Asymmetric phase grating as 4.7 THz beam multiplexer for GUSTO

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Abstract—**The grating design for the 4.7 THz channel of GUSTO (Galactic/ Extragalactic ULDB Spectroscopic Terahertz Observatory) has been reported in this paper, which acts as a beam multiplexer for coupling a single QCL (Quantum Cascade Laser) beam to an 8-pixel mixer array. The design and analysis are based on modeling and simulations showing a successful accommodation of the requirements from the designed optical system. The asymmetric feature is used and to be applied for the first time at such a frequency range.**

Index Terms— **Array receivers, GUSTO, Heterodyne, Phase grating, Terahertz.**

I. Introduction

GUSTO is a super-THz heterodyne instrument planned to be launched at 2021 from Antarctica to mainly study the star formation and the life cycle of the interstellar clouds in our galaxy and beyond. Molecular and atomic fine structure lines at three scientifically valuable frequencies of 1.4, 1.9 and 4.7 THz will be measured by GUSTO, each with an 8-pixel heterodyne receiver, continuously for around 100 days, the most efficient super-THz observation ever.

A single heterodyne receiver with extremely high spectral resolving power of 10^7 consists mainly of a mixer and a local oscillator (LO). The former mixes the celestial signal with LO in order to down-convert it to the gigahertz range. A multi-pixel heterodyne receiver requires multiple parallel receivers; each with its own LO beam. In general, advanced fabrication technology allows making relatively uniform array of mixers, so that within a certain variation of the LO power they still deliver receiver sensitivities with negligible differences.

While the mixer technology (superconducting hot electron bolometer mixers) is the same for all three frequency bands of GUSTO, the local oscillators of the two lower bands are solid-state frequency multiplied sources and for the 4.7 THz channel, a QCL [1]. Waveguide splitters are used to generate 8 LO beams for lower channels and a phase grating is applied for multiplexing a QCL beam into 8 for the highest channel. The phase grating is the only applicable multiplexer technology at such a high frequency. It is a periodic arrangement of a unit cell with a specific surface morphology for phase manipulation of the incident coherent radiation in order to make multiple image beams in the far-field. Here we report the design and analysis of a phase grating fulfilling the requirements of the optical system design for the highest frequency receiver of GUSTO.

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II. Requirements

Although we have recently demonstrated and published the base technology of THz phase gratings [2,3], geometrical limits of the higher frequency channel of GUSTO demands an advanced design to accommodate the tough requirements on the beam distribution scheme. The force is originated from the fixed distance of the mixer array to the cryostat window, which together with the strict volume constraint of the warm coupling optics determine the beam size on the phase grating to be 2.95 mm of radius. This consequently defines the unit cell size upper limit since for grating to function, at least two unit cells should be covered by the beam.

Since symmetry makes the application and analysis of an optical component easier, previously demonstrated THz gratings [2,3] provide a symmetric spatial distribution among the diffracted beams. 8-pixel gratings for example have symmetric employment of the diffraction orders (±1, ±3), which leave a gap of one beam in between the adjacent pixels. The tight required angular distance of 1.83° in combination with the incident angle of 15° put a lower limit on the unit cell size too, since the latter has an inverse proportion to the beams separation. Such a confined range for the unit cell size does not leave any room to miss the intermediate diffraction orders in the symmetric structures. In other words, all the consecutive orders have to be employed to realize the small distances between the beams, which immediately breaks the symmetry since the array has a 2x4 arrangement. We have created an alternative design based on asymmetry to accommodate the abovementioned requirement being elaborated in the next section.

III. Design

We use the method given in references [2,3] with a modification for generating asymmetric feature for designing the grating. Since the surface profile in the mentioned references is symmetric and so an even function, the Fourier series include only cosine terms. For the asymmetric design however, we applied both sine and cosine terms in the Fourier series. Doing so and performing an optimization process we could come up with a surface profile fulfilling the requirements mentioned in the previous section. The 3D plot of such a profile together with the cross sections are shown in Figure 1. Each orthogonal cross section is responsible for multiplexing the beam either to 2 or to 4 so that a rectangular 8-beam pattern is generated.

The computational characterization is performed using 3D modeling in COMSOL Multiphysics, while the design is done

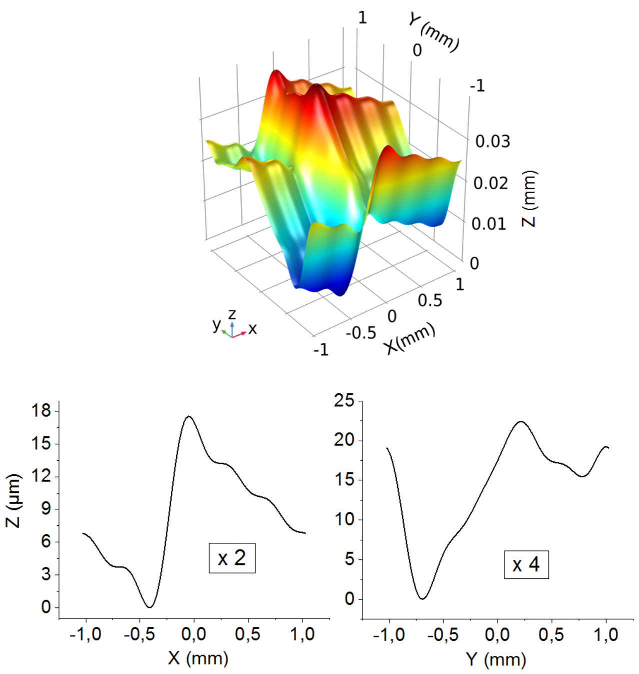

Fig. 1. 3D plot of the designed surface profile (top). At the bottom, orthogonal cross sections are plotted, each multiplexing the beam to 2 (left) or 4 (right).

in MATLAB. The performance of the grating can be assessed in 3 main aspects. The first is the efficiency defined as the ratio between the total power in the desired modes and the power of the incoming beam. We expect an efficiency of about 70 % for this design.

The second aspect is the uniformity of the power distribution among the diffracted beams. Assuming an array of similar mixers optimized for a certain LO power, variation among the diffracted beams degrades the average sensitivity of the array. In this sense more uniformity is desirable. For this design we expect a power variation of about 13 %, which is defined as $(P_{max}-P_{min})/P_{average}$. This level of variation lowers the array's average sensitivity by less than 2 %.

The third important factor is the spatial distribution of the beams, which should comply with the requirement of the optical system, in which the grating will be implemented. The angular distance between adjacent beams is expected to vary between 1.83° and 1.849°. Such a small deviation from the requirement of 1.83° has a negligible effect on the coupling of the beams to the mixer array.

IV. Influence of the Machining Accuracy

The designed surface of the grating will be transferred to an aluminum plate using a CNC (Computer numerical control) micro-milling machine. Figure 2 shows an SEM (Scanning Electron Microscope) photo of the 4.7 THz grating reported in [2] giving a good impression of the milling capability. Having a large minimum radius of curvature of 1.4 mm makes it easier to manufacture in the sense that the structures are not extremely fine. However, reaching the required machining accuracy might be another issue, which is discussed here in this section.

In order to effectively model the effect of possible machining inaccuracies on the grating performance a Monte Carlo study is desirable. However, since our simulation tool

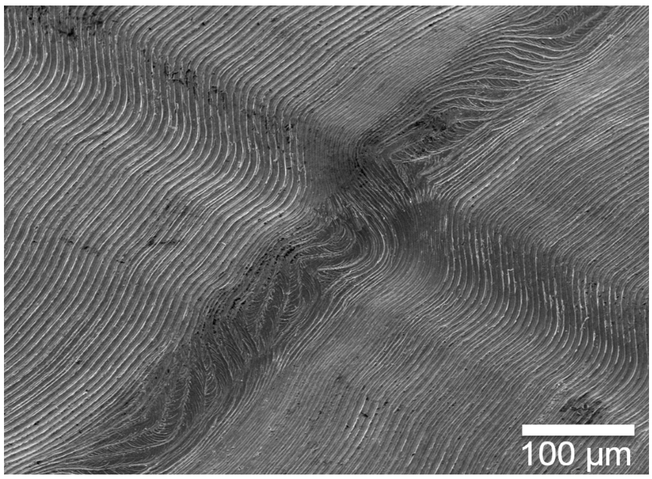

Fig. 2. An SEM photo of the machined 4.7 THz grating reported in [2].

uses finite element modeling with a long processing time, it is not feasible to have such a study. Therefore we include surface deviations to our model to make the closest similarity to the potential machining errors. For that, a sine variation is added on top of the ideal grating profile with 1 mm of period and different amplitudes. This variation is applied in two orthogonal phases to cover the possible effect of the phase in order to derive the largest effect on the performance. Such variations with ± 1 μm are represented in figure 3, where all the surfaces are in the same scale let the reader have a clearer comparison.

Since the beams traveling direction is solely dependent on the unit cell size, this factor does not change with surface deviation. This simulation shows that such surface deviations cause negligible effect on the grating efficiency, while the main influence is on the power uniformity among the beams. Table 1 summarizes the latter for the phase with larger effect for different extents of deviation from ± 0.2 to ± 1 μm. For GUSTO we choose a ± 0.5 μm allowable tolerance in machining, which together with power variations caused by

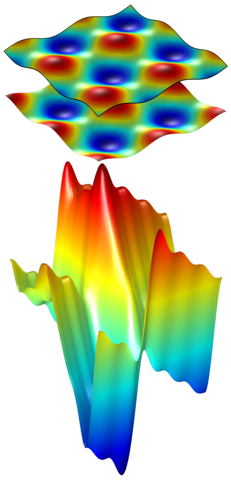

Fig. 1. Applied sine variations with 1 mm of period and 1 μm of amplitude on top of the grating surface profile.

other elements in the optical system degrades the average sensitivity of the array by 3 %. This is seen to be tolerable for the mission science goals.

It should be mentioned that GUSTO would have a finely adjustable mount for grating which can correct any possible errors caused during mounting i.e. tilt, rotation and translation. We also evaluate the effect of possible temperature variation during the mission on the unit cell size through thermal expansion/contraction. We find a negligible influence on the grating performance.

TABLE I
SIMULATION RESULTS OF THE EFFECT OF THE SURFACE VARIATION ON THE POWER UNIFORMITY OF THE GRATING

Variation (μm)	Uniformity Deviation
± 1	25 %
± 0.8	23 %
± 0.7	21 %
± 0.6	19 %
± 0.5	17 %
± 0.4	15 %
± 0.2	14 %
Ideal	13 %

V. CONCLUSION

The design and expected performance of an asymmetric phase grating being implemented as a 4.7 THz beam multiplexer has been discussed in this paper. This grating is capable to fulfill the requirements by the designed optical system of the higher frequency channel of GUSTO. An analysis over the effect of the machining accuracy is also given in this paper for the first time.

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