Proceedings Paper:

Ellison, BN, Rawlings, T, Brewster, N et al. (6 more authors) (2017) 3.5 THz dual feedhorn quantum cascade laser a step towards achieving a frequency stable supra-THz heterodyne local oscillator. In: 2017 International Symposium on Antennas and Propagation (ISAP). 2017 International Symposium on Antennas and Propagation (ISAP), 30 Oct - 02 Nov 2017, Phuket, Thailand. IEEE . ISBN 978-1-5386-0465-6

https://doi.org/10.1109/ISANP.2017.8229016

3.5 THz Dual Feedhorn Quantum Cascade Laser

A step towards achievng a frequency stable supra-THz heterodyne local oscillator

B.N. Ellison, T. Rawlings, N.J. Brewster and M.L. Oldfield
STFC, Rutherford Appleton Laboratory Space Department
Rutherford Appleton Laboratory
Didcot, United Kingdom

A. Valavanis, Y. Han, E.H. Linfield and A.G. Davies
School of Electronic and Electrical Engineering
University of Leeds
Leeds, United Kingdom

E. Saenz
Radio Frequency Payloads & Technology Division
European Space Agency
Noordwijk, The Netherlands

Abstract—We present the first antenna power measurements from a double metal terahertz-frequency quantum cascade laser (THz QCL) mounted within a waveguide cavity and incorporating dual diagonal feedhorns that enable directional output coupling of THz radiation from both laser facets. The feedhorn antenna patterns have been measured simultaneously at a frequency of 3.5 THz and with the QCL operating at an ambient temperature of 60 K in continuous wave mode. Comparison with a feedhorn theoretical model shows good pattern correlation and implies that the QCL signal is likely propagating within the waveguide in a fundamental mode.

Keywords—QCL; terahertz; heterodyne; local oscillator; waveguide; feedhorn;

I. Introduction

The chemical constituents of the Earth's upper atmosphere play an important role in influencing weather and future climate change. In particular, the mesosphere and lower thermosphere (MLT) are strongly affected both by natural and anthropogenic inputs from the surface, and by solar and space-weather impacts from the space environment above. Gaining a full understanding of the global distribution of key chemical species, e.g. O, NO, OH, that exist within the MLT is therefore essential in order to improve the validly and accuracy of related climate models. This is best accomplished through the spaceborne deployment of high-resolution terahertz (THz) heterodyne radiometers. However, in developing spaceborne radiometers that must operate at frequencies in excess of 1 THz, and that are compliant with small satellites, critical technical barriers need to be overcome. One of these is the stabilisation of the radiometer local oscillator (LO) source and for which we describe here a notable technical advancement.

II. Quantum Cascade Laser as a Local Oscillator

The use of THz radiometry has been well demonstrated at frequencies below 1 THz. However, the development of space compliant systems operating in excess of this frequency (the supra-THz range) challenges existing technology in two primary areas, viz. the heterodyne mixer and LO. The former requires the fabrication of sensitive semi-conducting diodes that are able to respond to the applied supra-THz signal and that, in combination with the applied LO tone, efficiently down-convert it to a lower frequency, whence it can be signal processed to reveal related spectral information.

Generating a THz LO signal with sufficient power to 'pump' the mixer diode, typically at the milliwatt level, is challenging in the THz range, and even more so at supra-THz frequencies. The latter has previously required the development of complex gas-laser systems that are incompatible with a small satellite platform. Moreover, the LO must provide a stable frequency output to avoid influencing the retrieved spectral lineshape; thereby further increasing its complexity. Thus, the generation of a frequency-stabilised LO signal, typically to better than 1 MHz, and in a space compliant form, is a crucial requirement of supra-THz heterodyne spectroscopy.

A highly attractive solution to the above is offered by a relatively new device, the quantum cascade laser (QCL). This bandgap engineered semiconductor structure provides a source of supra-THz power from a highly compact configuration that needs only a simple direct current (dc) input source. However, when used in a native and unpackaged form, QCLs suffer a poor coupling to free-space and need to be frequency stabilised. In a step towards addressing these disadvantages, we have integrated a 3.5 THz QCL structure into a miniature waveguide cavity and have, for a first time, measured the simultaneous free-space signal emerging from each end of the cavity via two integrated diagonal feedhorn antennas.

A. Description of the QCL, waveguide and feedhorn structure

The QCL used in this system was based on a GaAs/AlGaAs phonon-assisted "hybrid" design [1]. The active region of the device was grown using molecular-beam epitaxy and processed into a 1-mm-long Au–Au ridge-waveguide structure, as described previously in [2]. The unmounted device was found to operate in continuous-wave (cw) mode at heat-sink temperatures up to 86 K, with output power in excess of 0.4 mW.

The waveguide cavity was machined with a cross-section dimension of 0.16x0.08 mm^2. Two identical diagonal feedhorns with an across-diagonal aperture of 1.56 x 1.56 mm^2 and a slant angle of 7.5º, were also machined along the signal propagation direction of the waveguide. Bias connection to the QCL was achieved through the use of a standard SMA connector and a series of wire bonding steps that also included a stage of heat sinking. Fig. 1a, shows the fabricated cavity and feedhorn structure with a QCL placed in the waveguide.

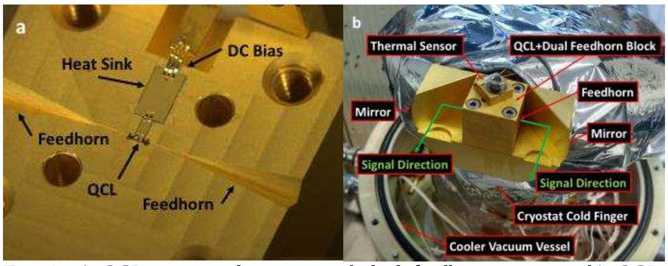

Fig. 1: a) QCL, waveguide cavity and dual feedhorn structure; b) QCL, feedhorn block and mirrors mounted on cold finger. Window not shown.

III. Experimental System and Method

In order to achieve the necessary electron population states within its multilayer bandgap structure, the QCL must be cooled to a low ambient temperature. To achieve this, the integrated QCL and feedhorn block was attached to the 'cold finger' of a Stirling cycle cooler and operated at ~60 K in a cw mode. Two plane mirrors inclined at 45º to the signal propagation axis were machined into a gold-plated copper subcarrier and directed each feedhorn output through a single supra-THz semi-transparent vacuum window. Figure 1b shows the complete assembly mounted in the cooler.

An unpolarised Golay detector [4] mounted on a two-dimensional scanning system was used to measure the supra-THz emission intensity. With the detector located approximately 70 mm away from the feedhorn apertures, and thus in the antenna far-field, a series of discretely sampled intensity measurements were made in a rectangular coordinate reference plane orthogonal to the direction of signal propagation. The Golay input signal entrance aperture was approximately 3 mm in diameter and a step interval of 0.5 mm therefore assured adequate spatial sampling. With a scan range of 70 mm in each axis, equivalent to a total of 19,600 spatial samples, and a measurement dwell time of 0.5 seconds, the typical time required to complete a full scan was 3 hours.

IV. Simulation and First Measurement Comparison

A bespoke software modelling tool that expands the diagonal feedhorn aperture electric fields into Gauss-Hermite modes [3] has been used to simulate the antenna pattern of a single diagonal feedhorn, Fig. 2a. In addition to a bright central maximum, the model predicts regions of undulating intensity located on two 45º planes. The latter corresponds to sidelobes arising from wavefront diffraction at the feedhorn aperture.

Fig. 2b presents the first dual 3.5THz feedhorn antenna patterns obtained using the experimental arrangement. Because the QCL is emitting radiation from both ends of its facets, the signal emerging from each feedhorn is coherent and subject to interference at the detector. The dual feedhorn pattern is therefore more complex than its single feedhorn counterpart. Adding to this complexity is the presence of a secondary image that may be due to scattering from the mirror surfaces, reflection from the detector and its surroundings, or refraction by the vacuum window. However, two bright central areas that correspond to the reflected output of each feedhorn are clearly apparent, as are the predicted sidelobes. Comparison thus reveals a good degree of feature similarity and from this we surmise that the QCL signal is propagating in a fundamental transverse electric (TE10) mode within the waveguide, i.e. the same mode used to excite the feedhorn simulation model.

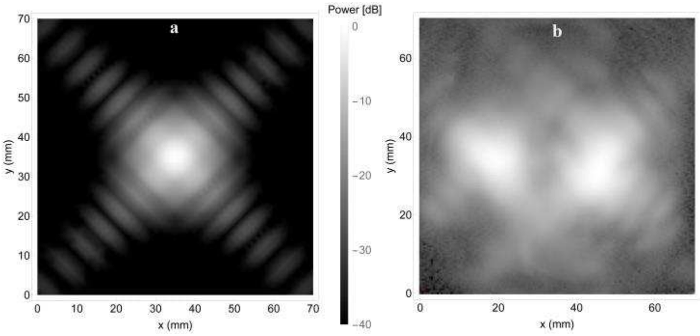

Fig. 2: a) Simulated single 3.5 THz feedhorn pattern; b) First measurement of the dual feedhorn QCL device at 3.5 THz. The scan extent in each case is 70x70 mm^2. The power scale applies to both images.

V. Conclusions

We have integrated a 3.5 THz QCL within a waveguide and a dual diagonal feedhorn structure. This novel device is a first step towards the development of a future QCL frequency stabilisation system required for performing high-resolution spectroscopic measurement of the Earth's upper atmosphere from space. Simultaneous supra-THz emission from the dual feedhorns has been detected and the measured antenna patterns show an excellent degree of correlation with a simulated single diagonal feedhorn antenna. We believe that this suggests a fundamental propagation mode is present within the waveguide.

Acknowledgements

The authors gratefully acknowledge the support of the RAL Millimetre-wave Group Precision Development Facility and their skilful fabrication of the waveguide and feedhorn structures. The development work has been funded via the European Space Agency General Support and Technology Programme (GSTP). We also recognise the support of the UK Space Agency with respect to this allocation of GSTP funding.

References

[1] M. Wienold, L. Schrottke, M. Giehler, R. Hey, W. Anders, and H. T. Grahn, "Low-voltage terahertz quantum-cascade lasers based on LO-phonon-assisted interminiband transitions," Electron. Lett., vol. 45, no. 20, pp. 1030–1031, Sep. 2009.

[2] A. Valavanis, Y.J. Han, N. Brewster, P. Dean, R. Dong, L. Bushnell, M. Oldfield, J.X. Zhu, L.H. Li, A.G. Davies, B. Ellison and E.H. Linfield, "Mechanically robust waveguide-integration and beam shaping of terahertz quantum cascade lasers," Electronics Lett. 51, No. 12, 2015, pp 919-921.

[3] J. Johansson, N Wyborn, P. R. Acharya, H. Ekstrom, S. W. Jacobsson, and E. L. Kollberg, Antennas for sub-millimetre wave receviers", Proceedings of the 2nd Int. Symp. On Space Terahertz Tech., 1991, pp 63-69.

[4] M. J. E. Golay Radiation Detecting Device, Patent, June 19, 1951.