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4×2 HEB receiver at 4.7 THz for GUSTO

J. R. G. Silva*[a,b], B. Mirzaei[c], W. Laauwen[a], N. More[a], A. Young[d], C. Kulesa[d], C. Walker[d], A. Khalatpour[e], Q. Hu[e], C. Groppi[f], J. R. Gao[a,c]

[a]SRON Netherlands Institute for Space Research, Groningen/Utrecht, the Netherlands; [b] Kapteyn Astronomical Institute, University of Groningen, Groningen, The Netherlands ; [c]Kavli Institute of NanoScience, Delft University of Technology, Delft, the Netherlands; [d]Steward Observatory, 933 N Cherry Ave., Rm N204, University of Arizona, Tucson, Arizona 85721, USA [e]Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts 02139, USA; [f]School of Earth and Space Exploration, Arizona State University, AZ, USA;

ABSTRACT

GUSTO will be a NASA balloon borne terahertz observatory to be launched from Antarctica in late 2021 for a flight duration of 100-170 days. It aims at reviewing the life cycle of interstellar medium of our galaxy by simultaneously mapping the three brightest interstellar cooling lines: [OI] at 4.7 THz, [CII] at 1.9 THz, and [NII] at 1.4 THz; along 124 degrees of the galactic plane and through a part of the Large Magellanic Cloud. It will use three arrays of 4x2 mixers based on NbN hot electron bolometers (HEBs), which are currently the most sensitive mixers for high resolution spectroscopic astronomy at these frequencies.

Here we report on the design of a novel 4.7 THz receiver for GUSTO. The receiver consists mainly of two subsystems: a 4×2 HEB quasi-optical mixer array and a 4.7 THz multi-beam LO. We describe the mixer array, which is designed as a compact monolithic unit. We show, for example, 10 potential HEB detectors with the state of the art sensitivity of 720 K measured at 2.5 THz. They have a variation in sensitivity smaller than 3%, while also meeting the LO uniformity requirements. For the multi-beam LO we demonstrate the combination of a phase grating and a single QCL at 4.7 THz, which generates 8 sub-LO beams, where the phase grating shows an efficiency of 75%. A preliminary concept for the integrated LO unit, including QCL, phase grating and beam matching optics is presented.

Keywords: Astronomy, GUSTO, heterodyne, hot electron bolometer, phase grating , quantum cascade laser, terahertz

1. INTRODUCTION

1.1 GUSTO Science

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 allowed for shedding some light about 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 diverse types of astronomic telescopes 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.

GUSTO, the Galactic/Extragalactic ULDB Spectroscopic Terahertz Observatory, follows 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

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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 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.

1.2 GUSTO instrument description

The GUSTO instrument concept can be found in Figure 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.

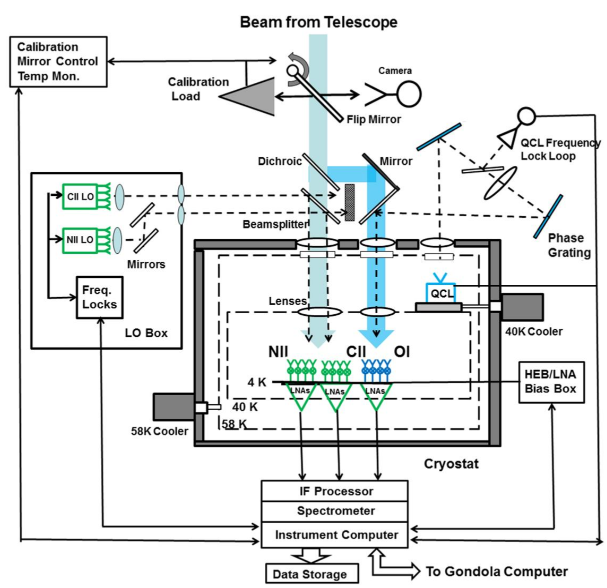

Figure 1. GUSTO instrument block diagram, which was in the original proposal. It is still in progress with regard to, in particular, the 4.7 THz LO

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.

Because each pixel requires a signal from an LO, for a given array we need multiple LO signals, generated from the same reference in order to share the same frequency and phase. 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. However, the use of a QCL induces major challenges regarding to the generation of multiple LO beams. Using multiple QCLs to pump the HEB array is essentially ruled out because of the cryogenic footprint. Furthermore, it's very challenging to achieve the same frequency among different QCLs, besides the complexity of phase or frequency locking of such a system. Therefore, it requires a solution to generate multiple beams from a single QCL. There are two ways to do so: defocused LO [6], [7] or multiplexed LO [8]. Because of the limited output power of QCLs at 4.7 THz the first option is not wise to take since a considerable portion of the beam power would not couple into the devices. Thus, the best way to tackle our problem is to multiplex the LO beam into sub beams using a Phase Grating, whose surface structure modulates the phase of the incoming beam by means of constructive and destructive interference, allowing to obtain the desired 4×2 far-field beam pattern. Nonetheless, the combination of a Phase Grating with a QCL also brings new challenges regarding to the beam matching optics between the LO and the arrays that needs to be addressed.

In this paper, we will focus on the novel array receiver design being developed for the 4.7 THz channel, which can be divided into two integrated subsystems: the 4×2 HEB mixer array and the 4.7 THz multi-beam LO.

2. THE 4.7 THZ ARRAY RECEIVER FOR GUSTO

2.1 The 4×2 HEB mixer array

The mixer array architecture is being designed for eight pixels per 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. 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.

The preliminary array design can be seen in Figure 2. (a) represents the full assembled array as it will be placed in the cold plate. The main requirements ruling the design are as following: 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, 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.

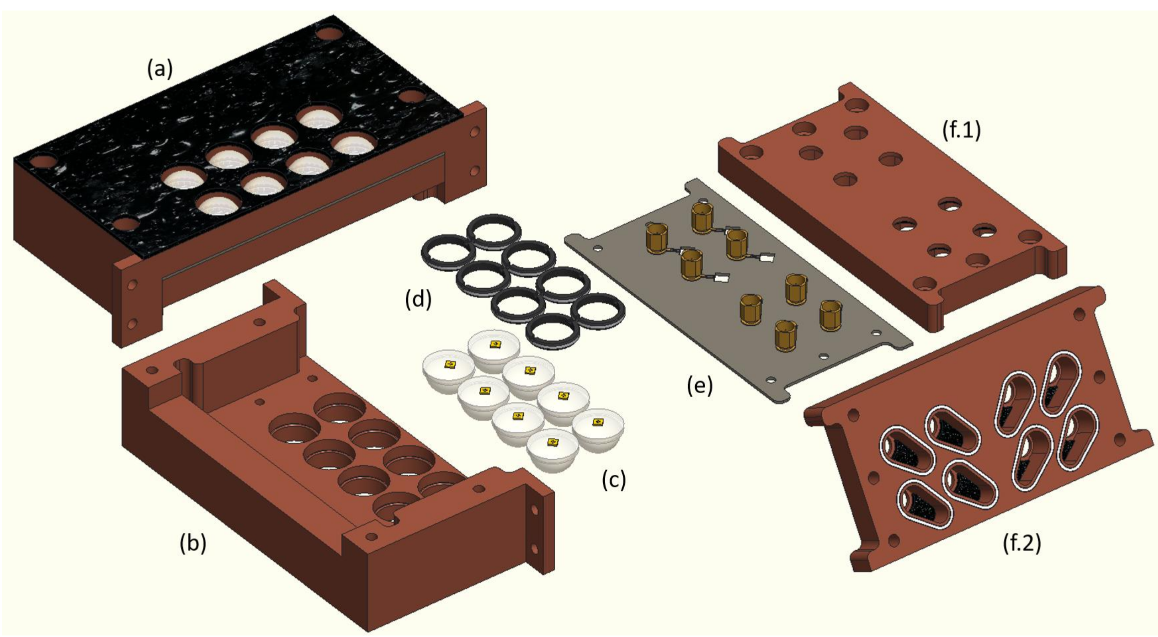

Figure 2. GUSTO 4x2 HEB mixer array mechanical design

The copper piece identified as (b) in Figure 2 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 a 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) (f.2) 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.

HEB mixers

In the device selection for GUSTO we aim for the highest possible performance and uniformity while having some flexibility. The selected HEBs, see Figure 3 (a), are thin superconductive bridges of NbN with $2\times0.2\ \mu m^2$ dimensions between the pads of tight wound spiral antennas. Such a combination has been shown to have good performance at 4.7 THz [9]. 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 [9]. 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 Figure 3 (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. The IF bandwidth is expected to be similar to previous devices which is around 4 GHz [9]. This is still the biggest limitation for operation at 4.7 THz since for higher frequencies of operation and the same IF bandwidth, the effective bandwidth drops. There are reports of new HEB developments using superconductor bridge of MgB2, which are able to extend the IF bandwidth up to 11 GHz [10] at the cost of sensitivity and higher LO power requirement. Furthermore, recently it has been reported the use of NbN HEBs on a Si substrate with a GaN buffer-layer that increase the bandwidth up to 7 GHz [11]. Both solutions are not yet at a point of maturity for a flight mission but are interesting for the future.

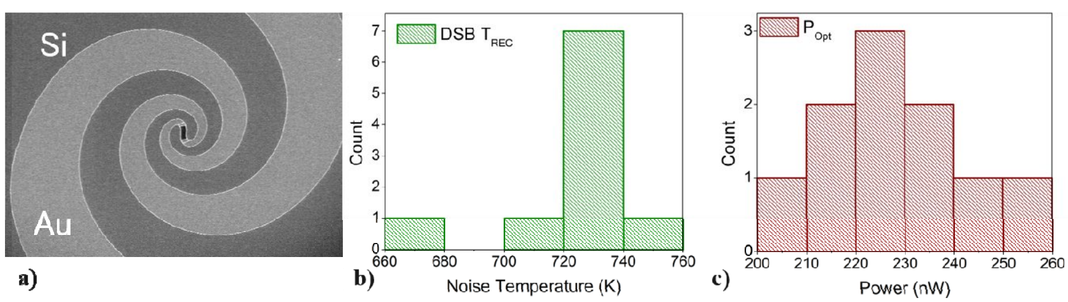

Figure 3 a) SEM image of a tight wound spiral antenna HEB; B) Measured Noise temperature distribution; c) Measured LO power distribution

The lenses

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 combine an extended 10 mm elliptical lens made of high purity SI with the spiral-antenna present on the HEB chip. The lens shape is designed as described in [12] which for ξ_{Si} of 11.4 [13] and 10 mm diameter gives an ellipticity of 1.047 and a total extension (including HEB substrate) of 1.55 mm.

In order to validate the design and predict the behavior of these lenses, the simulation tool PILRAP was used [14]. This tool was developed in order to simulate custom lens-antenna systems in the submillimeter range. Despite PILRAP's challenges to simulate a spiral antenna, it has been demonstrated that the measured far-field beam pattern of a lens-spiral antenna matches very well with the predictions for the same lens with a twin-slot antenna [9]. For the simulations a twin slot with a slot length of 0.2847λ, slot separation of 0.1633λ and slot width of 0.0233λ at 4.75 THz were considered. Based on the simulations without taking into account the AR coating, the expected beam waist is 3.83mm, the waist location 17.52 mm from the lens apex in the direction of the elliptical part, and a Gaussian beam efficiency of 86%. The far-field beam pattern is plotted in Figure 4. Based on these results, we expect a high Gaussian beam component and very collimated beam pattern.

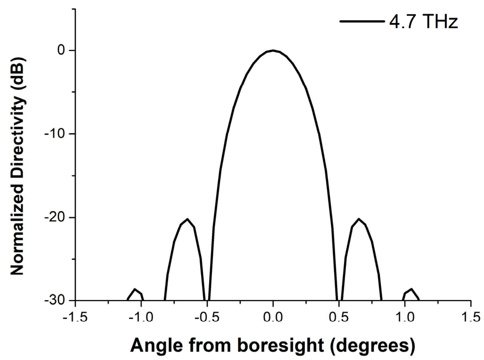

Figure 4. 10 mm lens far-field beam pattern simulated at 4.7 THz assuming a twin slot instead of the spiral antenna in practice.

2.2 4.7 THz multi-beam LO

The 4.7 THz LO for GUSTO is based on two key elements: a QCL and a phase grating. In this system, the phase grating structure is engineered in such a way that from a single incident coherent QCL beam, we are able to generate 4x2 beams in the far-field matching the array. Such multi-beam LO scheme has been successfully demonstrated at 1.9 THz for 7 beams[4] and at 4.7 THz for 8 beams [15].

QCL technology

A QCL is a type of laser that makes use of intersubband transitions in a repeated structure of quantum well heterostructures tuned to emit at given frequency. The current generation of LO-qualified THz QCLs, such as the third order DFB QCLs [16], have been used to pump single pixel HEBs,[17] but doing the same with an entire array will be very difficult. The main reasons for this are the highly non-Gaussian and divergent beam pattern that reduces the usable power. Therefore, GUSTO demands a QCL with high power in the continuous-mode operation (>1 mW), tight beam pattern and single mode emission. Such technology is presently being developed by MIT, with progress on the power level and beam pattern recently reported [18]. In **Figure 5** we compare the beam pattern from an old QCL (a) and a first prototype of the new generation of QCLs (b). There is a clear improvement on the beam pattern, now more concentrated.

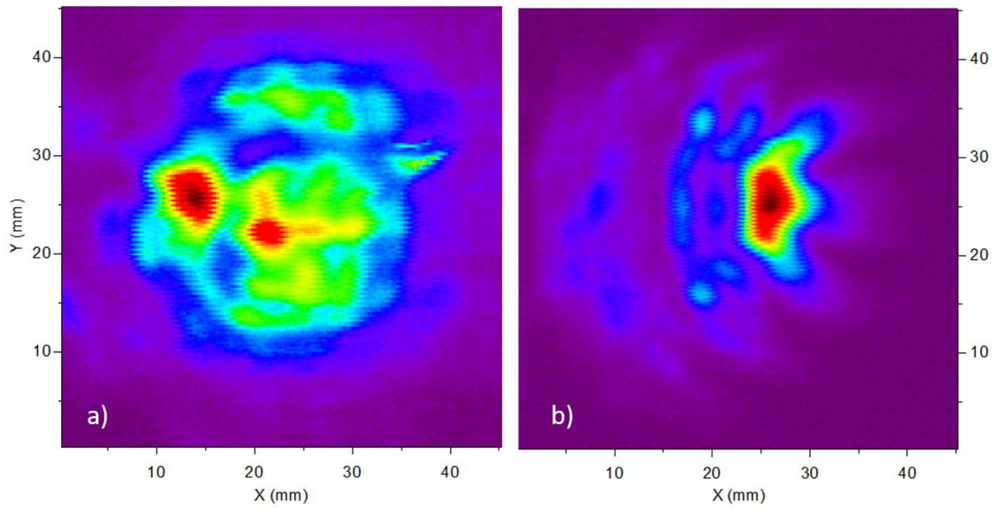

Figure 5. QCL beam pattern comparison. a) old QCL. b) new generation QCL prototype**.**

Phase Grating

A phase grating is a periodic arrangement of a unit cell with a specific surface morphology, determined by the Fourier series and based on a limited number of Fourier Coefficients (FCs), which modulates the phase of the incoming coherent beam [6]. Such a surface profile determines the intensity distribution among the diffracted beams, their angular configuration, and the diffraction efficiency. Because the THz regime still has relatively long wavelengths such an optical element can be machined using a CNC machine.

A prototype phase grating was developed for 4.7 THz. First we calculated the two sets of FCs to obtain the 2D profiles needed for beam multiplexing by 4 and by 2 using a MATLAB algorithm. Secondly these were further optimized using a genetic algorithm in order to guarantee a global optimization of the problem, yielding maximum efficiency. Finally, the FCs are orthogonally superimposed to make the surface morphology of a rectangular 8 beam grating. 13 FCs were considered and a total surface area of 3x3 cm^2 was machined having each unit cell 1.2×1.2 mm^2. The grating is designed for operation centered at 4.7 THz with 25˚ incident angle with respect to the normal. Figure 6 presents a 3D visualization of a part of the grating together with the calculated and manufactured profiles.

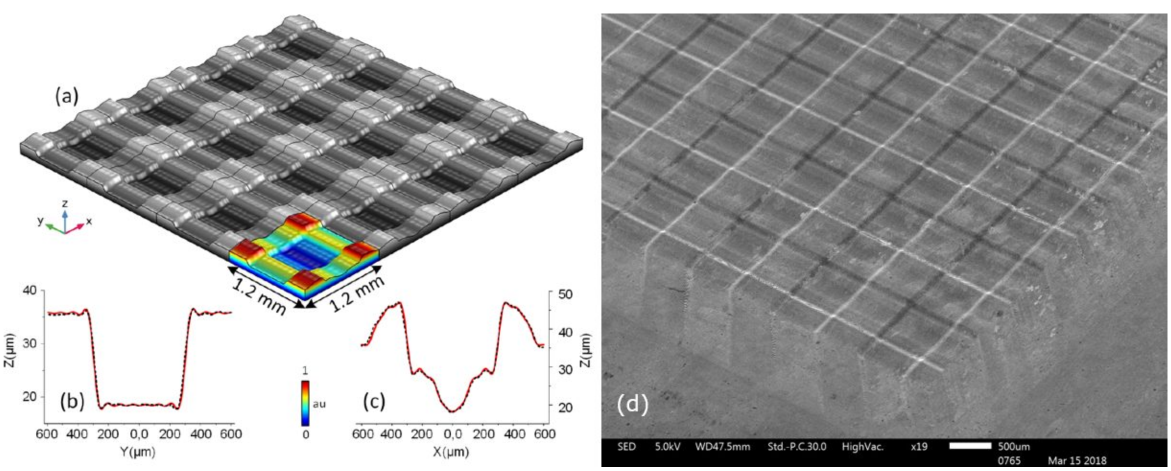

Figure 6. (a) 3D drawing of 16 unit cells of the phase grating. A single unit cell is shown in color. The height is out of scale for clarity, (b,c) the calculated and manufactured 2D cross-section profiles of a unit cell. Z shows the height, and X and Y are the two lateral directions. The dashed black and solid red curves are the manufactured and calculated results. (d) SEM image of the grating, credits to Marcel Ridder.

Multi-beam LO at 4.7 THz

To demonstrate a multi-beam LO at 4.7 THz, we combined an old generation third order DFB QCL with the phase grating prototype. The QCL used operates in single mode at 4.756 THz, with this frequency chosen mainly because of the relative low water absorption in air. The power output of this QCL was expected to be around 0.25 mW.

To characterize the far-field beam pattern of both QCL and phase grating outputs, a room temperature pyro-electric detector with an aperture of 2 mm, mounted on a X-Y stage was used. The QCL beam besides being highly divergent has a very non-uniform pattern as shown in **Figure 5**(a), making it impractical to be directly used in our system. Therefore, we have introduced a spatial mode filter presented in Figure 7 (a). After the beam passes through this filter we obtain the far-field beam pattern as seen in Figure 7 (b) and the phase grating diffraction pattern is presented in Figure 7 (c). The diffraction meets expectations with a 6 degrees angular separation between adjacent beams. Moreover, each individual beam is almost a perfect mirrored copy of the incoming beam. We measured an efficiency of 74.3%, which is a close match to the 75.4% predicted by the 3D simulations using COMSOL. Nevertheless, it is also crucial to study the beam uniformity. By measuring the power in each individual diffracted beam in Figure 7 (c) and comparing to the original incoming beam we have, starting from the top to bottom, on left column 9%, 10.4%, 9.5%, 8.6% while for the right column 8.6%, 10.3%, 9.3% and 8.4%. Based on these results we have a 21% variation between two extremes. Although the inter-beam variation is high, based on our experimental data we see less than 4% degradation in device performance for such LO power variations[15]. Therefore we conclude that this multi-beam LO can pump a uniform HEB array without compromising its sensitivity. More details on both the QCL and phase grating can be found in [15].

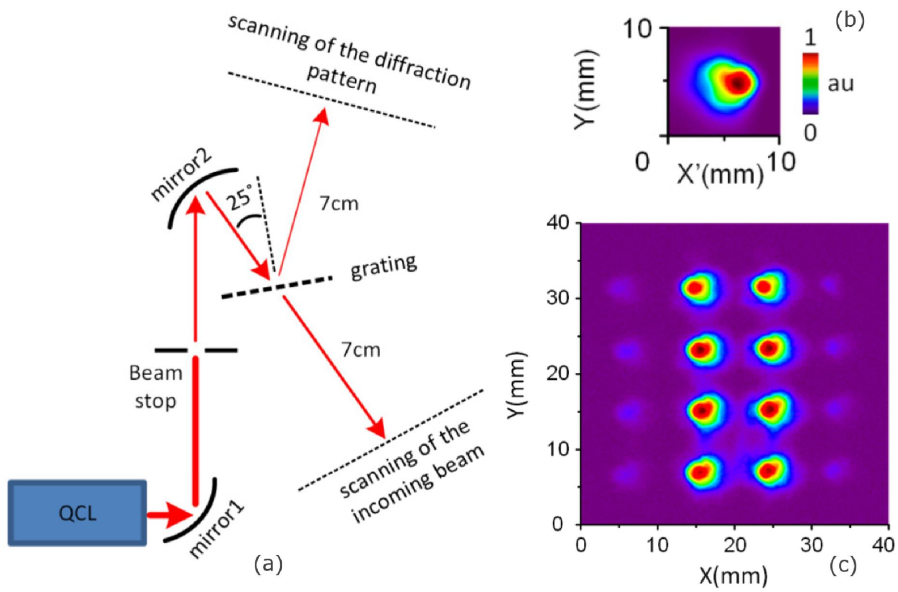

Figure 7 (a) Optical Setup for collimation and filtering the 4.7 THz QCL beam. The line thickness is an indication of the intensity. (b) Incoming collimated beam to the grating. (c) Measured diffraction pattern

To test the performance of the designed multi-beam LO system, we performed an experiment where we used one of the eight diffracted beams to pump an HEB mixer. We calculated that we could illuminate the grating with only 9 μW of power because of the highly constrained optical path and air absorption between the QCL and the grating. Additionally, another beam stop was used to select only a single diffracted beam, followed by an HDPE lens to direct the radiation into the device lens, increasing the losses on the optical path. With this setup we successfully pumped the HEB with 50 nW of power, which is derived from the pumped IV characteristics using the isothermal technique [19]. Based on this experiment and considering some assumptions [15] we estimate a requirement of 1 mW power from a QCL in order to pump an eight pixel array using the selected HEB devices.

Integrated design for GUSTO

GUSTO requires a 4.7 THz LO unit, integrated with a QCL and phase grating. Furthermore, the output beams of the grating should be matched to those of the HEB array. There are two main challenges to realize: spatial filtering of the QCL beam and matching the diffracted beams from the grating into the array. For the beam correction of the QCL we expect to use a similar optical scheme as presented above. In terms of the beam matching between the diffracted beams and the array, the challenge lies in the angular offset that each diffracted beam has, leading to the beam pattern getting wider as the radiation travels in free space. A possible way to correct for this effect is to make use of an off-axis parabola mirror after the grating that will bring all the beams into a less divergent pattern. Assuming the input beam on the grating is collimated, the use of this mirror would introduce an extra focusing effect to each beam, which is based on the current prototype and expected distance between the LO unit and the array would create a focus at the wrong location, not matching the one of the lens-antenna system. Consequently, another mirror is required before the phase grating. With this two mirror system it would be possible to obtain a beam pattern with parallel beams, tuned to match the array pitch size, beam waists and waist locations. The concept of the optical path described above is presented in Figure 8. Another important element in this LO unit is the use of a voice coil [20] to stabilize the LO amplitude wise, increasing the Allan time of the system. Because it's not of the scope of this paper we omitted the phase locking subsystem, although the concept for it can be found in [9].

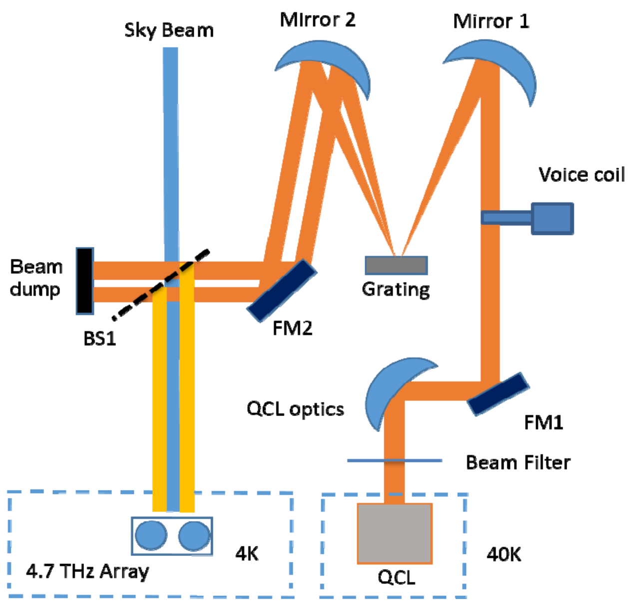

Figure 8. Optical path concept for the 4.7 THz multi-beam LO unit for GUSTO

3. SUMMARY

In this paper we summarized the 4.7 THz array receiver being developed for GUSTO. Two of the three subsystems are discussed: the 4x2 HEB mixer array and the 4.7 THz LO unit.

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 10 mm elliptical Si lenses. We also reported on HEB device selection, which yields the 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. The Si lens design is also simulated, resulting in a highly collimated beam and high Gaussian beam efficiency of 86%.

For the multi-beam 4.7 THz LO we demonstrated an optical scheme that combines the use of a QCL with a phase grating at 4.7 THz, resulting in a diffracted beam pattern of 8 beams with an efficiency of ~75%. We also demonstrated the feasibility of pumping HEBs using the diffracted beams although more powerful QCLs are required. Finally, a concept is presented to integrate the QCL and phase grating with two parabolic mirrors into a single unit that achieves beam matching between the LO and the array.

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