White Rose Research Online
eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk
Universities of Leeds, Sheffield and York

Deposited via The University of Leeds.

White Rose Research Online URL for this paper:
https://eprints.whiterose.ac.uk/id/eprint/103427/

Version: Accepted Version

Proceedings Paper:

Linfield, EH, Valavanis, A, Han, YJ et al. (2016) Terahertz frequency quantum cascade lasers for use as waveguide-integrated local oscillators. In: 10th European Conference on Antennas and Propagation (EuCAP 2016). 10th European Conference on Antennas and Propagation (EuCAP 2016), 10-15 Apr 2016, Davos, Switzerland. IEEE. ISBN: 9788890701863.

https://doi.org/10.1109/EuCAP.2016.7481523

© 2016 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other users, including reprinting/ republishing this material for advertising or promotional purposes, creating new collective works for resale or redistribution to servers or lists, or reuse of any copyrighted components of this work in other works.

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.

UNIVERSITY OF LEEDS
University of Sheffield
UNIVERSITY of York

Terahertz frequency quantum cascade lasers for use as waveguide-integrated local oscillators

E. H. Linfield[1], A. Valavanis[1], Y. J. Han[1], L. H. Li[1], J. X. Zhu[1], R. Dong[1], P. Dean[1], A. G. Davies[1], N. Brewster[2], L. Bushnell[2], M. Oldfield[2], and B. N. Ellison[2]
[1] School of Electronic and Electrical Engineering, University of Leeds, Leeds LS2 9JT, U.K., e.h.linfield@leeds.ac.uk
[2] Rutherford Appleton Laboratory, STFC, Harwell Oxford, Didcot OX11 0QX, U.K.

***Abstract*—Since their first demonstration in 2002, the performance of terahertz frequency quantum cascade lasers has developed extremely rapidly. We consider the potential use of terahertz frequency quantum cascade lasers as local oscillators in satellite-borne instrumentation for future Earth observation and planetary science missions. A specific focus will be on the development of compact, waveguide-integrated, heterodyne detection systems for the supra-terahertz range.**

***Index Terms*—terahertz frequency, quantum cascade laser, heterodyne detection, waveguide-integration, Earth observation, plentary science.**

I. INTRODUCTION

The last 20 years have witnessed a remarkable growth in terahertz (THz) frequency science and engineering (300 GHz – 10 THz), which is maturing into a vibrant international research area. A wide range of organic and inorganic crystalline materials and gases exhibit characteristic vibrational/rotational modes in the THz frequency range [1], which have been exploited using current technology to create new methodologies for process monitoring and non-destructive testing in the pharmaceutical and electronics sectors, *inter alia*.

However, despite the current success and future potential of THz spectroscopy, even a cursory comparison between what is currently possible in this part of the spectrum with that in the neighbouring microwave and optical regions reveals THz frequency science and technology to be still very much in its infancy. The principal reason for this has been the lack of compact, convenient, semiconductor-based THz sources, capable of operation at room temperature or even with a Peltier cooler. Work to date principally exploits THz sources that although operational at room temperature, nonetheless require expensive, bulky and power hungry femtosecond pulsed near-infrared lasers.

One of the most promising, high power, compact sources of THz radiation is the quantum cascade laser (QCL) – an inter-subband semiconductor laser based on a sophisticated layered superlattice. The THz frequency QCL was first demonstrated in 2002, and can provide intense, precisely controlled, monochromatic radiation [2].

II. TERAHERTZ FREQUENCY QUANTUM CASCADE LASERS

Since their first demonstration, progress in developing THz QCLs has been rapid. They have been shown to have a unique and desirable set of source characteristics including a narrow, quantum-limited linewidth (~200 Hz) [3], high output powers (>1 W) [4], pulsed operation up to a temperature of 200 K [5], and a frequency coverage from ~1 – 5 THz.

The long wavelength of the emitted radiation has readily allowed THz QCLs to be photonically engineered, leading to the tailoring of the emitted beam profile, frequency and output power, including using photonic crystal lasers [6,7], graded photonic heterostructures [8], and 'spoof' surface plasmons [9, 10]. And, with these developments has also arisen electronic control, including the demonstration of THz pulse amplifiers based on QCL cavities [10], and active mode-locking of THz QCLs, leading to the first measurement of sampling coherence in a QCL [11, 12].

Progress over the last decade has been extremely rapid, with an increasing number of researchers investigating THz QCLs year-on-year. But, the question remains – what is the long-term prospect for THz QCL technology being translated into applications outside the laboratory, and where do these devices offer significant advantages compared with competing terahertz technologies, such as time-domain spectroscopy? And here, despite the recent development of a broad range of compact and cryogen-free cryostats, the current maximum operating temperature for THz QCLs remains a barrier. But, there is one application area where THz QCLs appears to be the only solution, and where THz QCLs are suitable for uptake now – satellite-based instrumentation for Earth-observation and planetary science.

III. SATTELITE-BASED INSTRUMENTATION FOR THE SUPRA-TERAHERTZ RANGE

The possibility of using THz QCLs for Earth-observation and planetary science is well exemplified by their potential for the study of the mesosphere and lower thermosphere (MLT) region of the Earth's atmosphere (between 55 and 150 km).

The MLT forms the gateway to our near space environment, and is considered to be a key indicator of global climate change. Its exotic chemistry is driven by high-energy atomic O and OH radicals, and is characterized by strong spectral features within the THz band, including O (4.7 THz), and OH (4.7 THz and 3.5 THz), together with O_3 (4.7 THz), CO (3.5 THz) and HO_2 (3.5 THz). But, measurements of these important atmospheric species have yet to be made directly in satellite missions owing to the lack of suitable THz instrumentation, and in particular high power, compact, local oscillators for heterodyne spectrometry. The THz QCL has sufficient continuous-wave output power (~mW) to address this need, and space-qualified cryocoolers have the cooling power necessary for THz QCL operation at cryogenic temperatures (e.g. <100 K). The opportunity exists, but the technology readiness levels need to be increased to achieve the strict specifications required for space flight. This includes the need to integrate THz QCLs into robust sub-components.

IV. INTERGRATING TERAHERTZ FREQUENCY QUANTUM CASCADE LASERS INTO MICROMACHINED WAVEGUIDES

We have demonstrated [13] a highly reproducible technique for integrating a double-metal THz QCL into a precision micro-machined waveguide channel, which has previously been developed to support waveguide-integrated THz-frequency mixers. Unlike previous integration schemes, this technique does not require fragile assemblies of antennas or lenses attached to the device or complex semiconductor processing. Furthermore, our method does not perturb the optical or electronic performance of the QCL, and is sufficiently mechanically robust for use in satellite-based platforms.

An array of 13 parallel 3.4-THz QCLs ($110 \times 980\ \mu m^2$ dimensions) was mounted in a cavity within a copper block, and the central device was aligned with a $300 \times 75\ \mu m^2$ precision-machined waveguide channel, where it was ribbon-bonded to an electrical connector. The exterior of the block provides a robustly mounted, and industry standard, SMA connector, an integrated temperature sensor and precision-machined mounting points for attachment to a cryostat.

The far-field profile of the THz beam exhibits a near-Gaussian shape, with no evidence of spatial "ringing" effects, and a divergence < 20° in all directions, representing a significant improvement over the ~120° divergence of unmounted double-metal devices. The threshold current for continuous-wave emission at 10 K, and the maximum operating temperature were $I_{th} = 130$ mA and $T_{max} = 77$ K respectively for the waveguide-integrated QCL, representing only a small change (*c.f.,* $I_{th} = 100$ mA and $T_{max} = 80$ K) compared with an equivalent, unmounted device. The emission spectrum, measured with an FTIR spectrometer, was also found to be unperturbed.

V. CONCLUSIONS

There is an undoubted need for high power, compact, local oscillators for heterodyne spectroscopy in the terahertz frequency range, and one exceptionally promising solution is the use of THz QCLs. Should sufficiently high technology readiness levels be attained, then the possibility is opened up for satellite-borne Earth-observation missions, as well as for future planetary science missions. This access to the supra-THz frequency range (2–5 THz) has simply not been possible before, and the prospects look extremely bright.

ACKNOWLEDGMENTS

We acknowledge support from the UK's Engineering and Physical Sciences Research Council, Natural Environment Research Council, and the Centre for Earth Observation and Instrumentation. We also acknowledge support from the Wolfson Research Merit Scheme, and the European Space Agency.

REFERENCES

[1] A. G. Davies, A. D. Burnett, W. Fan, E. H. Linfield, and J. E. Cunningham, "Terahertz frequency spectroscopy of materials of security relevance," *Materials Today*, 11(3), pp. 18-26, March, 2008.

[2] R. Köhler, A. Tredicucci, F. Beltram, H. E. Beere, E. H. Linfield, A. G. Davies, D. A. Ritchie, R. C. Iotti, and F. Rossi, 'Terahertz semiconductor-heterostructure laser," *Nature*, 417, pp. 156-159, May, 2002.

[3] M. Ravaro, S. Barbieri, G. Santarelli, V. Jagtap, C. Sirtori, S. Khanna, and E. Linfield, C. Manquest, "Measurement of the intrinsic linewidth of terahertz quantum cascade lasers using a near- infrared frequency comb, *Optics Express*, 2012, 20(23), pp. 25654- 25661, October, 2012.

[4] L. Li, L. Chen, J. Zhu, J. Freeman, P. Dean P, A. Valavanis, A. G. Davies, and E. H. Linfield, "Terahertz quantum cascade lasers with >1 W output powers," *Electronics Letters*, 50(4), pp.309-311, February, 2014.

[5] S. Fathololoumi, E. Dupont, C. W. I. Chan, Z. R. Wasilewski, S. R. Laframboise, D. Ban, A. Mátyás, C. Jirauschek, Q. Hu, and H. C. Liu, "Terahertz quantum cascade lasers operating up to ~ 200 K with optimized oscillator strength and improved injection tunneling," *Optics Express*, 20, pp. 3866–3876, February, 2012.

[6] . Chassagneux, R. Colombelli, W. Maineult, S. Barbieri, H. E. Beere, D. A. Ritchie, S. P. Khanna, E. H. Linfield, and A. G. Davies, "Electrically-pumped photonic crystal terahertz semiconductor lasers controlled by boundary conditions," *Nature*, 457, pp. 174-178, January, 2009.

[7] M. S. Vitiello, R. Nobile, A. Ronzani, A. Tredicucci, F. Castellano, T. Talora, L. Li, E. H. Linfield, and A. G. Davies, "Photonic quasi-crystal terahertz lasers," Nature Communications, 5, 5884, December, 2014.

[8] X. Gangyi, R. Colombelli, S. P. Khanna, A. Belarouci, X. Letartre, L. Li, E. H. Linfield, A. G. Davies, H. E. Beere, and D. A. Ritchie, "Efficient power extraction in surface-emitting semiconductor lasers using graded photonic heterostructures," *Nature Communications*, 3, 952, July, 2012.

[9] N. Yu, Q. J. Wang, M. A. Kats, J. A. Fan, S. P. Khanna, L. Li, A. G. Davies, E. H. Linfield, and F. Capasso, "Designer spoof surface plasmon structures collimate terahertz laser beams," *Nature Materials*, 9, pp. 730–735, August, 2010.

[10] G. Liang, E. Dupont, S. Fathololoumi, Z. R. Wasilewski, D. Ban, H. K. Liang, Y. Zhang, S. F. Yu, L. Li, A. G. Davies, E. H. Linfield, H. C. Liu, and Q. J. Wang, "Planar integrated metasurfaces for highly-collimated terahertz quantum cascade lasers," *Scientific Reports*, 4, 7083, November, 2014.

[11] N Jukam, S S Dhillon, D Oustinov, J Madeo, S Barbieri, C Sirtori, S Khanna, A G Davies, E H Linfield, and J Tignon,"Terahertz amplifier based on gain switching in a quantum cascade laser," *Nature Photonics*, 3, pp. 715–719, January 2009.

[12] S. Barbieri, M. Ravaro, P. Gellie, G. Santarelli, C. Manquest, C. Sirtori, S. P. Khanna, E. H. Linfield, and A. G. Davies, "Coherent sampling of active mode-locked terahertz quantum cascade lasers and frequency synthesis," *Nature Photonics*, 5, pp. 306–313, April, 2011.

[13] A. Valavanis, Y. J. Han, N. Brewster, P. Dean, D. Rui, 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 Letters*, 51(12), pp. 919-921, June, 2015.