4×2 Hot electron bolometer mixer arrays for detection at 1.46, 1.9 and 4.7 THz for a balloon borne terahertz observatory

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***Abstract*— We present a comprehensive characterization of three 4×2 HEB mixer arrays developed for the Galactic/Extra-Galactic ULDB Spectroscopic Terahertz Observatory (GUSTO), a NASA balloon borne terahertz observatory. These arrays were designed for operation frequencies of 1.46, 1.9 and 4.7 THz, respectively. The results regarding sensitivity, IF bandwidth and LO power requirements are presented, including their performance in the GUSTO instrument in the lab.**

***Keywords*— GUSTO, HEB, lens-antenna, mixer array**

I. Introduction

GUSTO [1] is a NASA balloon borne THz observatory that is led by the University of Arizona and is scheduled to be launched from Antarctica in late 2023 for a flight duration of about 70 days. It aims at unveiling the physical structure and kinematics of star forming regions by mapping three THz fine structure lines: [NII] at 1.46 THz, [CII] at 1.9 THz and [OI] at 4.7 THz; along the galactic plane of Milky Way and a part of the Large Magellanic Cloud. With such detailed information one can unveil the dynamics and processes that dominate regions of star formation [2-3]. To achieve high spectral resolution, it will employ three 8 pixel arrays based on NbN hot electron bolometers (HEBs). Here we present comprehensive characterizations of the HEB mixer arrays developed for GUSTO.

II. HEB Mixers Arrays and Experimental setup

All HEB mixer arrays were designed to allow for eight pixels in a 4×2 configuration within a single metal block. All the pixels in an array share the same basic configuration that is shown in Fig. 1a. For each pixel THz radiation is collected on the surface of the elliptical Si lens. It is then focused, as it propagates through a lens and then an HEB chip substrate, to a spiral antenna, where the radiation is converted to an AC electrical current that is fed to the HEB. Through bonding wires, the HEB is connected to a co-planar waveguide (CPW) line that is used to both DC bias the device and collect the IF signal from the mixer. Each pixel is terminated with an IF connector that acts as the interface to a low noise amplifier (LNA). The lenses and the substrate of the HEB chips are made of pure, highly resistive Si (≥5 kΩ cm). Each HEB chip consists of a NbN bridge integrated with a planar logarithmic spiral antenna [4].

Two models of detector arrays were designed to accommodate the two types of lenses with different diameters. In Fig. 1b we show the completed B1 and B2 arrays, using elliptical Si lenses with 10 mm diameter and having a pitch size of 11 mm. The two arrays make use of

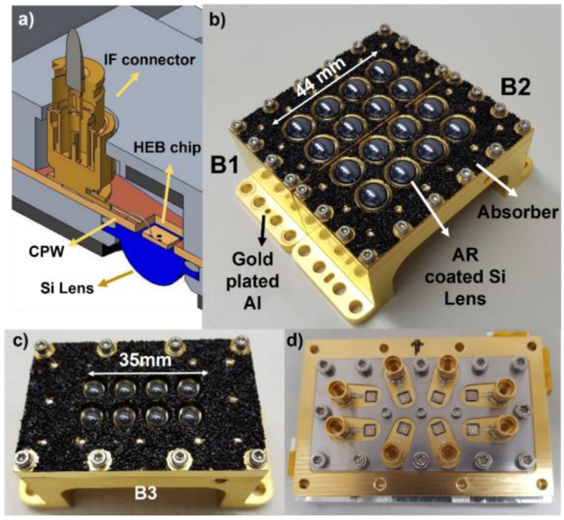

Fig. 1. 4×2 HEB mixer arrays. a) Schematic of the single pixel configuration used in all the arrays. b) Completed B1 and B2 arrays, for operation at 1.46 and 1.9 THz, respectively. c) Completed B3 array designed to operate at 4.7 THz. d) A back side view of the partly assembled B3 array, where the eight HEB chips, CPW lines and IF connectors are shown, from [5].

the same model and were optimized for operation at 1.46 and 1.9 THz, respectively. Because these two frequencies are very close, it is difficult to separate them in the optical path of the instrument. Thus, B1 and B2 were designed to be placed side by side on the cold plate of the cryostat, mimicking a 4×4 array. The devices used have a NbN bridge of 2 µm in width, 0.15 µm in length, and 5 nm in thickness. The critical temperature of the NbN bridges is about 10 K. In Fig. 1c we show the completed B3 array that uses elliptical lenses of 5 mm diameter and has an 8 mm pitch size. This array is optimized for operation at 4.7 THz. In Fig. 1d we present a back side view of the B3 array, while partly assembled, where the eight detector chips, CPW lines and IF connectors are shown. The HEB devices used in this array are similar to the ones used in the other arrays (from the same wafer), however, the NbN bridge lengths are longer, being 0.2 µm instead.

Each of the arrays has a different lens design, optimized to meet the GUSTO optical beam requirements, with details and verification reported elsewhere [4]. The methodology used to mount and align HEB antenna with the lens optical axis has also been described elsewhere [5]. With this methodology we were able to obtain beam pointing errors <0.1 deg relative to the array normal direction.

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We measure the DSB receiver noise temperature (T_{rec}^{DSB}), the receiver conversion loss (L_{rec}^{DSB}), and the required LO power (P_{LO}) for each pixel in the arrays. The IF noise bandwidth (NBW) was measured in the IF frequency range between 0.5 and 5 GHz for a few selected mixers.

T_{rec}^{DSB} of the different pixels in each array were measured at a mixer operating temperature of 4.4 K using a standard air setup and using 1.39, 1.63 or 5.25 THz FIR gas laser lines as LOs, respectively. These frequencies are slightly different from GUSTO's respective B1, B2, and B3 frequencies due to not having the same LOs as GUSTO available at SRON. The IF chain consists of a bias-T and a cryogenic SiGe low noise amplifier (LNA) at 4.2 K. The room temperature part of the IF chain includes two LNAs, a bandpass filter, and a microwave power meter. For T_{rec}^{DSB} measurements the IF was filtered by the bandpass filter centered at 2 GHz. For the noise bandwidth measurements, we replaced the components from the bandpass filter up to the power meter with a spectrum analyzer.

III. Results and Discussion

The T_{rec}^{DSB} is obtained using the Y-factor technique where the Callen-Welton blackbody temperatures are used to correct the physical temperature of both hot and cold load [6]. The L_{rec}^{DSB} is obtained using the U factor technique [7]. The P_{LO} is estimated using the isothermal technique [8]. For GUSTO we are interested in T_{mixer}^{DSB} and L_{mixer}^{DSB} which are defined as the noise temperature and conversion loss, respectively, after correcting for the effect of all optics in front of the Si lens. Additionally we also correct for the difference in frequency between LO used in the measurements and GUSTO target frequency.

To measure the NBW of an HEB mixer in our arrays we repeat the T_{rec}^{DSB} measurements over a wide IF range when it is biased at an optimal operating point. For both a B1 and a B3 pixels, operated at 1.39 and 5.25 THz, respectively, we obtained a NBW of 3.5 GHz.

We summarize the average and standard deviation value of T_{mixer}^{DSB}, L_{mixer}^{DSB} and P_{LO}, for each array in Table 1. Not only the arrays demonstrate a state of the art T_{mixer}^{DSB}, which is in line with the best reported so far in the literature [9-11], but also very good uniformity. For L_{mixer}^{DSB}, we find that it increases with the array operating frequency. Such an increase is confirmed even in the intrinsic L_{mixer}^{DSB} after removing the optical loss of the lens and coupling loss between antenna and HEB. This can be explained by existing artifacts that are present around the gold spiral antenna arms, which may introduce additional ohmic losses to the THz RF current. This effect would be stronger for a higher frequency. In terms of P_{LO} we also see a very good uniformity within a single array. Additionally, we note for the B3 array it is slightly higher than that for B1 and B2 due to the longer HEBs used in the B3 array.

The performance of the arrays in the GUSTO instrument is also shown in Table 1. These values are slightly above what we predicted, which is explained by extra coupling loss due to sidelobe spillover throughout the optics and especially beam vignetting in some optical elements for some of the mixers. The GUSTO instrument is currently undergoing final integration with the Gondola in preparation for the launch in December 2023. During the final commissioning, the ultimate performance can be determined and a more detailed paper on GUSTO's performance will be prepared.

TABLE 1
Performance summary of the three HEB mixer arrays averaged over the 8 pixels in an array. It includes the measured mixer noise temperature (T_{mixer}^{DSB}) and mixer conversion loss (L_{mixer}^{DSB}) at 2 GHz IF, the GUSTO receiver noise temperature ($T_{rec,GUSTO}^{DSB}$), measured at the instrument in the lab. and optimum LO power at HEB (P_{LO}). In parentheses are the standard deviations within the respective array.

Array	Operating Frequency	T_{mixer}^{DSB} (K)	L_{mixer}^{DSB} (dB)	$T_{rec,GUSTO}^{DSB}$ (K)	P_{LO} (nW)
B1	1.46 THz	330 (10)	5.7 (0.6)	≈870	210 (12)
B2	1.9 THz	420 (14)	6.9 (0.7)	≈1100	190 (10)
B3	4.7 THz	700 (26)	9.7 (0.7)	≈1920	240 (15)

IV. Conclusions

We have successfully demonstrated three 4×2 heterodyne HEB arrays for GUSTO, which will be operated at local oscillator frequencies of 1.46, 1.9 and 4.7 THz, respectively. These arrays represent, to date, the highest pixel count using the quasi-optical scheme at supra-THz frequencies. Our results demonstrate the heterodyne arrays with not only excellent sensitivity, but also good uniformity of the performance parameters.

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