UNIVERSITY OF LEEDS

This is a repository copy of *Waveguide integrated terahertz quantum-cascade laser systems*.

White Rose Research Online URL for this paper:
https://eprints.whiterose.ac.uk/184804/

Version: Accepted Version

Proceedings Paper:

Nuttall, E orcid.org/0000-0002-1338-8732, Han, YJ, Pardo, D et al. (17 more authors) (2021) Waveguide integrated terahertz quantum-cascade laser systems. In: 2021 46th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz). 2021 46th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz), 29 Aug - 03 Sep 2021, Waveguide integrated terahertz quantum-cascade laser systems. IEEE . ISBN 978-1-7281-9425-7

https://doi.org/10.1109/irmmw-thz50926.2021.9567247

© 2021 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, 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 component of this work in other works. 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/

Waveguide integrated terahertz quantum-cascade laser systems

E. Nuttall[1], Y. J. Han[1], D. Pardo[2], M. D. Horbury[1], S. S. Kondawar[1], N. K. North[1], I. Kundu[1],
O. Auriacombe[2], T. Rawlings[2], N. Brewster[2] , M. Oldfield[2], M. Salih[1], L. H. Li[1], E. Zafar[1],
A. G. Davies[1], E. H. Linfield[1], E. Saenz[3], H. Wang[2], B. N. Ellison[2] and A. Valavanis[1]
[1]School of Electronic and Electrical Engineering, University of Leeds, LS2 9JT, UK
[2]RAL Space Department, UKRI-STFC, Harwell Campus, Didcot, OX11 6QX, UK
[3]Radio Frequency Payloads and Technology Division, European Space Agency, Noordwijk, The Netherlands

***Abstract*—We have developed precision micromachining techniques for integration of terahertz quantum cascade lasers (QCLs) with waveguides and feedhorns for use as local oscillators in satellite-borne receivers. We demonstrate these techniques using QCLs at 3.4 THz and 4.7 THz, as well as the first QCL with a monolithically integrated power modulator.**

I. INTRODUCTION

MANY gases exhibit characteristic emission lines within the terahertz (THz) range. As a result, THz spectroscopy is a powerful technique in Earth observation and space research. Measuring the chemical composition and dynamics, particularly of gases that appear in the Earth's upper atmosphere, can allow for more accurate climate models and aid in our understanding of how our atmosphere is changing in response to anthropogenic pollutants and "greenhouse" gases.

THz quantum cascade lasers (QCL) are an ideal source to be used as local oscillators (LOs) in heterodyne spectroscopy for the analysis of gases owing to their narrow intrinsic linewidths, high light intensities and compact size, which underpins their potential use on satellite platforms. However, QCLs are typically coupled optically with other instrumentation through the far-field, leading to large system sizes, power loss and poor mechanical robustness.

In this work, we discuss recent progress in the integration of 3.4-THz and 4.7-THz QCLs with precision micro-machined waveguides [1]. To further improve QCL performance for use as an LO, precise control is required over the emission frequency and output power. We show that by monolithically integrating a QCL with a racetrack resonator (RTR) structure [2] within a waveguide cavity, the THz output power can be modulated and controlled.

II. WAVEGUIDE AND FEEDHORN INTEGRATION

The QCLs used in this work were based on phonon-assisted bound-to-continuum active-region devices operating around 3.5 THz [3] and 4.7 THz [4]. These were processed into gold–gold double-metal plasmonic ridge waveguides with areas of $(57 \times 1000)\ \mu\mathrm{m}^2$ and $(72 \times 1200)\ \mu\mathrm{m}^2$ respectively upon substrates with 90-μm thickness.

Waveguide modules were produced using pairs of oxygen-free copper blocks, into which (160×80)-$\mu\mathrm{m}^2$ rectangular-cross-section channels were precision milled. Pairs of blocks were co-registered to form complete rectangular waveguide channels. A high surface quality was achieved through a diamond turning approach, followed by electro-less plating. To enable testing of the coupling of the QCL to the waveguide, the channels were out-coupled into a free-space propagating mode, using diagonal feedhorns with a slant angle of 7.5° and an across-diagonal aperture of $(1.56 \times 1.56)\ \mathrm{mm}^2$.

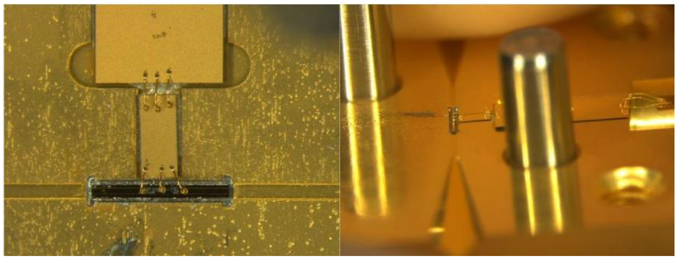

Fig.1. 4.7-THz QCL integrated within a waveguide cavity with two diagonal feedhorns. (left) Close-up view of QCL (right) feedhorns and waveguide channel

QCLs were soldered-mounted directly into the waveguide channel, and wire-bonded to an integrated electrical SMA connector via an intermediate thermal-isolation heatsink (Fig. 1). The complete modules were mounted on the cold-finger of a Janis ST-100 liquid-helium cryostat and driven using an Agilent 8114A high-current pulse generator. The emitted THz radiation was coupled into a helium-cooled bolometric detector using a pair of off-axis paraboloidal mirrors.

Fig. 2 shows the recorded detector signal as a function of QCL drive current for the 4.7-THz waveguide-integrated device, which is comparable to that of an equivalent unmounted device. A Bruker Fourier Transform Infrared (FTIR) spectrometer was used to measure the emission spectrum of the lasers at their peak emission power as 3.365 THz and 3.421 THz for the nominal 3.4-THz device, and 4.794-THz for the nominal 4.7-THz device.

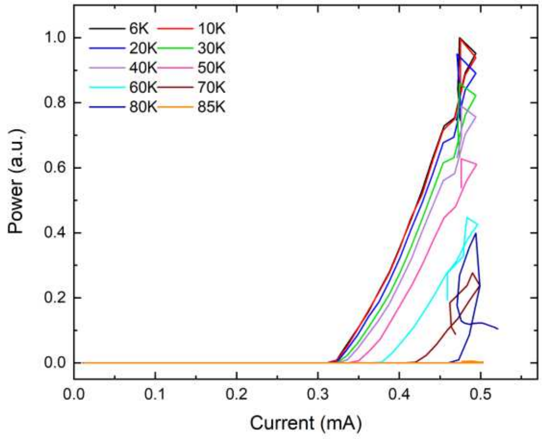

Fig.2. Light-current measurements of a 4.7-THz waveguide-integrated QCL as a function of operating temperature.

The 3.5-THz QCL was found to operate in continuous-wave mode, with a maximum operating temperature of 85 K and a threshold current of 120 mA at low temperature. By contrast, the 4.7-THz QCL operated only up to 95% duty-cycle. At low duty-cycle (2%), a maximum operating temperature of 80 K was achievable, and a threshold current of 320 mA was recorded at low temperature. An analysis of the output power as a function of pulse duty cycle was used to calculate the thermal resistance of the device as 30 K/W, indicating that the reduced performance was a result of imperfections in the thermal mounting rather than the QCL active region or waveguide properties.

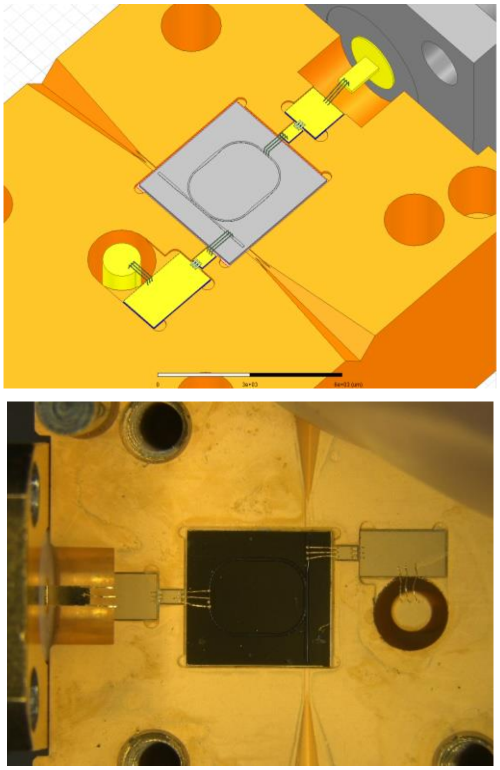

Fig.3. (top) 3D rendering and (bottom) microscope image of a QCL with integrated RTR mounted within a waveguide module.

III. INTEGRATED POWER MODULATION

We have previously shown that a racetrack-resonator (RTR) structure may be coupled to a QCL ridge. The optical mode coupling between the two structures may be controlled by adjusting the bias applied to the RTR. This causes a variation in the THz power from the QCL without changing the emission frequency. As such, we have investigated this structure as a potential route to integrated THz LO-power locking for satellite payload applications.

A 3.4-THz QCL–RTR device was processed using maskless photolithography and dry reactive-ion etching to define and electrically isolate the two structures. A waveguide module was produced using a similar precision-micromachining process to that described in Section II. The design was modified such that two electrical connectors were used to provide independent bias to the RTR and QCL sections.

The device was mounted and characterized using a similar method to that presented in Section II. A continuous d.c. bias was applied to the QCL such that the maximal THz power was recorded using a bolometric detector. A second, independent d.c. bias was then applied to the RTR and the variation in the emitted THz power was recorded. Figure 3 shows that a 100% modulation in the emitted power was achievable with the device operating at a 50-K heat-sink temperature.

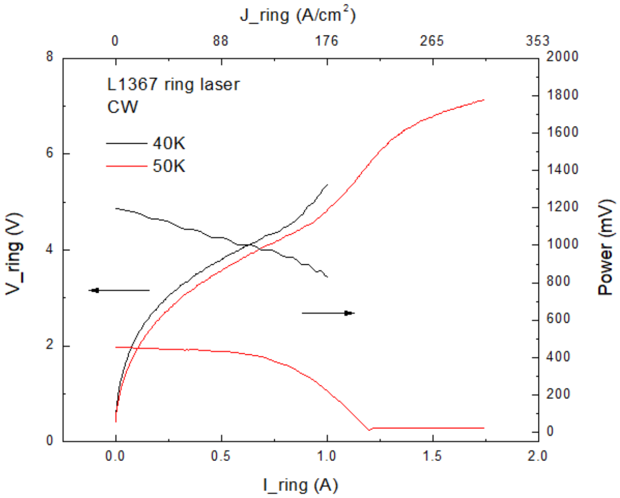

Fig.4. Measurements of the emitted THz power and RTR voltage from QCL–RTR device as a function of drive current through the ring.

IV. CONCLUSIONS

We have fabricated and integrated 3.4-THz and 4.7-THz QCLs into precision-micromachined waveguide cavities. In each case, the threshold current and operating temperature ranges are comparable with equivalent unmounted devices, indicating that the integration scheme does not adversely affect electrical performance of the device. The 4.7-THz device is limited to 95% duty-cycle operation, implying imperfections in the thermal mounting. However, the 3.4-THz device operates in continuous wave mode, demonstrating the viability of the integration scheme. Nevertheless, the 4.7-THz device shown here is the highest-frequency integrated QCL to be demonstrated to date.

A QCL with a monolithically integrated racetrack resonator has been shown to enable 100% power modulation and has been integrated within a micromachined waveguide structure similar to that of the individual QCLs. This will underpin future systems to lock the output power of QCL systems within satellite payloads. Future work will focus on optimizing the power outcoupling and thermal performance of QCL waveguide modules, and on investigating their terrestrial applications in THz gas spectroscopy and imaging.

REFERENCES

[1] B. Ellison *et al.*, *Int. J. Microw. Wirel. Technol.* **11**, 909–917 (2019).
[2] I. Kundu *et al.*, *Opt. Express* **28**, 4374–4386 (2020).
[3] M. Wienold *et al.*, *Electron. Lett.* **45**, 1030–1031 (2009)
[4] L. Schrottke *et al.*, *Semicond. Sci. Technol.* **28**, 035011 (2013)