Noise performance of a balanced waveguide NbN HEB mixer utilizing a GaN buffer-layer at 1.3 THz

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Abstract— **We report on the initial measurement results of a balanced waveguide phonon cooled NbN mixer employing a 5.5 µm thin GaN membrane, which was operated at frequencies around 1.3 THz. The uncorrected DSB noise temperature amounts to approximately 750 K at 1 GHz IF and increases to only 900 K at 4 GHz IF, which was deduced from the standard Y-factor measurement technique. The recorded IF spectrum from 0.5 GHz to 8 GHz suggests a measured noise bandwidth of approximately 7 GHz owing to the employment of a GaN buffer-layer, which promotes the single crystal growth of NbN films and provides high phonon transparency, thus lowering the phonon escape time.**

We emphasize with the implementation of a waveguide balanced receiver scheme and using NbN/GaN mixers the possibility to extend the operational IF range of phonon cooled NbN HEBs, yet providing low noise performance.

Index terms – **Hot Electron Bolometer mixer, THz receiver, NbN thin film**

I. INTRODUCTION

Hot electron bolometers (HEB) based on ultra-thin NbN films for low-noise heterodyne THz receivers have been the technology of choice for high-resolution spectroscopy for more than two decades. In recent years, the complexity of such receivers has increased by using balanced waveguide schemes [1], [2] or going to multi-pixel arrays operating at frequencies as high as up to 4.7 THz [3]. Superconducting NbN mixers are superior to Schottky diodes as THz mixer in terms of noise temperature and LO power consumption requirements. They do not experience, in principle, an upper RF frequency limit, and do not require an applied magnetic field unlike THz SIS mixers. However, phonon cooled HEBs show a deficit in their IF bandwidth, which is governed by intrinsic relaxation processes of electrons under non-equilibrium conditions, namely the electron-phonon interaction in the superconducting film and the phonon escape from the film to the substrate. The latter is believed to limit the operational IF bandwidth in these NbN film based devices to only 3-4 GHz [1], [4], [5], [6]. This restricts the efficient use of observation time as well as complicates the study of far distant objects, which are associated with increased spectral line broadening. Two promising approaches to enlarge the IF bandwidth have been pursued in recent years. With advances in the growth of thin layers of the high critical temperature (T_c) superconductor MgB_2, and utilizing its very short electron-phonon and phonon escape time, it was possible to demonstrate an extended noise bandwidth in a quasi-optical mixer setup operating at 1.63 THz [7]. However, the reported noise temperature of those MgB_2 based devices [7], [8] is still higher than these made of NbN, and they demand more LO power, which limits their prospective use in future, especially multi-pixel applications. Other studies focused on the improvement of NbN's film quality by exploring different buffer-layers [9], [10], [11] and reducing the phonon escape time, which is believed to limit the IF bandwidth. It has been shown that hexagonal GaN promotes the epitaxial growth of NbN ultra-thin films and enhances the phonon escape significantly compared to commonly used Si substrates due to the close acoustic match to NbN and a low defect interface [12], [13], [14]. Nonetheless, the noise performance of such THz mixers that employ a GaN buffer-layer has not been demonstrated before the work presented here.

II. EXPERIMENT

A. Receiver design

The balanced waveguide receiver scheme offers major advantages over the single-ended configuration at the cost of higher complexity. The separation of the RF and LO path in conjunction with a waveguide RF hybrid makes a potentially lossy beam splitter obsolete, utilizes all available LO power and provides more flexibility when designing receiver arrays. Moreover, amplitude modulations and thermal instabilities of the LO source are suppressed in the balanced mode [15] and higher receiver stability is achieved [1], which allows for prolonged integration times of astronomical observations.

The implemented layout consists of a waveguide RF quadrature hybrid and two NbN-on-GaN HEB mixers, which were integrated into a full-metal mixer block in back-piece configuration, as illustrated in Fig. 1. Details on the fabrication of the quadrature RF hybrid and waveguide components with cross-section of 90 µm x 180 µm can be found in [16], [17]. The HEB mixers have been designed and optimized in the full-wave

3D simulator *Ansys HFSS* and are, according to simulations, able to operate in the 1.0 THz to 1.5 THz frequency band [18]. The individual IF outputs of the HEBs are combined in-phase by using a compact superconducting multi-section Wilkinson combiner [19], which was followed by a cryogenic SiGe low noise amplifier (LNA) [20]. The IF chain was complemented with a warm broadband LNA and the read-out was performed with a spectrum analyzer.

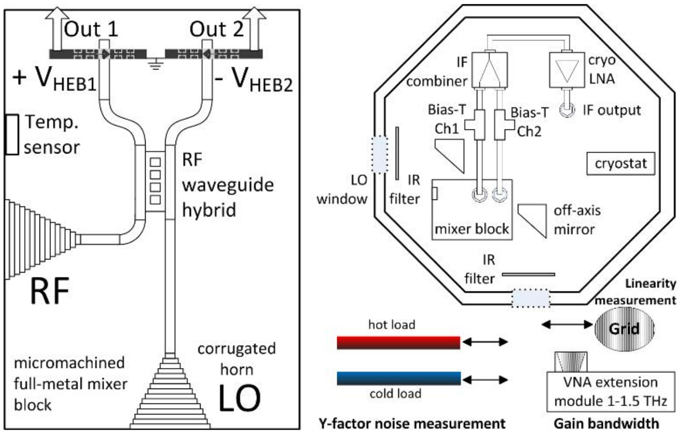

Fig. 1 Left: Schematic of the micro machined full-metal mixer block in back-piece configuration comprising of the RF hybrid and two NbN-on-GaN mixer chips. Right: Arrangement of the mixer block inside the wet cryostat. The receiver noise temperature is deduced from a Y-factor measurement on a hot and cold load.

The HEB mixer chips were processed on a thinned Si substrate onto which a 5.5 µm thick GaN buffer-layer was grown. The NbN film with approximate thickness of 4.5 nm was deposited by DC magnetron sputtering in a reactive N_2/Ar atmosphere at elevated temperatures. A detailed description of the deposition method can be found in [12]. The T_c of 12.8 K of the NbN film was deduced prior to processing by performing a resistance versus temperature measurement in a liquid helium Dewar.

The GaN beam has been defined by using photo-lithography and dry-etching techniques in chlorine chemistry, which is highly selective to the underlying Si substrate and provides a smooth surface and high process controllability. The patterning of the Si from the back into a Π-shaped structure as seen in Fig. 2 facilitated the mounting of the mixer and greatly improved the alignment accuracy [21], as the Fig. 2(right) suggests. The rigidity that is added with employing such Si frame makes it possible to use wire bonds for electrical contacting, which is considered a space-compatible technology. Details on the fabrication of such GaN beams can be found in [22].

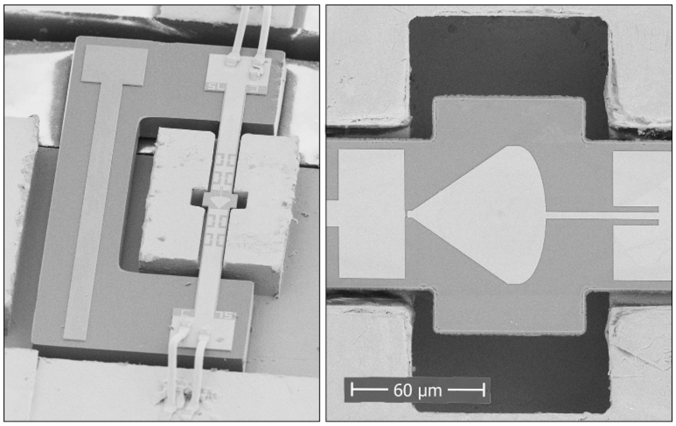

Fig. 2 Left: SEM images of the HEB mixer with bonding wire for DC bias and IF extraction. The Π-shaped Si frame, which hosts the suspended GaN membrane of 5.5 µm thickness, is a great aid for handling and alignment of the chips. Right: Shows the well-aligned mixer chips inside the waveguide opening. The HEB bridge is located between narrow part of the E-probe and the RF choke structure, which prevents leakage of the THz signal through the IF stripline.

III. RESULTS AND DISCUSSION

A. Current-voltage characteristics

The IVC provides valuable information on the actual operation state of the HEB mixer, and will depend on its physical temperature and the amount of applied LO power, i.e. the pumping of the mixer. The bath temperature, measured directly at the mixer block, was 4.6 K and remained constant throughout all performed measurements.

Under zero bias conditions and without applied LO power, the HEB mixers are in the superconducting state and reveal their critical current (I_c), which can be read to 150 µA, as seen in Fig. 3. More importantly, both HEB mixers feature nearly the same I_c, as well as normal state resistance of 125 Ω, which allows to fully utilize the advantages of the balanced receiver scheme.

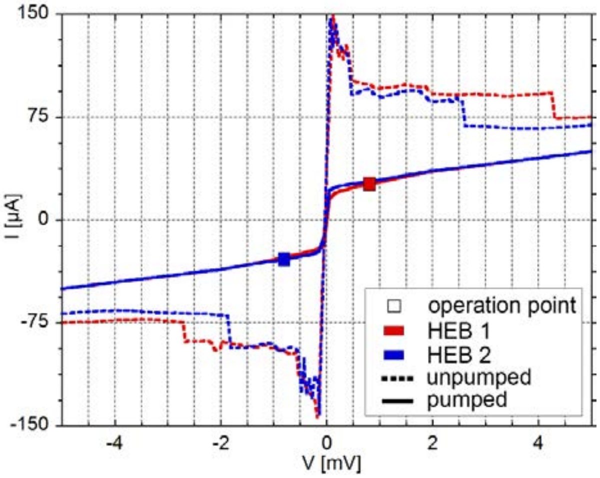

Fig. 3 Current-voltage characteristic (IVC) of both HEB mixers in the balanced receiver scheme. The operation points, which were used for the noise and gain bandwidth measurement are indicated with □. The I_c of both HEBs is nearly identical and measured to be 150 µA.

B. Noise measurement

The LO source was tunable in the range from 1.25-1.39 THz, however, the maximum output power of 9 µW [23] was only available in the frequency range between 1.28-1.29 THz and restricted the optimal pumping of the HEB mixers to these frequencies.

The receiver noise temperature was measured utilizing the Y-factor technique, which is based on two receiver output power measurements of black body emitters that are held at different physical temperatures (T_{hot}=296 K and T_{cold}=78 K). The IF power spectrum of the receiver was recorded with a spectrum analyzer for a hot load and a cold load in the frequency range from 0.5 GHz to 8 GHz and was used to calculate the DSB noise temperature of the receiver (T_{rec}).

The optimal bias voltage, yielding lowest noise performance was found to be in the range between 0.6-0.8 mV. The uncorrected DSB noise temperature is displayed in Fig. 4 as red curve, and suggests 750 K at 1 GHz IF and 900 K at 4 GHz IF, respectively. The measured noise temperature experienced a steeper than theoretically expected roll-off above approximately 5.5-6 GHz, which is most likely caused by the deteriorating noise performance of the used cryogenic LNA as indicated by the green curve in Fig. 4. However, its effect on the receiver noise roll-off can easily be removed, as measurement data on the LNA noise temperature was available and the total receiver conversion gain was deduced from a U-factor measurement, which is described in more detail in [24]. The blue curve in Fig. 4 shows the receiver noise temperature with removed frequency dependent LNA contribution. The noise bandwidth at which the noise temperature has increased to twice its value extrapolated to zero frequency, amounts to f_n=7 GHz.

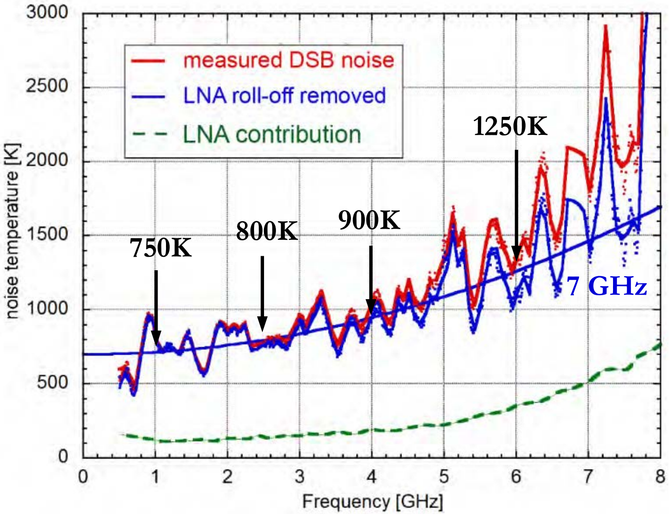

Fig. 4 DSB receiver noise temperature as measured (red) and without frequency dependent LNA contribution (blue). The green curve presents the corrected HEB mixer noise temperature. The fit suggest a nose bandwidth of f_n=7 GHz.

IV. CONCLUSION

A waveguide balanced NbN-on-GaN HEB receiver operating at 1.3 THz LO frequency has been presented. The uncorrected DSB receiver noise temperature was as low as 750 K at 1 GHz IF and 900 K at 4 GHz IF, respectively, and results in a noise bandwidth of 7 GHz, which is a substantially higher than the typically achieved 4 GHz for NbN-on-Si substrates HEB mixers. This improvement is ascribed to the employment of a GaN buffer-layer, which enhances the phonon escape of the epitaxially grown NbN film to the substrate. The contribution of the HEB mixer on the receiver noise temperature has been estimated to be 300 K or ~5 hf/k by taking into account losses in the optical path and waveguide components as well as the receiver's conversion gain, and is comparable to the sensitivity of state-of-the-art receivers.

The measurement results strongly promote the use of a GaN buffer-layer in future NbN based low noise THz heterodyne instruments with demands on an extended IF bandwidth, but also show its suitability to be implemented in balanced waveguide receiver schemes.

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