ITQW 2019

Infrared Terahertz Quantum Workshop

September 15-20, 2019

Ojai, California, USA

ITQW

OJAI, CA 2019

Program and Abstract Catalog

Modelling the intra-cavity dynamics behind phase locking of quantum cascade laser frequency combs

Nikola Opačak[1*], Gottfried Strasser[1,2], Benedikt Schwarz[1]
[1] Institute of Solid State Electronics, TU Wien, Vienna, Austria
[2] Center for Micro- and Nanostructures, TU Wien, Vienna, Austria
*Contact Email: nikola.opacak@tuwien.ac.at

Short Abstract A model based on Maxwell-Bloch equations was developed in order to study phase locking dynamics of a free running mid-infrared QCL frequency comb. A thorough study of the impact of the dispersion and optical nonlinearities on the cavity mode dynamics was conducted. Recent experimental findings were reproduced for the first time, giving important insight into the governing mechanisms.

1. Introduction

Lasers whose optical spectrum consist of a set of equidistant modes with an unambiguous phase relationship, i.e. optical frequency combs, have proven themselves as high-precision tools for spectroscopy [1]. Due to the fact that fundamental absorption lines of many molecules lie in the mid-infrared (MIR) region of the electromagnetic spectrum, the quantum cascade laser (QCL) has become of great interest for spectroscopic applications, being the dominant laser source in the MIR. Apart from that, a substantial third-order nonlinearity in the laser active region can result in phase locking of the cavity modes and frequency comb generation without any need for additional optical components [2], making QCL based frequency combs an extremely active research topic. Unlike mode locked lasers, which are amplitude modulated, possess a Gaussian spectrum with constant phases and emit short pulses at the roundtrip frequency, free-running QCL frequency combs do not show such behavior. It is known from experimental data that they are dominantly frequency modulated with almost constant output power and a unique linear-like pattern in the phase differences between adjacent modes (Figure 1(a)), which corresponds to a chirp of the instantaneous frequency [3,4]. In fact, QCLs possess ultra-fast gain dynamics which result in the ability of the population pulsations (PP) to follow intensity modulations of the light field. One can relate the PPs in fast gain media to the repulsive mean field coupling, where the mean field corresponds to the collective action of all inter-mode beatings between the frequency comb lines. Namely, strong PPs, which would be caused by an in-phase mode locked comb operation, would result in a large parametric suppression of the gain, so one can conclude that QCLs inherently prefer an out of phase locking of the cavity modes in order to minimize PPs and efficiently utilize the available gain. A chirp in inter-mode phase differences splayed over a range of 2π satisfies the requirements, yet so far it was not clear why is it preferred over many other solutions which would also minimize PPs, e.g. sinusoidal FM modulated output with a Bessel spectrum.

2. Results

We have developed an appropriate theoretical model in order to simulate the intra-cavity dynamics and the process of phase locking of QCLs along with the reproduction of the crucial linear chirp in the inter-mode phase differences [5]. This was done (Figure 1(b)) by utilizing a model based on spatio-temporal coupled density matrix and Maxwell equations (Maxwell-Bloch) employing the

slowly varying envelope approximation [6]. In order to obtain a chirp, additional terms need to be incorporated to account for complex interplay between the optical nonlinearities and the group velocity dispersion present in the cavity. We show that it is exactly the interplay of these two effects that governs the process of phase locking inside the QCL, since their inclusion in the model leads to excellent agreement with the experiments. Furthermore, we study the effect of group velocity dispersion on the cavity mode dynamics on its own, which has been neglected in previous research.

In order to simulate an adequate number of cavity roundtrips (around 50 000) for a thorough study, a highly efficient numerical implementation of the equations was required. Hence, the main body of the code is parallelized and implemented on a GPU. This resulted in a decrease in the calculation time by more than two orders of magnitude compared to a parallel implementation on a CPU.

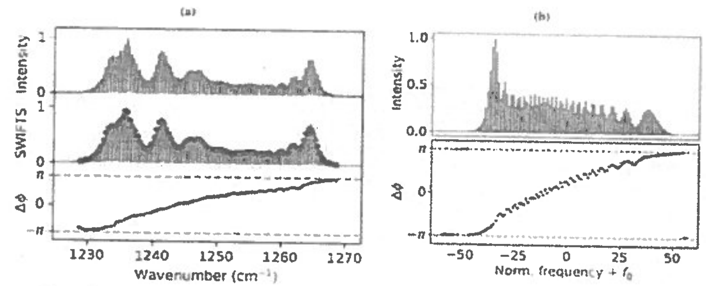

Figure 1: Intensity spectrum of the cavity modes and the phases of the intermode beatings between adjacent comb lines taken from: (a) measured data taken from [4]; (b) developed model, frequency is normalized to the roundtrip frequency [5].

References

[1] S. Schiller, "Spectrometry with frequency combs," *Optics Letters*, vol. 27, 766 (2002).

[2] A. Hugi, G. Villares, S. Blaser, H. C. Liu, and J. Faist, "Mid-infrared frequency comb based on a quantum cascade laser," *Nature*, vol. 492, 229 (2012).

[3] M. Singleton, P. Jouy, M. Beck, and J. Faist, "Evidence of linear chirp in mid-infrared quantum cascade lasers," *Optica*, vol. 5, 948-953 (2019).

[4] J. Hillbrand, A. M. Andrews, H. Detz, G. Strasser, and B. Schwarz, "Coherent injection locking of quantum cascade laser frequency combs," *Nature Photonics*, vol. 13, 101 (2019).

[5] N. Opačak, and B. Schwarz, "Theoretical investigation of phase locked quantum cascade laser frequency combs," *submitted*.

[6] R. Boyd, "Nonlinear Optics, 3rd ed., Elsevier, San Diego (2008).

Wednesday, September 18th

08:45-09:30 Session 10: Plenary Talk - Jérôme Faist
Chair: Daniel Wasserman

08:45 **Jérôme Faist**
Phonon-polariton lasers: optical and Raman emission (Plenary Talk)

09:30-10:30 Session 11: Frequency Combs 1
Chair: Alessandro Tredicucci

09:30 **Katia Garrasi**, Francesco Paolo Mezzapesa, Luca Salemi, Valentino Pistore, Sukhdeep Dhillon, Luigi Consolino, Saverio Bartalini, Paolo De Natale, Lianhe Li, Giles Davies, Edmund Linfield and Miriam Serena Vitiello
Quantum cascade lasers frequency combs at Terahertz frequencies

09:45 **Nikola Opačak**, Gottfried Strasser and Benedikt Schwarz
Modelling the intra-cavity dynamics behind phase locking of quantum cascade laser frequency combs

10:00 **David Burghoff**, Ningren Han, Filippos Kapsalidis, Nathan Henry, Mattias Beck, Jacob Khurgin, Jerome Faist and Qing Hu
Microelectromechanical control of the state of quantum cascade laser frequency combs

10:15 **Dmitry Kazakov**, Marco Piccardo, Benedikt Schwarz, Maximilian Beiser, Yongrui Wang, Michele Tamagnone, Wei-Ting Chen, Alexander Zhu, Alexey Belyanin and Federico Capasso
Frequency comb generation in ring injection lasers by defect engineering

10:30-10:50 Coffee Break (Exhibition is open)

10:50-12:50 Session 12: Mid-IR Quantum-cascade lasers and interband cascade lasers
Chair: Jérôme Faist

10:50 **Alexei Baranov**, Hoang Nguyen-Van, Zeineb Loghmari, Laurent Cerutti, Jean-Baptiste Rodriguez, Julie Tournet, Gregoire Narcy, Guilhem Boissier, Gilles Patriarche, Michael Bahriz, Eric Tournié and Roland Teissier
InAs-based quantum cascade lasers directly grown on silicon ***(Invited)***

11:20 **Seungyong Jung**, Daniele Palaferri, Feng Xie, Yae Okuno, Christopher Pinzone, Kevin Lascola and Mikhail Belkin
Monolithic integration of mid-infrared quantum cascade lasers coupled with low-loss passive InGaAs waveguides

11:35 **Hedwig Knötig**, Borislav Hinkov, Robert Weih, Sven Höfling, Werner Schrenk, Johannes Koeth, Johannes P. Waclawek, Bernhard Lendl and Gottfried Strasser
Continuous-Wave Operation of Ring Interband Cascade Lasers

11:50 Colin Boyle, Jeremy Kirch, Luke Mawst, Yuri Flores and **Dan Botez**
Impact of Interface-Roughness Scattering-Induced Carrier Leakage on High-Power, Mid-IR QCL Performance

12:05 **Zhixin Wang**, Yong Liang, Bo Meng, Yanting Sun, Giriprasanth Omanakuttan, Emilio Gini, Mattias Beck, Ilia Sergachev, Sebastian Lourdudoss, Jérôme Faist and Giacomo Scalari
Large Area Surface-Emitting Photonic Crystal Quantum Cascade Laser

12:20 **Matthew Suttinger**, Rowel Go, Ahmad Azim, Enrique Sanchez, Jonathan Brescia, Dagan Hathaway and Arkadiy Lyakh
Enhanced Midwave Quantum Cascade Laser Average Power with High Duty Cycle Pulsed Operation

12:35 **Hua Li**, Ziping Li, Wenjian Wan, Kang Zhou, Xiaoyu Liao, Sijia Yang, Chenjie Wang and Juncheng Cao
Compact terahertz multiheterodyne dual-comb spectroscopy based on self-detection quantum cascade lasers

13:00-20:00 Excursion and/or Free Time (www.itqw2019.com/social-program)

The conference excursion will be held in two parts:

13:00-15:30 Visit the **Old Creek Ranch Winery** for a wine tasting and **boxed lunch**. The Old Creek Ranch Winery is Ventura County's only rural winery and is located on an 850-acre ranch. The original winery was built in the late 1800's on property formerly known as Rancho Ojai. Guests can enjoy wines while relaxing in the beautiful outdoor seating areas. (Note – if some attendees would like to skip the winery and go straight to the beach, one bus will continue directly to Ventura).

15:30-20:00 The second part of the afternoon will be an **unstructured visit to Ventura**, a charming and historical California beach town about 15 miles from Ojai. After the buses drop off in Ventura, attendees are free to enjoy the beach and explore the town for several hours. Attractions include the Ventura Beach, Ventura Pier, bicycle path, Mission San Buenaventura, and Main Street which contains many stores, restaurants, and microbreweries. Local stores will rent bicycles, surfboards, and boogie boards. Buses will return to the Ojai Valley Inn at 18:00 and 20:00.