Preliminary design study of a 4×2 HEB array at 4.7 THz for GUSTO

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Abstract— Here we report on the design of the 4×2 HEB quasi-optical mixer array at 4.7 THz for GUSTO. Two studies are presented. The first is a statistical analysis of some of the key parameters of HEB devices within a single batch. In a population of 10 randomly selected devices we show a state of the art noise temperature of 720 K at 2.5 THz with only 3 % spread, while at the same time meeting LO uniformity requirement. The second study discusses the impact of different diameter elliptical lens on receiver performance. We conclude that 10 mm lens offers the best performance with the lowest risk to the project. At the same time we confirmed the value of 11.4 for the ξ_{Si} of silicon at 4.2 K. Furthermore, we describe the mixer array mechanical design resulting in a compact monolithic unit.

I. INTRODUCTION

The THz range of frequencies (0.1 to 10 THz) is known to be rich in astronomically important fine atomic/molecular lines. By using high resolution spectroscopic techniques it is possible to determine parameters such as density, temperature and velocity that can help unveil the dynamics and chemical processes that rule star forming regions. Nevertheless, only in the last decades, quantum and superconductive technology developments as well as local oscillator (LO) technology advances, have made it possible to shed some light on these regions. Currently, NbN HEBs are the most suitable mixers for high resolution spectroscopic terahertz astronomy at frequencies above 1 THz. High sensitivity and low LO power requirement make them unique at super terahertz, although the intermediate frequency (IF) bandwidth is still limited. So far, HEBs have been used in a wide range of astronomical observatories in order to observe different lines of terahertz radiation [1]–[3]. The use of multi-pixel receivers instead of a single pixel receiver improves the mapping speed of the telescope significantly. Thus, heterodyne arrays at THz frequencies are now demanded for airborne (SOFIA), balloon borne (STO-2, GUSTO) or possible future satellite (Origin space telescope, OST) THz observatories.

A. GUSTO Science

GUSTO, the Galactic/Extragalactic ULDB Spectroscopic Terahertz Observatory, follows up on the STO-2 mission's successful flight which demonstrated the feasibility of a balloon borne terahertz telescope. GUSTO is a Class D NASA balloon borne observatory mission. The University of Arizona as PI is responsible for the instrument design. The GUSTO platform is planned to be launched from McMurdo, Antarctica, in late 2021 for a flight duration of 100-170 days.

Gusto aims to:

1. Determine the constituents of life cycle of interstellar gas in the Milky Way
2. Witness the formation and destruction of star-forming clouds
3. Understand the dynamics and gas flow to and in the Galactic Center
4. Understand the interplay between star formation, stellar winds and radiation, and the structure of the interstellar medium (ISM) in the Large Magellanic Cloud (LMC)
5. Construct Milky Way and LMC templates for comparison to distant galaxies.

To achieve these goals GUSTO will survey ~124 square degrees of the Milky Way and the Large Magellanic Cloud (LMC) using three highly sensitive 4×2 HEB heterodyne array receivers to detect the 3 brightest interstellar cooling lines: [CII] at 1.9 THz, [OI] at 4.7 THz and [NII] at 1.4 THz.

B. GUSTO instrument description

The GUSTO instrument concept can be found in Fig. 1. The sky-beam from the telescope is split into two beams using a dichroic. The first beam (transmitted) will keep the information for the 1.4 and 1.9 THz channel while the second beam (reflected) will be used to detect the 4.7 THz line. The sky-beams are then reimaged onto 4x2 HEB mixer arrays, one for each channel, in the focal plane. The arrays for 1.4 and 1. 9 THz are placed side by side and therefore image slightly offset parts of the sky. The LO signals are folded into the arrays using beamsplitters, one for 1.4/1.9 THz and one for 4.7 THz. After mixing, the output signal contains the same phase and frequency information as the original sky signal. The output signals from each pixel are amplified in individual cryogenic LNA's and then further processed in the warm IF and spectrometer backend of the instrument.

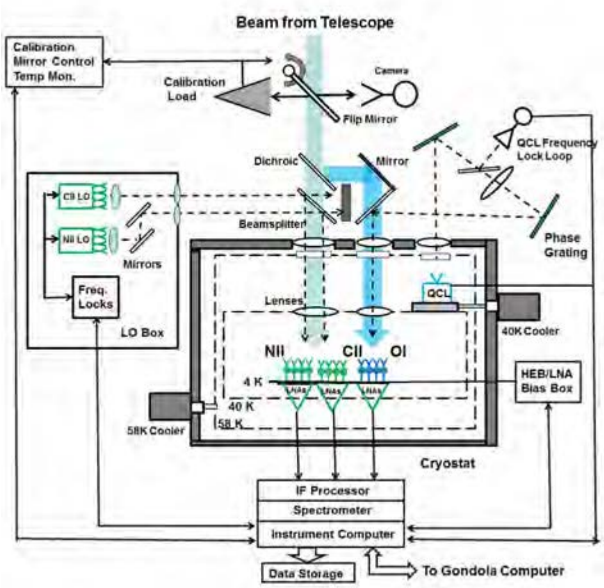

Fig. 1 GUSTO instrument block diagram, which was in the original proposal. It is still in progress with regard to, in particular, the 4.7 THz LO.

In the past, other HEB arrays have been developed [4] but these were designed with each pixel as a separate block. As GUSTO will implement the highest pixel count so far and demands a high level of integration, it requires a compact monolithic design. In addition to the need for device performance uniformity, both in sensitivity and LO requirement, it is also of utter importance to ensure the correct pointing of the individual pixels. Furthermore, because of the high integration level, challenges regarding cross-talk have to be addressed. Conceptually, each pixel will be used in a quasi-optical configuration to couple the radiation from the sky and LO into the HEB, through the use of a lens-antenna system. Each device will then be connected to a transmission line, at the end of which a connector will allow to extract the IF signal and supply dc-bias to the HEB.

For the two lower frequency channels multiplier-chain based solid state LOs will be used. At 4.7 THz it requires the use of a Quantum Cascade Laser (QCL) [5] as LO since this is the only applicable solid state source with enough power at such a high frequency.

In this paper, we will focus on the 4×2 HEB mixer array being designed for the novel array receiver the 4.7 THz channel of GUSTO.

II. PERFORMANCE EVALUATION

Preliminarily to the array design we realized two complementary studies where we evaluated/optimized the future performance of the array. The first study is a statistical analysis of some of the key performance parameters within a batch of devices. The second is trade study of design parameters of the Si lenses against performance.

A. Device performance statistics

In the device selection for GUSTO we aim for the highest possible performance and uniformity while having some flexibility. The selected HEBs, see Fig. 2 (a), are thin superconductive bridges of NbN with 2×0.15 μm^2 dimensions between the pads of tight wound spiral antennas. Such a combination has been shown to have good performance at 4.7 THz [6]. The use of a broadband spiral antenna allows for flexibility since it is possible with a single design to populate all the arrays.

For the device selection several fabrication batches were studied and one preliminary was selected. From this batch, 10 different devices were randomly picked and characterized. The measurements were performed in a vacuum setup at 2.5 THz using AR coated lenses. The measurement setup is similar to the one in [6]. The figures of merit for the evaluation were the sensitivity (noise temperature), the LO power requirement and the uniformity of these parameters among devices. The results are presented in Fig. 2 (b) and (c). The average noise temperature measured was 720 K with a 3% standard deviation. For the LO power requirement an average of 227 nW was measured with a standard deviation of 6%. The sensitivity measured reflects the state of the art, and the LO power requirement is low enough that the expected next generation QCLs will be able to pump the entire array (see next section). Moreover, the low deviation found for both parameters, 3 and 6%, indicates the potential for very uniform arrays.

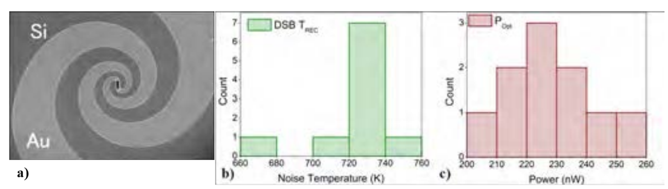

Fig. 2 a) SEM image of a tight wound spiral antenna HEB; B) Measured Noise temperature distribution; c) Measured LO power distribution

B. Lens Study

At high frequencies (>2 THz), the manufacturability of good quality waveguide structures becomes difficult due to the reduced size of the features. Therefore, the use of a quasi-optical coupling becomes the best solution to obtain high sensitivity. In our quasi-optical system, we usually combine an extended 10 mm elliptical lens made of high purity Si with the spiral-antenna present on the HEB chip. While for a single pixel receiver the lens size is not a limitation, when converging to arrays with high pixel count, the spatial footprint can become a problem. The most obvious solution for this is to simply reduce the lens diameter.

In this study two lens diameters, 5 and 3.1 mm, were compared with an existing 10 mm lens (see Fig. 3). These lens were designed as classical elliptical lenses as described in [7].

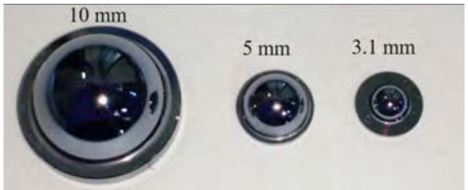

Fig. 3. Si Lens used on the experiments.

The value of ξ_{Si} is one of the parameters required for the design. In the past it has been thought this value at cryogenic temperature to be the same as room temperature, 11.7. However, more recently [8] it has been shown that the correct value should be around 11.4. Since there is still some uncertainty on this matter and we desire to optimize our system, different lenses for each set were designed. For the 5 mm lens we designed four different lenses L1, L2, L3 and L4, designed for a ξ_{Si} of 11.2, 11.3, 11.4 and 11.5 respectively. In the case of the 3.1 mm diameter we designed three lenses, L1, L2 and L3 designed for 11.2, 11.4 and 11.7 ξ_{Si} respectively. The real parameters of these lens were measured and are summarized in Table 1. In the 3.1 mm set we measured some relevant variations on the lens dimensions compared to the design, while for the 5 mm set the measurements matched the design.

Table 1. Measured lens parameters

Diameter	Lens	Ellipticity	Extension (incl. HEB)
10 mm	L1	1.0456	1.582
5 mm	L1	1.0480	0.783
	L2	1.0476	0.779
	L3	1.0468	0.775
	L4	1.0464	0.772
3.1mm	L1	1.0458	0.502
	L2	1.0471	0.498
	L3	1.0477	0.506

To evaluate the lens performance we measured the noise temperature using the same HEB-device for all the measurements. Moreover, a misalignment no bigger than 5 µm in a given direction was achieved, ensuring the performance differences were due to the lenses only. The experimental setup is similar to the one used in the device selection, only this time we used an air setup and no AR coating. As baseline we consider the noise temperature for the 10 mm lens, which best measured value was 1285 ± 25 K. The results for the noise temperature measurements for the other sets of lens can be seen in Fig. 4. For the 3.1 mm set the best noise temperature was measured for L2, with a value of 1447 ± 5 K, while for the 5 mm lens we measured 1368 ± 11 K for L4, although L2 show very similar values. Moreover L3 in the 5 mm set seems to be a clear outlier. For both these set of lenses the best noise temperature is found for designs assuming a ξ_{Si} close to 11.4 as expected. However, since we had some variations in the fabricated lenses, these could shift the real performance of the lenses. Therefore, each lens was simulated in PILRAP, a lens antenna simulation tool for the submillimeter range, using the real lens dimensions. From this tool we used as figure of merit the lens efficiency which is defined as the product of the multiple efficiencies within the lens (e.g. spillover, aperture, etc). For the simulations we assumed the real lenses dimensions and tested different dielectric values, founding that the best value that matched our experimental results was 11.4 confirming the previous conclusions. The curves for the simulated efficiency are plotted in blue in Fig. 4.

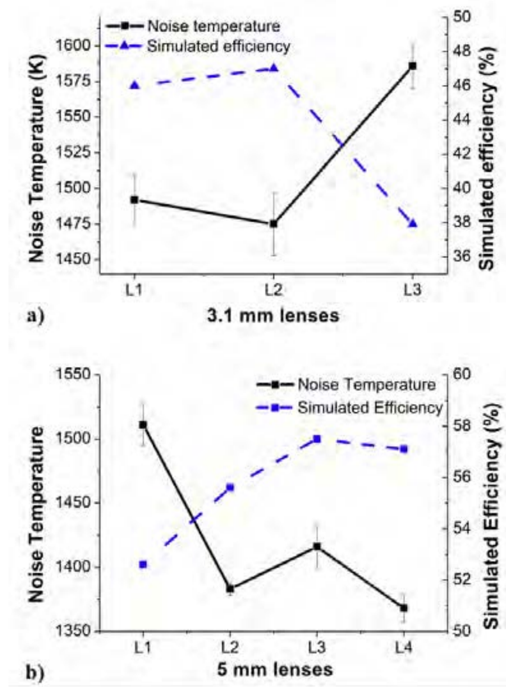

Fig. 4. Noise temperature measurements and PILRAP efficiency simulations. a)3.1 mm lenses. b) 5 mm lenses.

Besides knowing which dielectric value should be used in the design process, it is also important to know what are the tolerances acceptable in the fabrication. For the 3.1mm lenses we can see that a deviation on the extension of 5 µm can have a very big impact on the noise temperature (7%) increase while for the 5 mm lenses the variation between L2 and L4 in relationship to L3 is also 5 µm and we see a maximum absolute difference from the best (L4) of 4% (L3). Therefore drawing the conclusion that the bigger the lens the more tolerant to fabrication errors.

In Fig. 5 we compare the best lens for each set in terms of noise temperature and the predicted lens efficiency for that specific lens. To avoid confusion it should be noticed that a perfect rescaling of the same lens design has the same lens efficiency. Looking at the noise temperature measurements we see a clear trend where the noise temperature increases as the diameter is reduced. On the other hand the predicted efficiency doesn't match this behavior and seems to be decoupled from the lens diameter in study. Based on this, and because there is a clear difference on the noise temperature between sets, some other effect must be in play. When studying what is affected by the rescaling of lenses it was found the lens diameter affects the beam pattern. The smaller the lens the wider the beam pattern becomes. A hypothesis is that the noise temperature increase might have to do with the side lobes coupling improperly to the calibration loads (e.g. the side lobes are always looking at a cold or hot load). Therefore, for the smaller diameter, we should see the widest beam pattern and worse performance, matching the measurements. Further measurements should be performed minimizing the poor coupling of side lobes in order to verify this hypothesis.

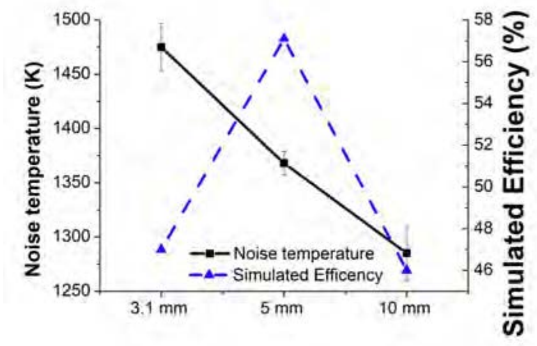

Fig. 5 Comparison of the best lens of each set and respective predicted efficiency.

Since we aim to implement eight pixel arrays, a relative low count, and the smaller lens diameter needs further study, due to the timeline it is chosen to fly 10 m lens as baseline. This choice reduces the risk for the mission since this diameter yielded the best performance from the different sets studied, and will allow to keep the relative fabrication error at the lowest possible. Furthermore this size has been flown previously in STO-2, with good flight performance. Moreover, based on our results, we will assume 11.4 ξSi for the baseline design.

III. THE 4×2 HEB MIXER ARRAY DESIGN

The mixer array is designed as an eight pixel array in a 4×2 configuration. The 4.7 THz HEB array is going to share the same architecture with the other two lower frequency arrays in order to reduce the development time.

The preliminary array design can be seen in Fig. 6 (a) represents the fully assembled array as it will be placed on the cold plate. The main requirements determining the design are as follow: 1) 4×2 pixel configuration; 2) 10 mm diameter Si lenses; 3) 12 mm pitch size between each individual pixel; 4) side by side placement of the two lower frequency channels while maintaining the pitch size, emulating a 4x4 array; 5) optical and IF path as similar as possible for all the pixels. 6) minimized optical and electrical crosstalk. 7) mechanical stability.

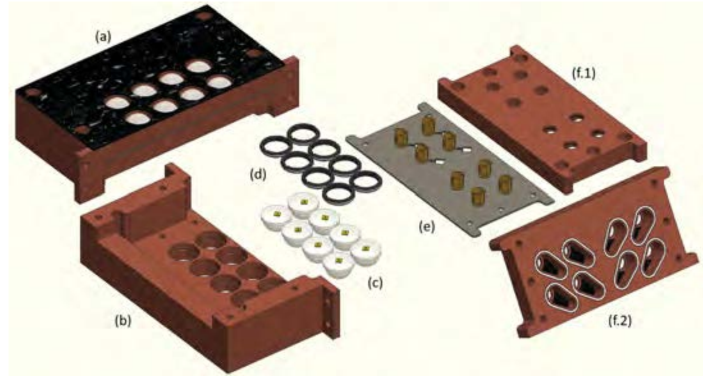

Fig. 6 GUSTO 4x2 HEB mixer array mechanical design

The copper piece identified as (a-front, b-back) in Fig. 6 is the array housing. It is the core structure of the array and defines the placement of the pixels. It will be coated with a layer of stycast mixed with SiC grains to reduce reflections. In this piece eight 10 mm Si lenses (c) will be placed with pre-aligned HEB chips and locked in place with retainer rings seen in (d). On the back of the lenses and covering them, a common PCB (e) is placed having eight independent co-planar waveguide (CPW) transmission lines and respective connectors. The devices will be connected to the CPW lines using bond wires. On top of the PCB another copper part (f.1-back, f.2-front) will be placed with the function to isolate each pixel electrically and optically. For this a spiral shield ring will be used (white in f.2) around the area of each CPW to create a faraday cage that avoids radiation to leak into adjacent pixels. In this same piece 8 stycast/SiC layers (black material in f.2) will be put to absorb any radiation that is not directly coupled into the HEB, reducing the potential for optical cross-talk in the array.

IV. SUMMARY

In this paper we have summarized the preliminary design study for the 4×2 HEB array receiver being developed for GUSTO.
We discussed the study regarding HEB device performance statistics which yielded state of the art sensitivity of 720 K at 2.5 THz, low LO power requirement of 227 nW and very good uniformity of 3 and 6% standard deviation respectively, thus matching the requirements for the array performance. Furthermore a lens optimization study was conducted from which we concluded to choose to fly 10 mm lens instead of smaller diameter lenses. These lenses showed the best performance from the set of lenses measured and are expected to the most tolerant to fabrication deviations. Moreover the smaller diameter lens needs more research before being properly understood. Furthermore, the experimental data indicates the correct ξ_{Si} at cryogenics to be 11.4.
For the 4x2 HEB mixer array we introduced the mechanical design required to support 8 pixels in a 4 by 2 configuration and with a 12 mm pitch size. It will use a quasi-optical configuration with the pre-selected 10 mm elliptical Si lenses.

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