Development of Quantum Cascade Lasers at 2.7 THz for Heterodyne detection

François Joint[1,2], Thibaut Vacelet[1], Gregory Gay[1], Yan Delorme[1], Raffaele Colombelli[2]

[1]*LERMA, Laboratoire d'Études du Rayonnement et de la Matière en Astrophysique et Atmosphères*

[2] *Centre de Nanosciences et de Nanotechnologies, CNRS, Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay cedex, France*
***Email**:* francois.joint@u-psud.fr

***Abstract*-We have developed a single mode emission, low power consumption THz QCL operating at a specified target frequency for sensitive heterodyne detections. The Fabry-Pérot THz QCL is of limited use since its output power is distributed over many spectral modes. The approach we have chosen is the distributed-feedback (DFB) architecture, in particular the 3rd-order DFB grating that can provide single mode emission as well as small beam divergence. To obtain single mode operation at the desired frequency we have fabricated several devices with different grating periods and/or grating duty cycle. This strategy allows to thinly cover a relatively broad range of emission frequencies. Upon electro-optical characterisation of the lasers, the devices that best suit the application can be selected. The laser design is based on judicious electromagnetic modelling. Particular care has been taken to reduce the overall size as much as possible, in order to minimise the power dissipation. We obtained devices with very low electrical dissipation, which is suitable for embedded THz detection systems.**

I. INTRODUCTION

There is a particular interest in astronomy for the detection of radiation from cold interstellar gases. These emissions typically fall in the THz range of the electromagnetic spectrum: for instance, an important transition of deuterated hydrogen falls at 2.7 THz (90 cm^{-1}). Heterodyne detection is ideally suited to capture these signals with high spectral resolution.

Heterodyne detection requires local oscillator sources that operate a few GHz away from the frequency of interest. THz quantum cascade lasers [*1*] (QCL) emerged recently as suitable sources for the detection of signals above 2 THz. The combination of a THz QCL with an ultra-sensitive hot electron bolometer (HEB), cooled at 4K for mixing [*2*], is a very attractive solution to achieve heterodyne detections with very high sensitivity and at frequencies around or far beyond 2 THz.

II. 3RD ORDER DFB LASER: FABRICATION AND CHARACTERISATION

The third order DFB QCL has been developed at C2N Orsay. The QCL is based on a metal-metal waveguide with deeply etched lateral corrugation (fig. 1). The active region is a 14 µm thick GaAs/$Al_{0,15}$GaAs quantum cascade structure which has been grown by molecular beam epitaxy on a semi-insulated GaAs wafer. The design of the active region is based on a four-well structure with a longitudinal optical phonon resonant depopulation mechanism. After the growth, the wafer is thermo-bonded with gold to a GaAs wafer. The grating and wire-bonding pads were defined by optical lithography then by gold deposition (Ti/Au, 5/250 nm). Laser ridges and lateral corrugation were defined by inductively coupled plasma reactive ion etching.

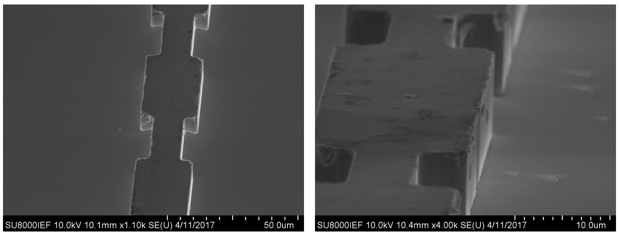

Fig. 1: SEM images of the third-order DFB QCL with deeply etched lateral corrugation

The emission of such QCL is mainly determined by the periodicity of the grating and also by the filling factor between the narrow and the wide part of the waveguide.

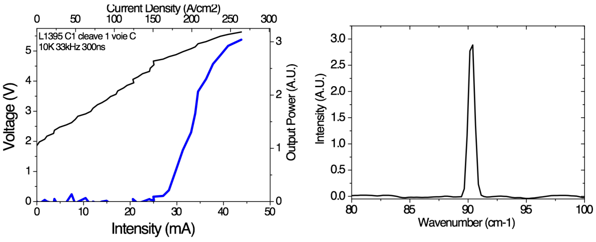

Fig. 2: I-V curve and I-L curve (left) of the third-order DFB QCL and measured spectrum of the QCL (right) at 10K in pulsed mode

We have characterised the lasing spectrum with a Fourier Transform Spectrometer using a deuterated triglycine sulfate (DTGS) Terahertz detector. The important aspect of this work is that we achieved single mode emission at the target frequency (90cm^{-1}). By finely adjusting the grating periodicity and filling factor during the design of the lithography mask, we managed to obtain devices with the emission exactly at our target frequency. This is of interest when we consider heterodyne detections of molecular transitions as one needs a local oscillator emission very close to the specific frequencies.

The measured laser emission stays single mode from the lasing threshold to the limit of applied current on the device and up to 75 K. In In CW (Continuous Wave) mode, the current-voltage-power (I-V-L) curves of the third-order DFB QCL (Figure 2) at 10 K show a very low threshold driving current (< 30 mA) while the DC dissipation of the device stays below 250 mW over the whole operation range. These characteristics make the component compatible for compact integration. The maximum output power measured with an absolute power meter in CW at 10 K was 800 µW, which is among the state-of-art results.

As shown in the modeling and simulations [3] of a third order DFB waveguide, the third-order diffracted mode is used for the distributed feedback while the first and the second-order diffracted modes for the output coupling. If the effective index of the cavity is set at $n_{eff} = 3$, and the grating periodicity is equal to half of the free space wavelength, then the radiations coming from each of the apertures are adding up constructively at both ends of the waveguide. One can compare the functioning of the 3rd order DFB QCL light extraction process to a one dimensional end-fire antenna array.

We have performed the far-field beam pattern measurements using a room temperature Golay cell with a 2D rotation test setup. The laser operating in pulsed mode was cooled down to 4K and was at a distance of 90 mm from the detector. We can see that the QCL has a single lobed emission and the FWHM of the beam is roughly 15x20 degree.

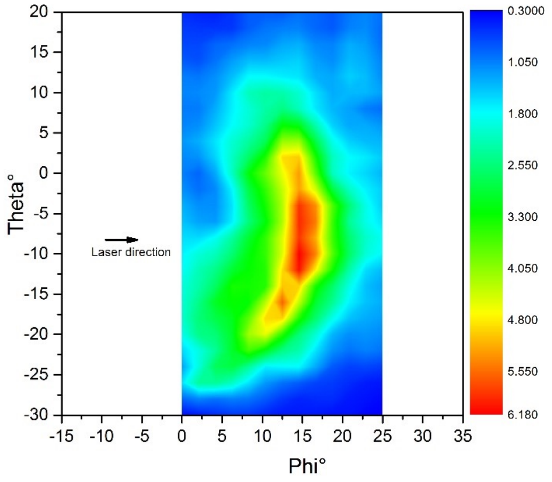

Fig. 3: Measured beam pattern of the third-order DFB QCL.

III. CONCLUSION

We have designed and fabricated the 3rd Order DFB lasers and have demonstrated by measurements that it is possible to get a single mode emission at a specified frequency. The single lobed beam has a FWHM around 15 x 20 degree, which is rather small compared to standard metal-metal waveguide. The low driving currents and low power dissipation of those devices make them suitable for ultra-compact systems, such as THz heterodyne detectors for space applications.

In order to increasing the coupling efficiency between the QCL and our mixers, we are currently working on several solutions to improve or re-shape the QCL's beam pattern, such as hollow dielectric waveguides, mirrors and dielectric lenses.

We thank Edmund H. Linfield and Lianhe Li from Leeds University for providing us with the QCL epitaxy structure (L1395). We acknowledge financial support from the Centre National d'Etudes Spatiales (CNES). The device fabrication has been performed at the nano-center CTU-C2N.

IV REFERENCES

1. C. Sirtori, S. Barbieri, R. Colombelli, *Wave engineering with THz quantum cascade lasers. Nat. Photonics. 7, 691–701 (2013).*
2. G. Gay, *Mélangeurs à bolomètres à électrons chauds sur membranes fonctionnant au-delà du THz pour l'instrument post-Herschel (2013) (available at https://tel.archives-ouvertes.fr/tel-00976996/).*
3. M. I. Amanti, G. Scalari, F. Castellano, M. Beck, J. Faist, *Low divergence Terahertz photonic-wire laser. Opt. Express.* ***18****, 6390–5 (2010).*