Development of a Phase-modulating Beam Multiplexer for a THz Local Oscillator

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***Abstract*— We propose a novel approach to multiplex a single Gaussian beam from a THz source into seven beams arranged in a hexagonal configuration, matching an array of Hot Electron Bolometer (HEB) mixers. This configuration is necessary for the High-Resolution Receiver (HiRX) instrument on the proposed NASA Single Aperture Large Telescope for Universe Studies (SALTUS) space mission. The beam splitter relies on a reflector that introduces a phase shift to the incident Gaussian beam; after propagation, the desired amplitude distribution is achieved at the mixer array plane. Unlike existing THz multiplexers, our method does not use a phase grating based on the repetition of a unit cell. Instead, we employ an iterative phase reconstruction (Gerchberg-Saxton) algorithm to retrieve the required phase shift. This paper discusses the scientific motivation, current state of the art, design methodology, simulation outcomes, and experimental validation of the reflector.**

***Keywords*— Heterodyne, Local Oscillator, mixer array, multiplexer, phase retrieval, SALTUS.**

I. INTRODUCTION

ELECTROMAGNETIC radiation is exploited for the most different purposes, from medical imaging to information transmission, from renewable energy to optical sensing. To fully characterize electromagnetic waves, both amplitude and phase must be considered. Amplitude determines brightness, while phase describes the wave's position in its oscillation cycle. Measurement setups rely on translating wave information into an electric, mechanical, thermal or chemical signal. In most cases, the response time of physical devices is too slow to keep up with the rapid changes of a system it is intended to monitor. Detectors average out the rapidly oscillating wavefront over time; the output is its average intensity over the measurement period. In this process, the phase information, which encodes the precise timing and spatial variation of the wave oscillations, is unavoidably lost. The result is that many of those cutting-edge technologies that leverage electromagnetic radiation for the most ambitious goals are still using just half of the information that waves carry. The problem complicates if such waves are in the "Terahertz gap", laying in the range between microwave and infrared, where the realms of electronics and optics overlap. Implementing technologies for generating and detecting Terahertz radiation is particularly challenging [1]. However, the pace of progress in THz technology has accelerated significantly in recent years, witnessing innovative laser sources and highly sensitive detectors. The initial aim of this project was the development of a reflective Fourier grating to generate a THz local oscillator with seven uniform beams. However, after delving more deeply into the topic, we decided to undertake a different route. The idea is to explore a novel way to manipulate radiation, exploiting the relatively simple principles of phase reconstruction and reflection. The challenge is that two still relatively unexplored worlds, that of phase retrieval techniques and that of Terahertz radiation, are meeting. The drive is that, if a proof of concept is obtained, we propose a simple, general yet powerful method which can be exploited for a wide range of applications. Thus, the implementation of our beam multiplexer is not just a fulfillment by itself, but it also tests the feasibility of a broad technique to manipulate electromagnetic fields.

II. SCIENTIFIC MOTIVATION

The terahertz spectral region is essential for understanding star formation and the composition of dense interstellar clouds; the latter contain ionized atoms and complex molecules, detectable through their emission and absorption lines. Mapping these spectral lines provides insights into the structure, temperature, density, and chemical composition of astrophysical objects [2]. SALTUS (Single Aperture Large Telescope for Universe Studies) is a mission proposed to NASA, designed to address these scientific challenges by deploying a far-IR space observatory [3]. If accepted, the launch is scheduled currently in 2031. The mission aims to explore the evolution of galaxies and their supermassive black holes, trace the formation of cosmic structures, and evaluate habitability by mapping astrochemical signatures in protoplanetary disks. SALTUS will employ a 14-meter inflatable, lightweight telescope achieving arcsecond-scale angular resolution, a record for far-IR space observatories. This high-resolution capability is crucial for overcoming the spatial confusion limit, where densely packed celestial sources blur together.

The High-Resolution Receiver (HiRX) instrument on board of SALTUS [4] will include cryogenic heterodyne receivers across four frequency bands: Band 1 (455-575 GHz), Band 2 (1.1-2.1 THz), Band 3 (2.475-2.875 THz), and Band 4 (4.744 and 5.35 THz). The HiRX instrument is designed to detect and resolve significant astrophysical lines, such as those from water

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and deuterium hydride (HD), with a high spectral resolution (ranging from 10^5 to 10^7). To detect faint signals from distant sources, high-sensitivity and high-resolution technologies like heterodyne receivers are essential. Such receivers can bring unprecedented spectral resolution ($\nu/\Delta\nu > 10^7$), providing information about the type of emitter, as well as the temperature, density, and motion of gases [2]. Their working principle relies on down-converting the THz signal to the GHz range, where low-noise amplifiers are available, by mixing it with a Local Oscillator (LO) signal. Bands 2 to 4 will use superconducting Hot Electron Bolometers (HEBs), which offer coherent detection with low noise levels and no upper frequency limit. To increase mapping speed, multiple pixels can be simultaneously employed. Band 4 in the HiRX instrument includes a seven-pixel array arranged in a hexagonal pattern, with one pixel in the middle. Due to difficulties in achieving the same frequency from all Quantum Cascade Laser (QCL) sources and due to power dissipation, it is necessary to use a single QCL and distribute its output into multiple beams.

The goal of this project is to develop a beam multiplexer to split one incoming THz beam from a single source onto multiple detectors, ensuring a high efficiency, equal power distribution, and Gaussian-shaped beams. The design will focus on two frequencies: 4.7 THz, required for the mission, and 1.627 THz, for a proof of the concept purpose.

III. A NOVEL APPROACH

Commonly, phase gratings (Fig.1) are employed in heterodyne receiver systems as LO beam multiplexers [5].

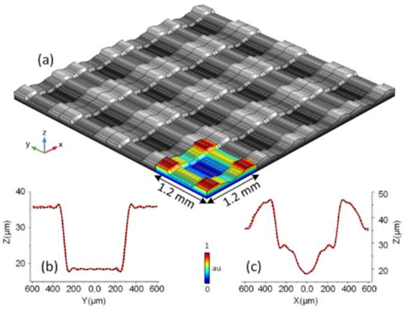

Fig. 1. (a) 3D drawing of 16 unit cells of a phase grating realized for a 4.7 THz source (height is out of scale) [6]. The unit cell is in color. (b)(c) Calculated and manufactured 2D cross sections of a unit cell along x and y directions. The dashed black and solid red curves are the manufactured and calculated profiles respectively.

Such reflective devices are based on the periodic repetition of a single unit cell. Based on diffraction, a beam incident on the grating is split among multiple orders; the size of the unit cells determines the angular separation between modes, while its shape affects power distribution. So-called "pseudo-2D" phase gratings, obtained by orthogonally superimposing two 1D gratings, can only generate rectangular patterns [7]; moreover, a fraction of the input power is unavoidably lost in unwanted diffraction modes.

In this project, we explore a novel approach to design a beam multiplexer by dropping the periodicity assumption on which phase gratings rely. The goal is to design a reflector which induces a position-dependent phase shift to the incident wavefront; after reflection and subsequent propagation, the desired amplitude is obtained at a specified distance from the reflector. If the surface is designed properly, the target distribution at the mixer array plane is achieved without additional collimating optics. This method aims to minimize power in unwanted modes and demonstrate that phase reconstruction can be a powerful and general tool for manipulating radiation for various applications.

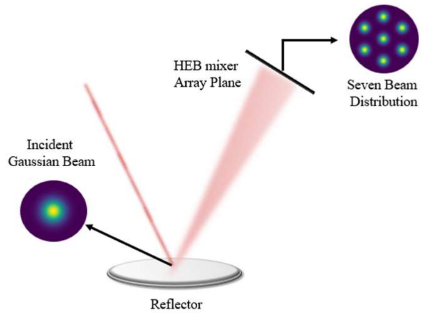

Fig. 2. Working principle of the reflector. The incident beam acquires a position-dependent phase shift through reflection by the surface; after propagation, the seven-beam amplitude is obtained at the HEB mixer array.

IV. DESIGN AND SIMULATION

The design of the surface lies in determining the necessary phase shift to apply to the initial wavefront; this translates into solving a phase retrieval problem [8]. When an electromagnetic wave reflects off the surface, each point on the wavefront undergoes a different optical path, resulting in a position-dependent phase shift. By carefully controlling this phase shift, the reflected wave can be manipulated to produce a desired far-field pattern, in this case, seven Gaussian beams at the HEB mixer array. To recover the required phase information, various computational techniques can be employed. One common approach is the use of iterative algorithms that update an initial estimate of the phase based on measured amplitude data and some prior knowledge or constraints. These algorithms aim to minimize a cost function that quantifies the discrepancy between the measured and reconstructed wave. The Gerchberg-Saxton (GS) algorithm (Fig.3) is a widely used method for phase retrieval [9]; an initial guess of the phase at the initial

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plane is multiplied by the constrained initial beam amplitude. The resulting field is propagated to the image plane by performing a Fourier transform, resulting in a complex field. The amplitude of this complex field is then replaced by the desired target amplitude while keeping the phase component unchanged. An inverse Fourier transform is applied to return to the initial plane, and the process is repeated iteratively.

The algorithm converges when the difference between the target intensity distribution and the current one is minimized.

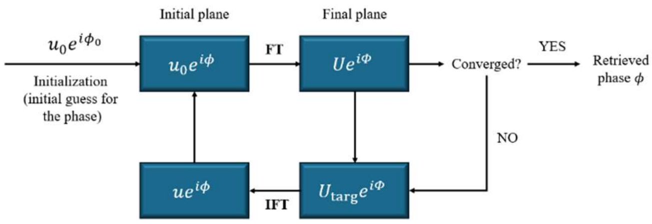

Fig. 3. Flow diagram of the principle of the Gerchberg-Saxton algorithm.

Such method was implemented on Python. The initial single Gaussian beam amplitude and the target seven-beam amplitude were defined as constraints in the algorithm. After convergence, phase patterns were obtained; adding such phase shifts to an incident Gaussian amplitude and propagating it for 10 cm yields amplitude distributions similar to Fig.4.

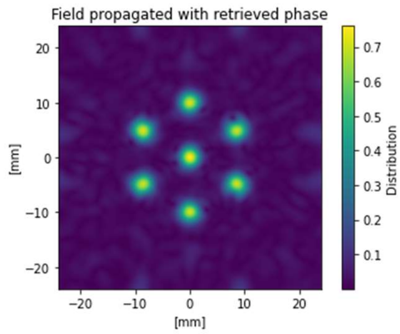

Fig. 4. Seven-beam distribution obtained by adding the position-dependent phase shift to the single Gaussian beam distribution and propagating it for 10 cm (1.627 THz).

The simulated efficiency, i.e. the ratio between the power inside the seven beams and the overall power, for the 1.627 THz and the 4.7 THz reflectors, is 62.6 % and 71% respectively.

To translate phase information into a surface profile, we can apply the ray optics relation $d = \lambda \Delta\phi / (4\pi \cos\theta)$, where d is the reflector groove depth, $\Delta\phi$ is the phase modulation, λ is the working wavelength and θ is the angle of beam incidence. The latter must be considered so that elements in the experimental setup do not block the beam path and the laser emitting source and the detector don't overlap. 3D plots of the reflectors are shown in Fig.5, while Table I summarizes the design parameters.

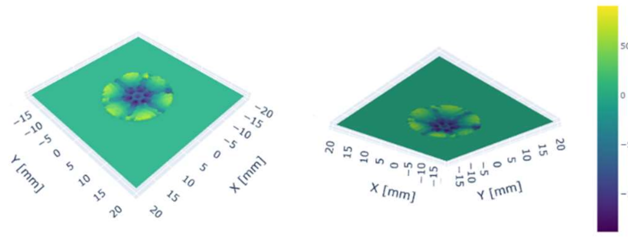

Fig. 5. Seven-beam distribution obtained by adding the position-dependent phase shift to the single Gaussian beam distribution and propagating it for 10 cm (1.627 THz). The color bar shows the scale in the z-direction (in µm)

TABLE I – PARAMETERS FOR THE REFLECTORS

Parameter	1.627 THz	4.7 THz
Reflector dimensions	Δx = 19.16 mm Δy = 18 mm	Δx = 19.16 mm Δy = 18 mm
Reflector-scanning plane distance	10 cm	10 cm
Angle of beam incidence (with respect to the normal to the reflector)	20°	20°
Design beam waist (radius)	4 mm	5 mm
Minimum Radius of Curvature (MRC)	1.23 mm	0.55 mm
Coordinates of MRC	x = -6.96 mm y = 6.04 mm	x = 4.67 mm y = 7.75 mm

V. FABRICATION

Prototypes for both 1.627 THz (Fig.6) and 4.7 THz frequencies were fabricated at the Fraunhofer Institute for Applied Optics and Precision Engineering IOF in Jena, Germany.

The reflectors, made from Aluminum RSA6061 with dimensions of 48 mm x 15 mm, were produced using diamond machining in fast tool servo mode. Surface smoothness was enhanced by removing outlier points; according to simulations, the seven-beam pattern would not be visibly affected. The 1.627 THz prototype had significant surface smoothing, which may affect performance. Three additional prototypes for the 1.627 THz surface were created at the SRON Netherlands Institute for Space Research in Groningen, using CNC machining with increasingly finer tools. The 1.627 THz prototype manufactured

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in Germany has a smoother surface, while the latter exhibits a horizontal line pattern and sharper features due to the CNC process. The reflector with a lower surface roughness would suggest better experimental performance.

Fig. 6. Optical micrography of the prototype at 1.627 THz manufactured via diamond machining at Fraunhofer IOF (Jena, Germany).

VI. EXPERIMENTAL RESULTS

Characterization of the reflector at 1.627 THz was conducted at SRON Netherlands Institute for Space Research in Groningen, where a Far-Infrared (FIR) gas laser at such frequency was available. A scheme of the experimental setup is shown in Fig.7.

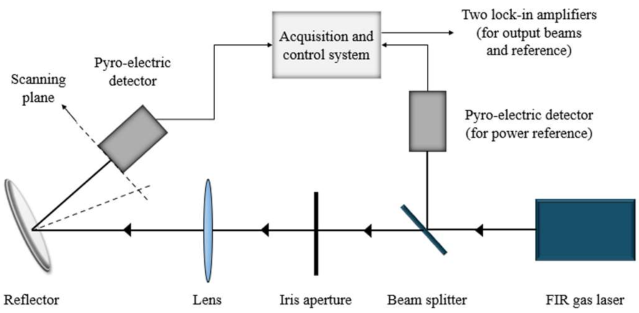

Fig. 7. Scheme of the experimental setup for characterization of the reflector at 1.627 THz. The laser beam is emitted by a Far-Infrared gas laser source at 1.627 THz; through a 6 µm beam splitter, a fraction of the power is sent to a pyro-electric detector for reference. To obtain a Gaussian profile, the transmitted beam is adjusted by an iris aperture; through a lens, we get the proper beam waist size (4 mm) at the location of the reflector. The reflected field intensity is measured through another pyro-electric detector mounted on a xy stage. The data is sent to an acquisition and control system. Two lock-in amplifiers are needed for simultaneous measurement of the output beams and the reference beam.

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First, the reflector fabricated at Fraunhofer IOF (Prototype I) was tested. The initial scans at a 10 cm distance from the reflector reveal a clear pattern with seven beams, showing a central beam with significantly higher power (39.5%) compared to the others (ranging from 8.7% to 11.7%). The horizontal line pattern visible from the scans is caused by the offset between the position of the detector and the moment of acquisition from the measurement system.

Following adjustments aimed at correcting power imbalances among the upper and lower parts of the hexagonal ring; a subsequent scan shows improved power distribution in favor of the lower-right beams. This highlights the impact of alignment on the power distribution of the beams. Increasing the incident beam waist, we aimed to mitigate the power discrepancy between the central and outer beams. To achieve this, we replaced the lens to achieve a larger beam waist of approximately 5.5 mm (compared to a design beam waist of 4 mm). The dominance of the central beam persisted, but an overall balanced distribution among the six beams in the hexagon was obtained (Fig.8).

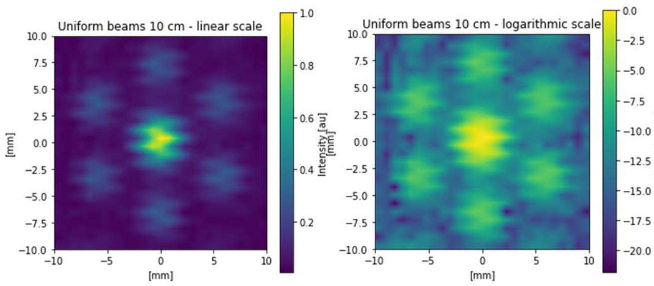

Fig. 8. Scan of the output pattern from Prototype I after adjusting the optical setup and increasing the beam waist of the incident beam (reflector-scanning plane distance: 10 cm, step size: 0.25 mm) in linear (left) and logarithmic (right) scale.

We further performed scans of the output beams at a greater distance (15 cm); although a hexagonal pattern is still discernible, the individual beam shapes do not resemble a Gaussian profile; this emphasizes the sensitivity of the performance to distance parameters.

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The next phase involved testing Prototype II, the reflector manufactured at SRON. The experimental setup remained unchanged from the previous measurements, with an input beam waist of approximately 5.5 mm. A distinct 7-beam pattern is achieved through this reflector, with improved power uniformity among the six beams in the ring compared to Prototype I (Fig.9). Prototype II also exhibits a higher concentration of power within the hexagonal area.

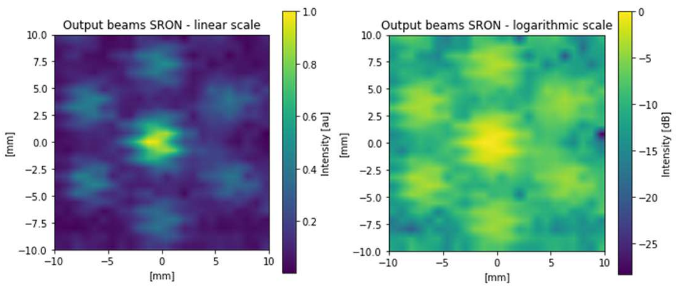

Fig. 9. Scan of the output pattern obtained through Prototype II (reflector-scanning plane distance: 10 cm, step size: 0.25 mm) in linear (left) and logarithmic (right) scale.

To determine the efficiency, the total power of the beam reflected by a flat mirror was initially scanned at a 20° angle of incidence before placing the reflector. Due to the instability of the laser source, normalization of scans was crucial. This involved adjusting each data point by the corresponding value from a reference pyro-electric detector, normalized to its maximum intensity to mitigate laser fluctuations. Support functions were defined to isolate areas for efficiency calculations. For the single Gaussian beam, efficiency was evaluated within a circle four times larger than its beam waist; for the seven-beam pattern, comparisons were made using either a seven-circle support or a single circle enclosing the entire hexagon. Table II reports efficiency estimations, where values are corrected for the reference power.

TABLE II – EFFICIENCY CALCULATIONS

Reflector Prototype (1.627 THz)	Seven-circle support	Single circle support
Prototype I	41.2%	42.4%
Prototype II	60.2%	62.9%

The analysis focuses on two main results: the disparity in power distribution between central and outer beams, and the different performances from Prototype I and Prototype II.

The simulations were run keeping into account only the phase-modulation effect. The idea was that, after reflection, each point in the field has some constructive or destructive interference with the others; this is made in such a way that, at 10 cm, the combination of constructive and destructive interference among points has maximum amplitude in the seven beams, minimum elsewhere. However, if only a fraction of the input beam undergoes this process, while the rest is reflected as by a simple mirror, we would expect the central part of the output pattern to be more intense, as it corresponds to the peak of the Gaussian beam. In other words, the resulting pattern could be a superposition of a single Gaussian beam and the desired pattern obtained through phase manipulation. That could justify the enhanced power of the central beam. The partial phase modulation might be caused by the accuracy of approximations made in the design.

Second, discrepancies in reflector performance between the prototypes may arise from the fabrication process. While simulations only considered phase modulation effects, practical reflector implementations can deviate due to fabrication imperfections. Variations in groove depth across the reflector's surface might influence phase modulation efficiency and affect the output beam distribution. It turns out that surface corrections and interpolation between points during the fabrication process can have an impact on reflector performance.

CONCLUSIONS

We have investigated a novel method for multiplexing a single Gaussian beam into seven beams using a reflector that introduces a position-dependent phase shift. This phase modulation, determined through the Gerchberg-Saxton algorithm, ensures the desired output pattern is achieved at a specific distance. Two reflector prototypes were fabricated for 1.627 THz and 4.7 THz. Prototype I, manufactured via diamond machining, exhibited higher surface smoothness, while Prototype II, produced using CNC machining, maintained design fidelity despite a visibly less polished finish. Experimental testing at 1.627 THz revealed an imbalance in power distribution between the central and outer beams, potentially due to incomplete phase modulation of the field distribution. Adjustments to the optical setup alignment and input beam waist improved power uniformity among the hexagonally distributed beams. The efficiency of the two reflectors was approximately 42% for Prototype I and 61% for Prototype II, compared to the simulated expectation of 67.6%. It appears that point smoothing can negatively impact efficiency.

To further improve the multiplexer for LO applications, we propose the following research activities: a) Increasing phase

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modulation efficiency, potentially by enhancing the angle of incidence, to minimize the imbalance between central and outer beams; b) Implementing rigorous diffraction treatments for higher angles of incidence to refine phase retrieval algorithms, as discussed in [10]; c) Adding phase constraints to ensure Gaussian phase profiles of the seven output beams, which is crucial for optimal coupling to the HEB mixer array; d) Characterizing and further investigating the feasibility of our method with the already manufactured 4.7 THz reflector.

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REFERENCES

[1] Pawar, Ashish Yashwantrao et al. “Terahertz technology and its applications.” *Drug Invention Today* 5 (2013): 157-163.
[2] C. Walker, “Terahertz Astronomy”, *CRC Press* (2015)
[3] Chin, Gordon et al. “Single Aperture Large Telescope for Universe Studies (SALTUS): Science Overview.” (2024).
[4] J. R. Silva et al., “High-resolution receiver (HiRX) for the Single Aperture Large Telescope for Universe Studies (SALTUS)”
[5] Graf, U.U., & Heyminck, S. (2001). “Fourier gratings as submillimeter beam splitters”. *IEEE Transactions on Antennas and Propagation, 49*, 542-546.
[6] Mirzaei, B., Silva, J.R., Hayton, D.J., Groppi, C., Kao, T., Hu, Q., Reno, J.L., & Gao, J.R. (2017). “8-beam local oscillator array at 4.7 THz generated by a phase grating and a quantum cascade laser”. *Optics express, 25 24*, 29587-29596.
[7] Graf, U.U. (2018). “Enhanced diffraction efficiency of two-dimensional phase gratings”. Optics express, 26 25, 32739-32742.
[8] Taylor, L.S. (1981). The phase retrieval problem. *IEEE Transactions on Antennas and Propagation, 29*, 386-391.
[9] Zalevsky, Z., Mendlovic, D., & Dorsch, R.G. (1996). “Gerchberg-Saxton algorithm applied in the fractional Fourier or the Fresnel domain”. *Optics letters, 21 12*, 842-4.
[10] Matsushima, K., Schimmel, H., & Wyrowski, F. (2003). Fast calculation method for optical diffraction on tilted planes by use of the angular spectrum of plane waves. *Journal of the Optical Society of America. A, Optics, image science, and vision, 20 9*, 1755-62.

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