UNIVERSITY OF LEEDS

This is a repository copy of *Development of Terahertz Quantum-Cascade Lasers for Satellite-Borne Measurement of Key Gas Species*.

White Rose Research Online URL for this paper:
http://eprints.whiterose.ac.uk/147827/

Version: Accepted Version

Proceedings Paper:

Valavanis, A orcid.org/0000-0001-5565-0463, Han, Y, Nuttall, E et al. (8 more authors) (2019) Development of Terahertz Quantum-Cascade Lasers for Satellite-Borne Measurement of Key Gas Species. In: Conference on Lasers and Electro-Optics (2019). Conference on Lasers and Electro-Optics (CLEO 2019), 05-10 May 2019, San Jose, USA. Optical Society of America . ISBN 978-1-943580-57-6

https://doi.org/10.1364/CLEO_AT.2019.AW3P.5

© 2019 The Author(s). This is an author produced version of a paper published in Conference on Lasers and Electro-Optics (2019). Uploaded in accordance with the publisher's self-archiving policy.

Reuse

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

White Rose
university consortium
Universities of Leeds, Sheffield & York

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

Development of Terahertz Quantum-Cascade Lasers for Satellite-Borne Measurement of Key Gas Species

Alexander Valavanis[1,*], Yingjun Han[1], Eleanor Nuttall[1], Esam Zafar[1], Diego Pardo[2], Olivier Auriacombe[2],
Thomas Rawlings[2], Nart Daghestani[2], Edmund H. Linfield[1], Brian N. Ellison[2] and A. Giles Davies[2]
[1]School of Electronic and Electrical Engineering, University of Leeds, Leeds LS2 9JT, UK
[2]STFC Rutherford Appleton Laboratory, Harwell Oxford, Didcot OX11 0QX, UK
*a.valavanis@leeds.ac.uk

Abstract: We present key developments towards atmospheric chemistry studies using terahertz quantum-cascade lasers (QCLs), including ~1-cm^3-scale integration of THz QCLs with waveguides and antennas using precision micromachining, and broadband multimode spectroscopy based on detector-free self-mixing. © 2019 The Author(s)

OCIS codes: (140.5965) Semiconductor lasers, quantum cascade; (300.6495) Spectroscopy, terahertz.

1. Introduction

Terahertz-frequency quantum-cascade lasers (THz QCLs) are ultra-compact solid-state sources of coherent THz radiation, which offer great potential for space research and atmospheric chemistry. These devices generate high-powered narrowband radiation in the ~1–5-THz band through intersubband transitions in a periodic semiconductor heterostructure [1], with continuous-wave output powers in excess of 100 mW (or ~2.5 –W pulsed) being achievable.

A particular area of focus for study in the THz band is the Mesosphere and Lower Thermosphere (MLT) region of the Earth's upper atmosphere, which in many respects is a "gateway" to the near-space environment, where natural and anthropogenic energy-flux inputs from Earth meet solar radiation and energetic particles from above. The MLT is of great interest to climate researchers, in part because its thermal response to "greenhouse gas" accumulation and ozone depletion appears to be an order of magnitude greater than that of the lower atmosphere, thus providing a very sensitive indicator of climate-change phenomena [2]. To date, though, many of the principal gas species in the MLT (O, OH, CO, NO etc) have only been observed directly through limited "one off" rocket-based measurements, and no continuous global mapping experiments have been achievable. This is because the spectral features of these gases lie within the THz band of the electromagnetic spectrum (e.g., O: 4.7-THz, OH: 3.5-THz), which cannot be observed using conventional infrared or millimeter-wave instruments, and existing THz instruments are too large, complex and power-hungry for satellite-based operation. Furthermore, numerous aspects of the chemistry in this atmospheric region remain unstudied, e.g., the break-down of volatile-organic compounds, and their impact on the methane lifetimes, leading to considerable uncertainty in climate models. Although the species of interest (e.g., peroxy radicals) have THz spectral feature, no laboratory instrumentation has been developed with the bandwidth, precision or sensitivity needed for a detailed analysis of the reaction chemistry.

We present techniques to address these needs: compact and integrated QCL-based systems with the robustness and low-power consumption for satellite-receiver deployment, and a broadband gas-spectroscopy method, based on self-mixing, enabling ~17-GHz spectroscopic bandwidth without the need for a terahertz detector.

2. Waveguide integrated THz-QCL satellite payloads

A low-Earth-obit radiometry satellite, LOCUS (Linking Observations of Climate, the Upper-atmosphere and Space-weather) has been proposed [3], which includes 3.5-THz and 4.7-THz receivers employing QCL-based local oscillators (LOs). These present advantages over conventional gas laser LOs, as the QCLs are just ~1-mm-long, and require no pump laser or reference oscillator. Previous QCL-LOs for airborne [4] and balloon [5] deployment are unsuitable for satellite use, owing to their use of discrete components. By contrast, we have integrated QCL-LOs with micro-machined waveguides and a pair of diagonal feedhorns to deliver a robust ~1-cm^3 system, which has been demonstrated within a space-compliant cryocooler and integrated with Cassegrain-telescope fore-optics.

A ~3.5 THz QCL was processed into a double-metal ridge waveguide with (75 ×980)-μm^2 top-surface area, with substrate thickness of 90 μm. The device was cleaved to 980-μm length and diced into a 110-μm-wide chip, and solder-mounted within a precision micro-machined (130 × 75)-μm^2 channel within an oxygen-free copper enclosure (Fig. 1, left). The device was ribbon-bonded to an integrated SMA connector, and a second copper section was attached to form a rectangular waveguide enclosure around the QCL [Fig. 1(middle)]. A diagonal feedhorn at each end of the waveguide, provides a high-quality far-field emission with 5–8° divergence [Fig. 1(right)] and enables simultaneous coupling to the receiver, and a frequency-stabilisation subsystem. Operation was achieved within a satellite-compliant cooler, at a stable ~60 K, with an output power in excess of 8 mW.

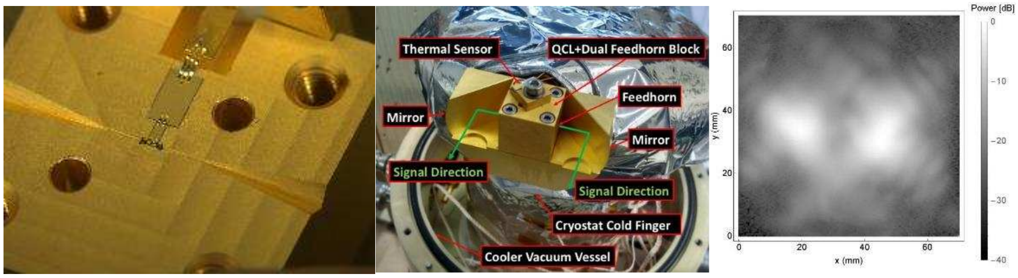

Fig. 1. (Left) Photograph of interior of QCL-LO module, showing a 3.5-THz QCL located within a waveguide channel, with a pair of diagonal feedhorns, (middle) Exterior view of complete assembled block, with mirrors attached for beam profiling, and (right) THz beam profile using a raster-scanned Golay detector

3. Multi-mode detector-free gas spectroscopy

We have demonstrated gas spectroscopy using the emission from a single-feedhorn waveguide-integrated QCL similar to that described above [6]. The radiation emitted from the feedhorn was directed through a gas-cell containing methanol vapour at 5 Torr, and reflected back through the cell into the laser cavity [Fig. 2(c)]. The resulting “self-mixing” perturbation to the laser field led to a QCL voltage perturbation, which was dependent on both the feedback strength (i.e., gas absorption), and on the optical phase (i.e. total optical path length). The QCL voltage was recorded while the optical path was extended using a pair of mirrors on a linear translation stage to obtain a total 800-mm interferogram. The QCL emission spectrum was then inferred by taking a Fourier transform allowing multiple emission lines to be analyzed simultaneously. The spectrum of the gas [Fig. 2(a,b)] was determined by adjusting the QCL mode frequencies via its drive current, and calibrating the signal against an empty reference cell. A total measurement bandwidth of ~17 GHz was achieved, with a minimum detectable absorption coefficient of 3×10^{-4} cm^{-1}.

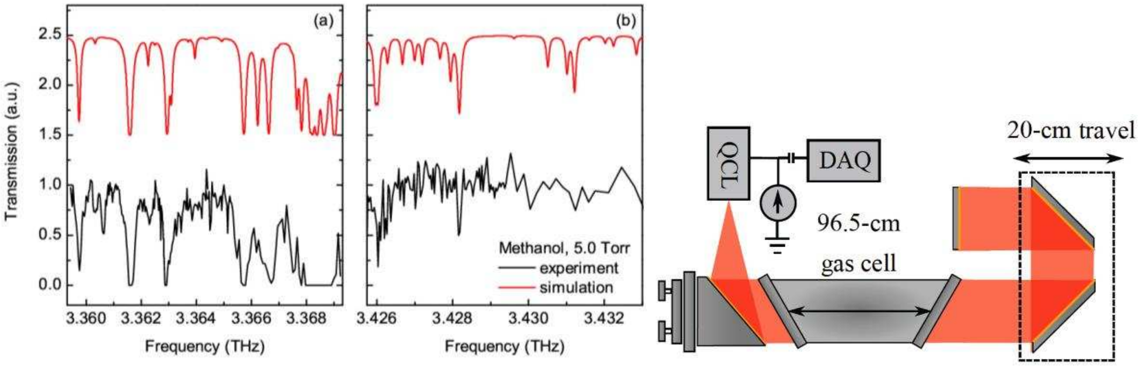

Fig. 2. (a,b) Methanol transmission spectra at 5 Torr, around each principal laser emission mode, (c) schematic of self-mixing spectroscopy system

In conclusion, we have shown that a precision micro-machining technique enables the development of ultra-compact QCL-based local-oscillators, which are compliant with satellite-ready payload environments, and a self-mixing “detector free” technique enables their use in high-bandwidth spectroscopy.

References

[1] R. Köhler et al., “Terahertz semiconductor-heterostructure laser,” Nature, vol. 417, pp. 156–159, May 2002.

[2] G. Beig et al., “Review of mesospheric temperature trends,” Rev. Geophys., vol. 41, no. 4, p. 1015, Dec. 2003.

[3] S. P. Rea et al., “The Low-Cost Upper-Atmosphere Sounder (LOCUS),” in 26th international symposium on space terahertz technology, Cambridge, MA, 2015.

[4] H. Richter, M. Wienold, L. Schrottke, K. Biermann, H. T. Grahn, and H.-W. Hubers, “4.7-THz Local Oscillator for the GREAT Heterodyne Spectrometer on SOFIA,” IEEE Trans. THz Sci. Technol., vol. 5, no. 4, pp. 539–545, Jul. 2015.

[5] D. J. Hayton et al., “A 4.7 THz HEB/QCL heterodyne receiver for STO-2,” in 2014 39th International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz), 2014, pp. 1–2.

[6] Y. J. Han et al., “Gas spectroscopy through multimode self-mixing in a double-metal terahertz quantum cascade laser,” Opt. Lett., OL, vol. 43, no. 24, pp. 5933–5936, Dec. 2018.