for the observation of e.g. molecular line emission in the interstellar medium, requires low-noise heterodyne receivers [1]. For frequencies above 1.2 THz the most sensitive mixers available today are superconducting hot-electron bolometers (HEB). HEB mixers made of thin NbN films (3-10 nm) with a Tc of 8-11 K have been employed in many radio astronomical facilities such as the Herschel space observatory [2] and SOFIA (4.7 THz mixer) [3]. Despite NbN HEB mixers offer a low noise temperature as well as a gain bandwidth of 3 GHz, nevertheless the astronomers demand a wider gain bandwidth which cannot be achieved using NbN films. Hence the exploration of a new superconductor such as MgB_2 is a promising solution. A high critical temperature (35 K even for very thin films) and a picosecond electron-phonon interaction time observed in MgB_2 films is expected to enhance the presently achieved gain bandwidth [4] up to 10 GHz or even higher. Moreover compared to NbN film, MgB_2 film could allow HEB mixers to increase the operating temperature up to >15-20 K where compact cryocoolers are available, opening a possibility for a much longer life time of space born THz observatories.

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In our recent work, we demonstrated a Double Side Band (DSB) receiver noise temperature as low as 600 K (at 600 GHz) for HEB mixers of 10 nm MgB_2 films with a Tc of 8.5 K [5]. For devices fabricated on similar films, more recent results have shown a DSB noise temperature of 700 K and 1400 K at 1.63 THz and 2.55 THz LO frequencies [6]. In [7] we reported a gain bandwidth as wide as 3.4 GHz for devices made from thin films (10 nm) with a Tc of 15 K. We have also demonstrated that MgB_2 HEB mixers exhibit a constant noise temperature up to 10.5 K in contrast to NbN HEB mixers where the noise temperature raised almost directly with the bath temperature. Moreover, a low noise performance (1700 K) is still feasible HEBs made of thicker MgB_2 films (20 nm) with a high Tc (22 K) [8, 9].

Apart of a low noise and a wide bandwidth, one of the important requirements for a radio astronomical heterodyne receiver is gain variations across the band [18]. Graduate gain drifts (e.g. roll-offs) can be compensated in the backend. On contrary, gain ripples are much more difficult to take care of and the ripples impose a strong limitation on the final receiver sensitivity. The origin of the gain ripples can be different, e.g. from a standing wave in the optical path. However, the biggest problem comes from standing waves in the IF chain, and, in the first hand, between the THz mixer and the first stage IF amplifier (the Low Noise Amplifier, LNA). Furthermore, such ripples are often varying with the mixer bias and the LO pumping level. The origin of the standing waves between two microwave components is an impedance mismatch. Therefore, the microwave impedance (at the IF frequencies) of THz HEB mixers is a very important characteristic which requires an accurate measurement technique. Finally, IF impedance has to be considered as an important parameter for HEB mixer optimization.

In this work an investigation of the MgB_2 HEB IF output impedance for two different devices at many bias conditions is presented. The measured impedance is analyzed within a HEB lumped model.

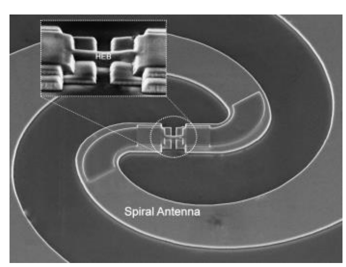

Fig. 1. Scanning electron microscope (SEM) picture of an MgB_2 HEB integrated with spiral antenna. The insert (top left in the image) shows a magnification of the bolometer bridge and the center part of the antenna.

II. DC CHARACTERISATION AND EXPERIMENTAL SETUP

MgB_2 HEB bridges are patterned using electron beam lithography followed by several lift-off processes as well as etching steps. SiN_x passivation is used to protect devices from external environment allowing to preserve their initial characteristics. After fabrication the bolometers showed a critical temperature, Tc, very close to the one of the continuous film, with a sharp transition between the normal and the superconducting state indicating a good process stability. More detailed explanation on the fabrication technique is presented in [9]. With this fabrication technique sub-micrometer size HEB have been fabricated (Fig. 1 shows a scanning electron microscope (SEM) image of a spiral antenna coupled MgB_2 mixer with a bridge area of 0.3 x0.3 um^2). The HEBs discussed in this work are made from 40 nm and 20 nm MgB_2 films which are expected to have 3dB gain roll-off frequencies at about 1 GHz and 2 GHz, respectively, based on the previous results. The HEB #1 has a bolometer area of 0.8 x 2 um^2 (40 nm film), a room temperature resistance (R_{300}) of 47 Ohm, and a critical temperature, Tc, of 30 K. For HEB #2 the area is 0.9 x 3 um^2 (20 nm film), the R_{300} is 250 Ohm, and the Tc is 22 K. The critical current, Ic, measured at LHe bath temperature was ~9 mA and ~1.9 mA for HEB #1 and HEB #2, respectively (see Fig. 3). The choice of these particular devices was motivated by large differences in the DC parameters and the MgB_2 film thickness.

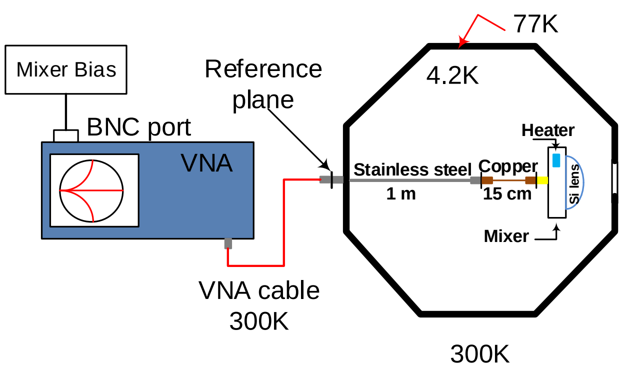

Fig. 2. Schematic of the experimental setup used for IF impedance measurements.

For the impedance characterization, the HEBs were mounted on a 5 mm diameter elliptical silicon lens and subsequently clamped in a detector block with an SMA connector and the IF terminal. The detector block placed in the cold plate of liquid helium (LHe) cryostat is then connected to 1 m long semi rigid coaxial cable (4.2 K) of the dewar through a 15 cm copper coaxial semi rigid cable (see Fig. 2). At room-temperature, a K-cable was used to connect the E8361A Vector Network Analyzer (VNA) to the cryostat. Using the VNA's internal bias-T, both the DC and the RF signals were applied to the HEB through the same coaxial cable. The IF frequency range adopted was 100 MHz to 10 GHz and the input power was chosen to be -60 dBm not to disturb the bias point of interest.

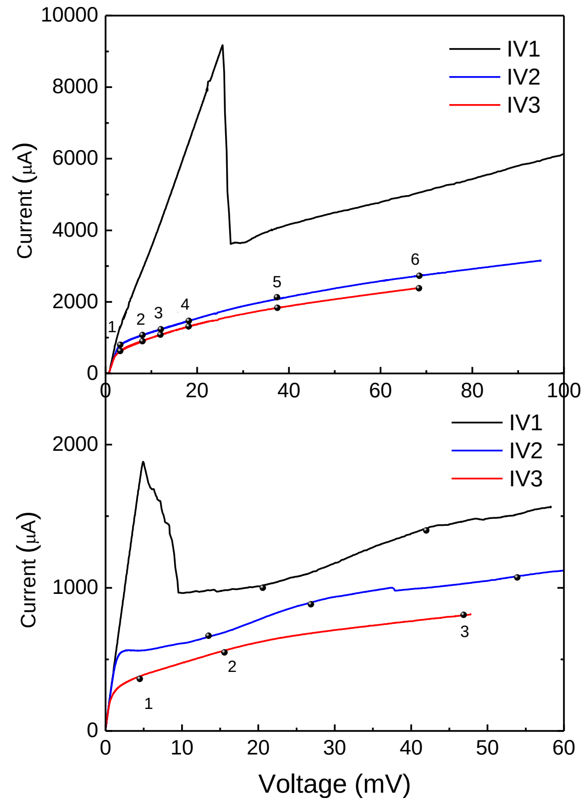

Fig. 3. I-V curves of HEB #1 (top figure) and HEB #2 (bottom figure) made from 40 nm and 20 nm MgB2 film. The circle in the figures indicate the bias point where the impedance was measured. The pumped I-V curves were obtained by simulating the effect of the LO illumination by elevating the operating temperature of the device.

The described measurement setup allows to measure the complex scattering parameter S_{11} and the device impedance, Z was extrapolate from it, using a method described below (see also [10]).

Superconducting MgB_2 HEBs require cooling to temperatures 4-20K. Therefore, room-temperature calibration of the experimental setup does not give accurate results since the electrical length and the propagation constant of the coaxial cables change at lower temperatures. In order to perform these measurements a not trivial coaxial cryogenic calibration is required.

Previously, several groups have reported on measurements of the IF impedance for NbN HEB mixers. The major challenge is to find proper calibration standards which would hold through the measurement procedure. In [11], the open standard was obtained by destroying the device with a large bias current at the end of the measurements. Non-destructive calibration procedure was developed in [12] achieving good results up to 5 GHz. Kooi et al. [13] used only two standards (short and load) to calibrate the VNA. Using a commercial calibration kit, three cooling cycles and de-emending technique, a detailed study of the HEB impedance (at frequency up to 8.5 GHz) was presented in [14].

In this work we propose a non-destructive broadband calibration procedure which uses only two cooling cycles (done once for the given set-up) in order to abstain the calibration files which can be used for the impedance measurement of any HEB in the same experimental setup. A standard open-short-load (SOL) calibration at room-temperature is initially performed at the VNA cable (Fig.2 reference plane). In order to extrapolate the error model for microwave measurements (directivity, E_D, source match, E_S, and reflection tracking, E_R) [15], the S-parameters of "new standards" were measured at the cryogenic temperature. The open standard was realized by using an already dead HEB (MOhm resistance) while for the short and load the HEB in the superconducting state and in the normal state. Conventionally, for the matched load, a 50 Ohm impedance is desired. Therefore, HEB #1 in the normal state was used to reproduce the matched load. The measured S11 for the open and the match load standards were also employed for the impedance extraction of HEB #2.

Using these error terms, Matlab programming and eq. (1) [15] the impedance was deducted from microwave reflection coefficient measurements.

$$S_{11,M} = E_D + \frac{E_R \cdot S_{11,A}}{1 - E_S \cdot S_{11,A}} \tag{1}$$

The terms $S_{11,M}$ and $S_{11,A}$ are the as-measured and corrected reflection coefficient, respectively.

III. Results and Discussion

The complex S_{11} parameters (hence, the IF impedance) of MgB_2 HEBs were measured for different I-V curves at several bias voltages, as shown Fig. 3 (HEB #1, top figure; and HEB #2, bottom figure). Normally, HEB mixers are at 4.2K (LHe) and are pumped with a Local Oscillator (LO) source, which increases the electron temperature in the HEB and changes the IV from a strongly hysteretic (IV1) to a smooth (IV2, IV3) shape. The lowest mixer noise temperature is obtained for IVs close to IV2-IV3 shown in Fig.3 [19], The same (or very similar) effect on IVs has an increase of the mixer physical temperature from 4.2K closer to the Tc. The IVs of HEB mixers at 4.2K and under LO can be closely matched by heating the mixer. This choice was made in order to initially simplify the experiment's setup.

Both the real and the imaginary parts of the measured impedance for HEB#2 (20 nm film) are shown in Fig. 4. The measured impedance at point 3 was fitted with a HEB lumped model (solid red line Fig. 4) through (2) [16]. In this case: V=46.8 mV and I=0.8 mA with a DC resistance R_{DC} of ~58 Ohm (i.e. about 1/5 of the normal state resistance, see IV3 in Fig. 3, bottom).

$$Z(f) = R_{DC} \cdot \left(\frac{1+C}{1-C}\right) \cdot \left(\frac{1 + j2\pi f \dfrac{\tau_m}{1+C}}{1 + j2\pi f \dfrac{\tau_m}{1-C}}\right) \tag{2}$$

where C is the self-heating parameter and τ_m is the intrinsic mixer time constant. Using both C and τ_m as fitting parameters, a fair agreement with the measured data was observed. The deviation at higher frequencies (especially for the reactive part) can be explained with uncertainties introduced by the calibration procedure. The extrapolated value for C and τ_m were ~0.5 and ~45 ps, respectively. The obtained value for the time constant agrees with what we have previously measured for MgB_2 HEB made from 20 nm film [17].

According to the lumped model the real part of mixer impedance (Re[Z]) approaches the differential resistance (dV/dI) and the R_{DC} of the bias point for lower ($f \ll 1/\tau_m$) and higher frequencies ($f \gg 1/\tau_m$), respectively [16]. A similar behavior is observed in Fig. 4. By linearly fitting the IV curve in a small range around the bias point, the dV/dI was extrapolated to be ~ 173 Ohm showing a correspondence close to one with Re[Z] in the frequency range of 100 MHz to 500 MHz. R_{DC} was 58 Ohm at this boas point, which is a bit lower than the Re[Z] at the higher frequency limit. From [16] (eq. 4) the self-heating parameter ($C=(dV/dI)-R_{DC}/(dV/dI)+R_{DC}$) is well predicted based on the device DC parameters. From Fig. 4 it is also possible to observe that the Im[Z] is always capacitive for the entire frequency range in agreement with the standard model. The real part of the impedance at bias points 1 and 2 are almost constant across the entire frequency range. Simultaneously, the imaginary part of the impedance is close to zero. These facts do not fit the HEB lumped model and will need further investigation.

In Fig. 5 the measured complex impedance of HEB #1 is shown. It has a substantially different behavior compared to HEB #2. At low bias voltage points the real part of the

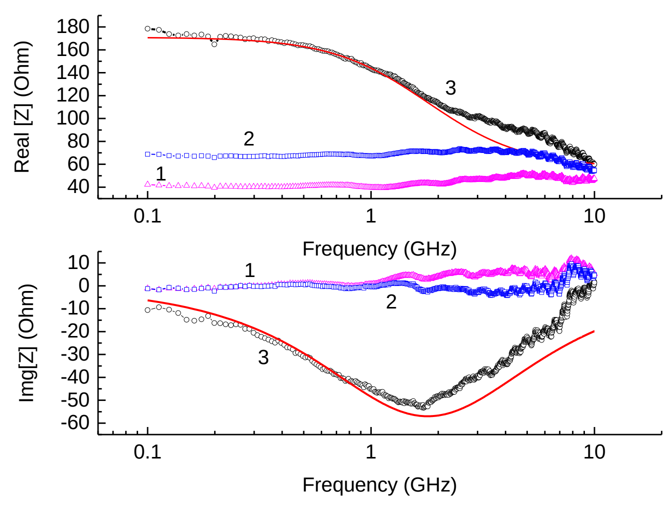

Fig. 4. Real and imaginary part of the impedance for HEB #2 measured at points 1,2, and 3 (see Fig. 3-bottom). The symbols are measured data. The red line is a fitting curve for the point 3 obtained from eq. 2 using the self-heating parameter and the mixer intrinsic time constant as fitting parameters.

impedance rises for frequencies higher 1GHz, while the imaginary part becomes positive. For higher bias voltages, when R_{DC} is close to the device normal state resistance, the reactive part becomes capacitive. The real part of the impedance does not approach the DC resistance at higher frequencies. The deviation from the lumped model for the device fabricated from a thicker film (40nm) is not well understood yet and more study is required. The expected time constant for the mixers made of 40nm MgB_2 films is about 80ps, i.e. the gain bandwidth if approximately 1GHz. At frequencies above 3GHz (i.e. where the most of the unexplained impedance behavior is observed) the mixer gain should have dropped by more than twice.

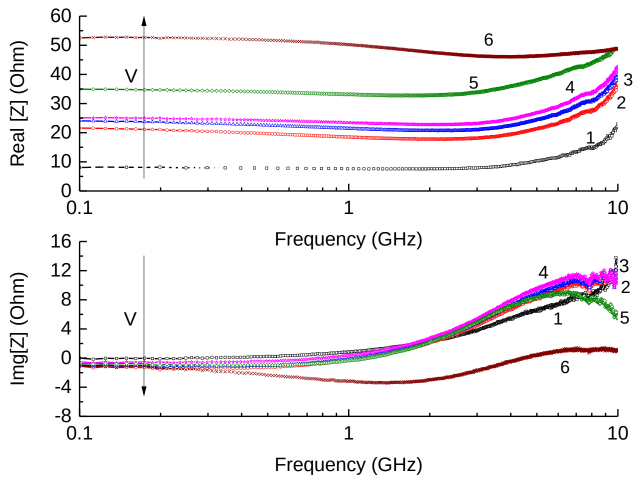

Fig. 5. Real and imaginary part of the impedance for HEB #1. Each curve corresponds to the impedance measured at each bias point indicated in Fig. 3 (IV2). The arrow indicate the increase of the bias voltage.

The lumped model predicts that at IFs below the 3dB gain roll-off the real part of the impedance has to be equal to the dV/dI. Therefore it was interesting to verify first, if there is a correlation between Re(Z) and dV/dI for different bias points and IV curves. Fig. 6 shows the DC resistance and the impedance real part plotted versus the dV/dI for HEB #1 and HEB #2 at which the open symbols are bias points where the impedance was not measured. For both devices, as expected, the dV/dI linearly increase with the DC resistance although for HEB #2 (bottom plot Fig. 6) the data look more scattered due to the different shape on the IV curves compared to HEB #1. The Re[Z] increases with the dV/dI showing a linear dependence with almost 100% of correlation between the two values at any bias point. Despite for HEB #1 the standard model does not predict the impedance at higher frequency however (Fig. 6 top plot) it can be applied to predict with high accuracy the impedance at lower frequency (i.e. IF < 3dB gain roll-off).

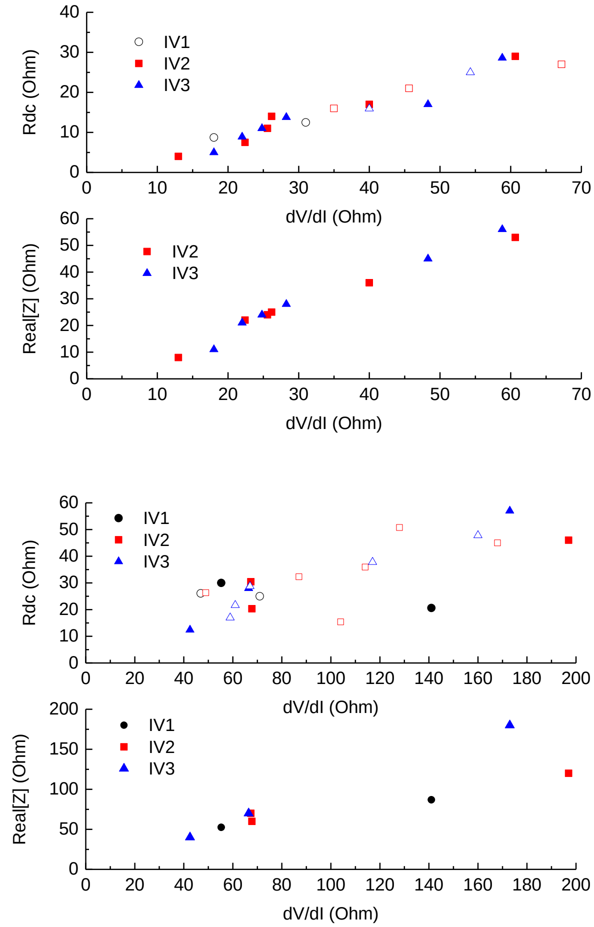

Fig. 6. DC resistance and real part of the impedance for HEB#1 (top figure) and HEB #2 (bottom figure). The impedance real part value is referred to the low frequency (100 MHz). Open symbols are bias point where the impedance was not measured.

IV. Conclusion

The presented experimental method allows for the HEB mixer impedance measurements with a single cool-down. The calibration hold for many measurements which has been confirmed by repeating some of the measurements. For the HEBs at bias voltages higher than optimal (for the noise temperature) the measured impedance follows the HEB lumped model. At the optimal bias points the real part of the impedance follows the model only in a limited frequency range, namely for IF below the gain 3dB roll-off frequency. This discrepancy is much less for thinner films (20nm vs 40nm). As it appear from the facts presented in this paper, the IF impedance of MgB_2 HEB mixers requires further studies both experimentally as well as theoretically.
With the knowledge of the HEB IF impedance future step is the design of a coupling network and possibly a packaged receiver.

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