Proceedings Paper:

Houver, S, Lebreton, A, Colombelli, R et al. (5 more authors) (2016) Nonlinear frequency mixing in quantum cascade lasers: Towards broadband wavelength shifting and THz up-conversion. In: 2016 41st International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz). 41st International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz) 2016, 25-30 Sep 2016, Copenhagen, Denmark. IEEE . ISBN 9781467384858

https://doi.org/10.1109/IRMMW-THz.2016.7758416

Nonlinear Frequency Mixing in Quantum Cascade Lasers: Towards Broadband Wavelength Shifting and THz Up-Conversion

S. Houver[1,*], A. Lebreton[1], R. Colombelli[2], L. Li[3], E. H. Linfield[3], A. G. Davies[3], J. Tignon[1] and S. S. Dhillon[1]

[1]Laboratoire Pierre Aigrain, Ecole Normale Supérieure-PSL Research University, CNRS, Université Pierre et Marie Curie-Sorbonne Universités, Université Paris Diderot-Sorbonne Paris Cité, 24 rue Lhomond, 75231 Paris Cedex 05, France

[2] Institut d'Electronique Fondamentale, Univ. Paris Sud, UMR8622 CNRS, 91405 Orsay, France

[3]*School of Electronic and Electrical Engineering, University of Leeds, Woodhouse Lane, Leeds LS9 2JT, U.K.*

**Contact Email: sarah.houver@lpa.ens.fr*

***Abstract*— Terahertz (THz) sideband generation on a near-infrared (NIR) carrier has been recently demonstrated using quantum cascade lasers (QCL), with potential applications in wavelength shifting and THz up-conversion. However, the NIR wavelength range and nonlinear efficiency were severely limited by absorption. Here we overcome this drawback through a novel reflection geometry, whilst preserving a large interaction area. As well as insights into the nonlinear mechanism, this allows a much large range of NIR pump energies, relaxing the criteria of using particular excitation wavelengths.**

I. I. INTRODUCTION

THz nonlinear optics is in constant development thanks to performances of high-intensity THz sources. However, these sources remain expensive and require a considerable operational know-how. We have recently demonstrated that it is possible to exploit the THz fields generated by a compact source, the quantum cascade laser (QCL) [1], for THz nonlinear optics. By exploiting resonant nonlinearities, we have shown [2, 3] nonlinear frequency mixing between a near infrared (NIR) pump (E_{NIR}) and a THz beam (E_{QCL}) within a QCL cavity for sideband generation i.e. $E_{NIR} \pm E_{QCL.}$

In these previous studies, sideband generation have been demonstrated in a transmission geometry, where E_{NIR} is coupled through one end of the cavity and the sideband exits the opposite end. However, sideband generation was inherently limited to a finite pump energy range, the sideband being rapidly absorbed by the bandgap. In this work, to overcome this absorption limitation and, by an appropriate novel reflection geometry, we demonstrate nonlinear frequency mixing between the external NIR and THz QCL photon on a much wider energy range.

II. QCL DESIGN

The active region of the THz QCL used in this work was a GaAs/AlGaAs quantum well system designed for laser action around 2.9 THz (12meV) [4]. The asymmetric quantum wells of the active region are the resonant nonlinear medium.

To implement the reflection geometry, engineered slits were realised on the metal top layer of the QCL, exposing the underlying quantum wells. The NIR pump is coupled into the active region by these slits. In this geometry, both NIR pump and sideband pass through 20µm of material, compared to the cavity length (~1.5mm) in transmission geometry. It is therefore possible to overcome absorption and observe sideband generation with NIR excitations at much higher energies.

III. SIDEBAND GENERATION IN REFLECTION GEOMETRY

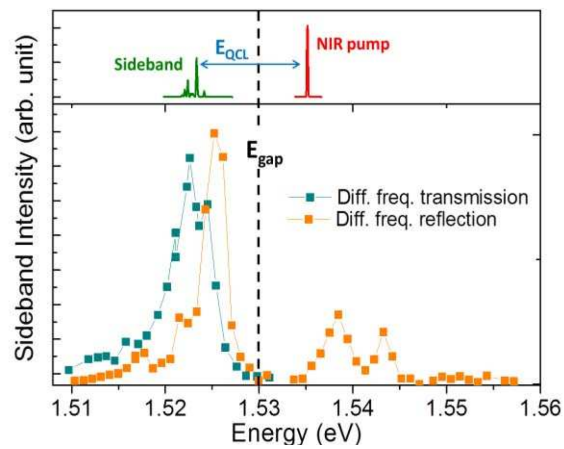

Figure 1: Top: typical spectrum of pump and sideband for difference frequency generation. Difference frequency generation as a function of sideband energy for transmission geometry (blue) and reflection geometry (orange)

We show that both difference and sum frequency sidebands are observed on an NIR energy range of 40 meV, up to 1.558eV, considerably greater than the bandgap. By reducing the interaction distance to 20 µm, it is possible to excite higher electronic levels which could not be observed in a transmission geometry. This shows that the inherent effect of absorption can be overcome. Moreover, by comparing the results with nonlinear susceptibility calculations, the electrons and holes states involved in sideband generation can be identified.

To conclude, sideband generation in a reflection geometry has been demonstrated in a THz QCL over a wide pump energy range (~40meV). It has been possible to largely overcome absorption and excite higher electronic states with the goal to reach higher sideband efficiencies. This will permit this work to be applied to THz up-conversion and all-optical wavelength shifting.

REFERENCES

[1].J. Faist et al., "Quantum Cascade Laser", *Science* **264**, 553-556 1994.

[2].J. Madeo et al. , "All-optical wavelength shifting in a semiconductor laser using resonant nonlinearities", *Nat. Photon.* **6**, 519-524 2012.

[3].P. Cavalie et al."High order sideband generation in terahertz quantum cascade lasers", *Appl. Phys. Lett.* **102**, 2013.

[4].M. I. Amanti et al., "Bound-to-continuum terahertz quantum cascade laser with a single-quantum-well phonon extraction/injection stage", *New J. Phys.* **11**, 2009.