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Multiple terahertz beams based on a Fourier grating and a quantum cascade laser

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***Abstract*-Large heterodyne receiver arrays (~100 pixel) allow astronomical instrumentations mapping more area within limited space mission lifetime. One challenge is to generate multiple local oscillator (LO) beams. Here, We succeeded in generating 81 beams at 3.86 THz by combining a reflective, metallic Fourier grating with an unidirectional antenna coupled 3rd-order distributed feedback (DFB) quantum cascade laser (QCL). We have measured the diffracted 81 beams by scanning a single pyroelectric detector at a plane, which is in the far field for the diffraction beams. The measured output beam pattern agrees well with a simulated result from COMSOL Multiphysics with respect to the angular distribution and power distribution among the 81 beams. We also derived the diffraction efficiency to be 94±3%, which is very close to what was simulated for a manufactured Fourier grating (97%). For an array of equal superconducting hot electron bolometer mixers, 64 out of 81 beams can pump the HEB mixers with similar power, resulting in receiver sensitivities within 10%. Such a combination of a Fourier grating and a QCL can create an LO with 100 beams or more, enabling a new generation of large heterodyne arrays for astronomical instrumentation. This paper is essentially a copy of our paper in Optics Express.**

I. INTRODUCTION

THz heterodyne detection, combining the light intensity measurement with an exceptionally high spectral resolution, has been widely used to study astronomic fine structure lines and rotational molecular lines at THz frequencies (0.3-1 THz) as well as the lines at supra-THz frequencies (>1 THz). In order to effectively map the lines from a large area of the sky, future heterodyne receivers need large arrays. Generating multiple beam local oscillators (LOs) is thus one of the key technologies demanded to realize such a goal.

In supra-terahertz region, quantum cascade laser (QCL) is the most promising LO source. However, generating multiple QCLs with the exactly same frequency and phase is quite challenging. A phase grating [1], illuminated by a single THz QCL, has demonstrated multiple beam LOs at supra-THz [2]. However, so far it has been limited to less than 10 beams. Here we report for the first time a 81-beam LO using a newly simulated and fabricated Fourier grating and a novel quantum cascade laser that is based on an unidirectional photonic wire concept and that emits single mode line at 3.86 THz [3]. This paper is essentially a copy of our paper in Optics Express [4].

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II. FOURIER GRATING

The working principle of a phase grating is based on the scalar diffraction theory [5]. The far-field distribution of a light transmitted/reflected by a phase grating is the Fourier transform of the phase modulation function $exp(j\Delta\phi(\xi,\eta))$ of the grating. A Fourier grating, by expanding its phase modulation function to Fourier series with a set of Fourier coefficients a_n, modulates the phase of the incident single-frequency beam to produce multiple output beams. Using the Fast Fourier Transform algorithm and the Standard multidimensional minimization algorithm in Matlab, a set of a_n is found for the desired number of diffraction orders with high diffraction efficiency and good uniformity. According to the relation between phase difference $\Delta\phi$ and groove depth d of the surface structure on the grating $d=\lambda\Delta\phi/4\pi cos\theta_i$, where λ is the wavelength of the input radiation and θ_i is the incident angle with respect to the normal direction of the grating, we can define the groove profile of the grating. A two-dimensional (2D) grating is generated by superposition of two 1D gratings orthogonally. We chose to start with a grating for 81 beams because our simulation shows that a 9×9 pixel grating can achieve 98% diffraction efficiency and also a relatively uniform power distribution among the diffracted beams.

Based on the equation for a 1D reflection grating, $D(sin\theta_m\text{-}sin\theta_i)=m\lambda$, where D is the periodicity and θ_m is the angle of the m'th diffraction order, the angular separation of the image beams is calculated to be ~3.8° (in our case, D = 1.2 mm, θ_i =12°, and λ = 78 μm). The grating is machined on an aluminum plate (Alcoa QC-10 Mold Alloy, of 5 mm thick) using an KERN EVO micro-milling machine. A photo of the manufactured grating and its 3D optical microscope image are shown in Fig. 1 (a) and (b), respectively. The entire grating contains 16×16 unit cells and is 2×2 cm^2 in size. We also measured the surface profile of a unit cell in two orthogonal directions using a Dektak XT30 stylus profiler. We found good agreement between the measured profile and the designed one

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with a deviation less than 1 μm in height (1/78 of the working wavelength). The effect of such a difference on the grating performance will be discussed in the results section.

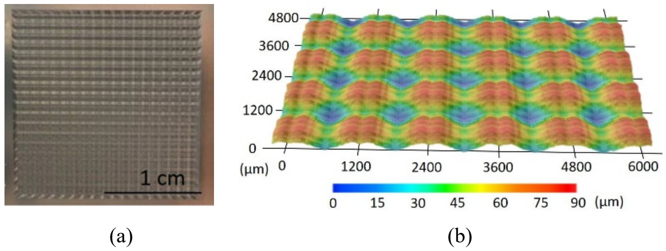

Figure 1. (a) 81 pixel Fourier grating machined on a 5 mm thick aluminum plate. (b) The surface topology of the 81 pixel grating taken by a 3D optical microscope. The color indicates the height.

III. Measurement setup

We apply an unidirectional antenna-coupled 3rd order distributed feedback (DFB) quantum cascade laser (QCL) at 3.86 THz as the input source for the grating. This laser can provide more than 10 mW output power. The unidirectionality, resulting from a "reflector" structure in the laser, enhances the power level of the forward beam by a factor of ~2. In our measurement, we used one of the lasers out of an array of 20 DFB lasers as the input source.

Fig. 2 shows our measurement setup schematically. The QCL was mounted in a pulse tube cooler working at ~10 K. The QCL beam is divergent (the full width at half-maximum (FWHM) divergence angles to be 23° and 14° in the vertical and horizontal directions) and obviously deviated from a fundamental Gaussian beam profile. A fundamental Gaussian beam is required to avoid overlap between the individual diffracted beams. Therefore, a lens and an iris aperture is introduced to collimated and filter the QCL beam to a symmetric and Gaussian-like beam with an FWHM divergence angle to be < 1°. Although the power of the modified beam is lower than the output power of the QCL (5-10% powers), there is still sufficient power to map output beams of the gratings with a good signal-to-noise ratio.

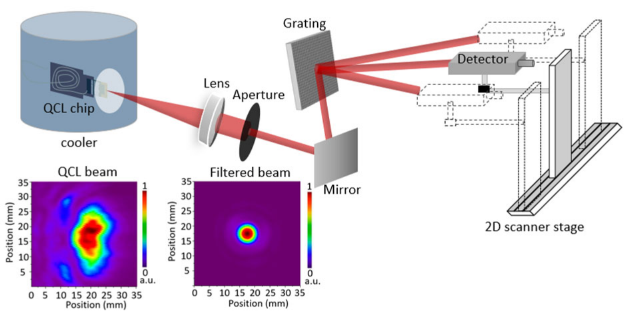

Figure 2. Schematic diagram of the measurement setup to test the performance of the grating.

The incident angles of the incoming beam are 12±2° and ±2° with respect to the normal of the grating plane in the horizontal and vertical directions, respectively. A pyro-electric room temperature detector mounted on a 2D scanner is used to map the image beam pattern at a distance of 12 cm from the grating surface. To compare the total power of the image beams of the desired modes with that of the input beam, we measured the input beam power by replacing the grating with a gold coated mirror, which reflects nearly 100% power. The reflected single beam is also mapped by the pyro-electric detector at the same distance as measuring the grating imaging beam (12 cm). In this way, the effect of water absorption due to the optical path is canceled out.

IV. Experiment results and discussion

Fig. 3 (a) shows our measured beam pattern in a plane with an area of 84×84 mm^2, at a distance of 120 mm from the grating surface. We observed 81 beams, which are well separated, and have angular directions matching to the 1D grating's equation. The distortions from a perfect rectangular beam distribution come from the fact that we recorded the beam pattern from a plane, but the diffracted beams propagate spherically in space. The different uniformity in horizontal and vertical directions is caused by the incident angle of 12° in the horizontal direction, but normal in the vertical direction.

Fig. 3 (c) shows the simulated diffracted beam pattern of the grating using COMSOL Multiphysics. The simulated far field beam pattern is also plotted along a plane, which has the same distance to the grating surface as in our experiment. We can clearly see that the simulated 81 beams well reproduce the measured 81 beams except that the uniformity of the simulated 81 beams is better than what is seen in the measurement, especially for the beams in the rightmost column.

For the non-uniformity in the measured beams, there are a few practical factors in the measurement that can affect the uniformity in the beam distribution: (1) There were humidity changes in the laboratory during the beam mapping, which took roughly 20 hours. During this period, the relative humidity varies between 25% and 45%, which in turn changes the absorption and influences the image beam intensity distribution. (2) Power coupling between the pyro-electric detector and the image beams. During the mapping of the image beams, the measured power is angle-dependent, with more power for the beams in the center, but less power for the outer beams. (3) There are possible errors to determine the exact incident angle. We estimate an error of ±2° on the incident angles, which can also influence the intensity distribution of the image beams. (4) Different distances between the grating and individual image beams. All these experimental errors can influence the measurement of the grating with regard to the diffraction efficiency and uniformity.

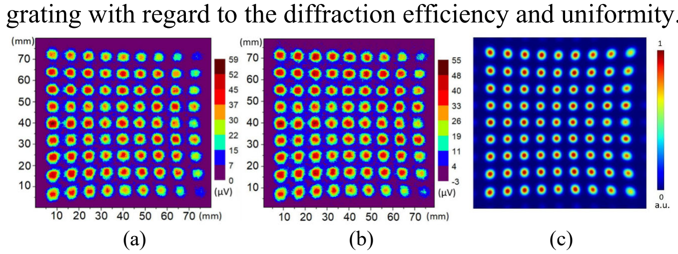

Figure 3. (a) Measured beam pattern. (b) Image beam pattern after calibrated the effect of the coupling with detector and removed the noise floor. (c) Simulated far field beam pattern of the designed grating.

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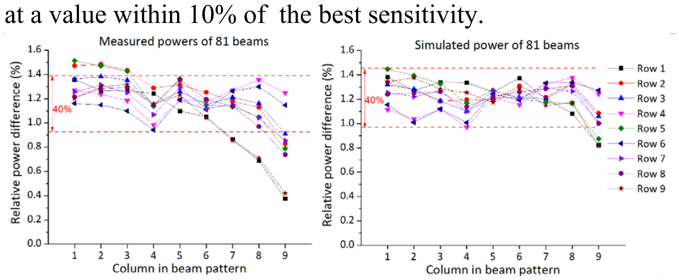
Fig. 3 (b) plots the beam pattern after correcting the error due to the angle-dependent power measured by the pyro-electric detector and the power loss due to different distances between the grating and individual image beams. This beam pattern agrees better with the simulated one in Fig. 3 (c). After removing the noise floor caused by the pyro-electric detector itself in the image beam data and in the input beam data, we then calculated the diffraction efficiency to be 94±3%, which agrees well with the simulated diffraction efficiency 97% of the manufactured grating surface. Clearly, it is a highly efficient Fourier grating. The error bar accounts mainly for the following two sources: the humidity changes in the laboratory and the ±2° error in the incident angle.

When the grating is used to generate multiple beams as a local oscillator, each beam will pump a mixer, and thus the power should be within certain range of the desired value, in which all the mixers will perform optimally. The details can depend on the sensitivity of the mixers and the optical components before the mixer. In supra-THz region, superconducting hot electron bolometer (HEB) mixers are the detectors of choice for heterodyne instrumentation due to their high sensitivities and low LO power requirements. However, the performance of HEB mixers is LO power dependent [6]. Based on a set of pumped current-voltage characteristic data with a variable LO power in [7] and the isothermal technique [8], we find that if the LO power changes within ±20% around its optimal power, the receiver noise temperature, which characterizes the sensitivity of a heterodyne receiver, remains at a value within 10% of the best sensitivity.



(a) (b)

Figure 4. (a) The power distribution of the measured image beams distributed in different columns. (b) The power distribution of the image beams from the simulation using a designed surface structure.

From the data in Fig. 3 (b), we calculate the relative power for each beam, and plot them in different columns in Fig. 4 (a). We found that the relative power varies from 0.4 to 1.5 %. For comparison, the simulated power distribution is plotted in Fig. 4 (b), where the relative power varies from 0.8 to 1.45 %. So the simulation gives a better uniformity. From Fig. 4 (a) the power of 64 beams out of 81 are within ±20% range, i.e., the 64 beams can be directly used to pump an uniform HEB mixer array, where every HEB requires the same LO power. In contrast, 78 beams out of 81 vary within this range from the simulation. The difference is likely due to the mismatch between the designed and the manufactured surface profile. By importing one unit cell of the manufactured surface topology into COMSOL Multiphysics and simulating the power distribution of the output beams, we find that 68 beams out of 81 are within ±20% around the nominal value. Therefore, the precision in manufacturing seems to play a crucial role in the uniformity of the grating. Besides, the humidity change in the laboratory may also affect the uniformity. Despite the non-uniformity in the measured beams, we can still effectively use all 81 beams by replacing the detectors that require lower or higher LO than the nominal value instead of an ideal uniform HEB array. It is relatively easy to control the required LO power of a HEB mixer by controlling the size of an HEB.

V. Conclusion

We report a 81-beams supra-THz LO array generated by a Fourier grating with a unidirectional 3rd-order DFB QCL emitting single mode radiation at 3.86 THz. We succeeded in measuring 81 diffraction beams and, due to a high output power of the QCL, we have achieved a good signal-to-noise ratio allowing us to determine the diffraction efficiency of the grating, which is 94±3%, and evaluate the power uniformity of the image beams. The measured diffraction efficiency agrees well with the simulated result using the profile of the manufactured Fourier grating. The latter gives 97% efficiency. Based on the measurements and uniformity requirement of the LO power for superconducting HEB mixers, we find 64 beams out of 81 have their power varying within ±20% around the nominal value and that the 64 beams can be used to pump a 64 uniform array, maintaining the sensitivity degraded less than 10%. Our results open a new route towards a large heterodyne array of order of 100 pixels for future space instruments. Our Fourier grating approach can improve the functionalities of the phase gratings, such as the diffraction efficiency, for orbital angular momentum beams for optical communications, UV beam splitting, and complex beam shaping.

Acknowledgment

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