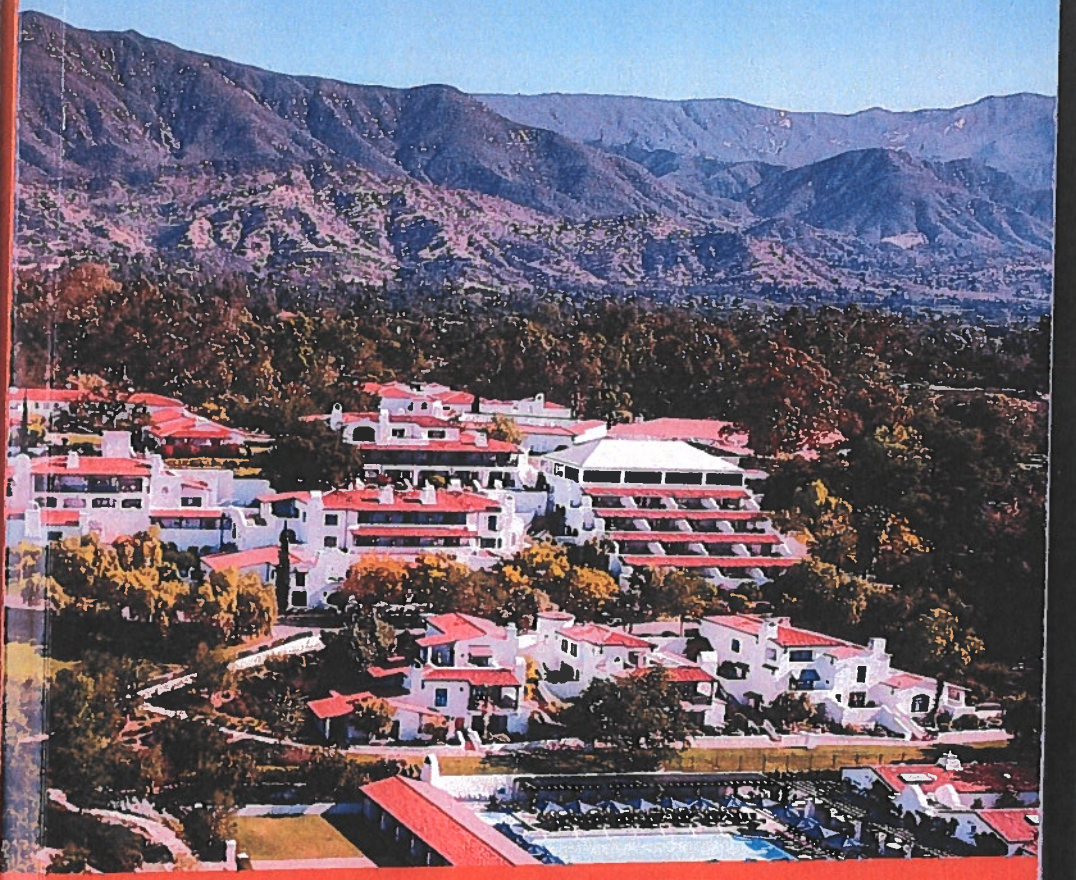
ITQW 2019

Infrared Terahertz Quantum Workshop

September 15-20, 2019

Ojai, California, USA



ITQW OJAI, CA 2019

Program and Abstract Catalog

Thursday, September 19th

09:00-09:10 Session 13: Industry Presentation

Chair: Heinz-Wilhelm Hübers

09:00 **Bob Shine**, Dave Caffey and Jeremy Rowlette
Markets and Applications of Commercial Quantum Cascade Laser Based Systems (Industry Presentation)

09:15-10:15 Session 14: Spectroscopy and Sensing

Chair: Heinz-Wilhelm Hübers

09:15 **Pierre Jouy**, Andreas Hugi, Markus Geiser, Raphael Horvath, Christopher Strand, Nico Pinkowski, Yiming Ding and Ronald K. Hanson
Dual comb spectroscopy with QCLs: shock tube applications and challenges for QCL frequency comb sources

09:30 **Florian Pilat**, Benedikt Schwarz, Hermann Detz, Aaron Maxwell Andrews, Bettina Baumgartner, Bernhard Lendl, Gottfried Strasser and Borislav Hinkov
QCLD-based lab-on-a-chip for μ-fluidic sensing

09:45 **Quankui Yang**
Hetero-cascading Quantum Cascade Lasers and their Application in Realtime Spectroscopy

10:00 **Alexandra Werth**, Yasin Kaya, Kalil Shaw, Noah Apthorpe, James Lee, Nsomma Alilonu, Sofia Inglessis and Claire Gmachl
Implementation of quantum cascade laser spectroscopy and multivariate analysis for noninvasive glucose monitoring

10:15-10:50 Coffee Break (Exhibition is open)

10:50-12:20 Session 15: Frequency Combs 2

Chair: David Burghoff

10:50 **Benedikt Schwarz**, Johannes Hillbrand, Maximilian Beiser, Nikola Opacak, Aaron Maxwell Andrews, Hermann Detz, Gottfried Strasser, Anne Schade, Robert Weih and Sven Höfling
*Towards monolithic and battery driven mid-infrared dual-comb spectrometers **(Invited)***

11:20 **Lukasz Sterczewski**, Mahmood Bagheri, Clifford Frez, Chadwick Canedy, Igor Vurgaftman, Mijin Kim, Chul Soo Kim, Charles Meritt, William Bewley and Jerry Meyer
Injection locking of interband cascade laser frequency combs

11:35 **Bo Meng**, Mattias Beck and Jérôme Faist
Mid-Infrared Frequency Comb from a Ring Quantum Cascade Laser

11:50 **Johannes Hillbrand**, Aaron Maxwell Andrews, Hermann Detz, Harald Schneider, Gottfried Strasser, Federico Capasso and Benedikt Schwarz
Actively mode-locked mid-infrared quantum cascade laser

12:05 **Andres Forrer**, David Stark, Martin Franckié, Tudor Olariu, Mattias Beck, Jérôme Faist and Giacomo Scalari
Injection locking and bi-stable operation of a homogeneous bound-to-continuum THz Quantum Cascade Laser spanning up to 1.65 THz

12:20-13:30 Buffet Lunch

14:30-16:00 Session 16: Metasurfaces and Topological Photonics

Chair: Carlo Sirtori

14:30 **Mercedeh Khajavikhan**
*Topological and Supersymmetric Laser Arrays **(Invited)***

15:00 **Leland Nordin**, Kun Li, Andrew Briggs, Evan Simmons, Seth Bank, Viktor Podolskiy and Daniel Wasserman
Enhanced Emission from a Long Wavelength Infrared Emitter

15:15 **Yue Shen**, Christopher Curwen, Luyao Xu and Benjamin Williams
THz time-domain characterization of amplifying quantum cascade metasurface

15:30 **Ali Basiri**, Jing Bai, Xiahui Chen, Jiawei Zuo, Pouya Amrollahi, Joe Carpenter, Zachary Holman, Chao Wang and Yu Yao
Circularly Polarized Light Detection Based on Efficient Chip-Integrated Metasurface

Towards monolithic and battery driven mid-infrared dual-comb spectrometers

Benedikt Schwarz[1*], Johannes Hillbrand[1], Maximilian Beiser[1], Nikola Opacak[1], Aaron Maxwell Andrews[1], Hermann Detz[1,2], Gottfried Strasser[1], Anne Schade[3], Robert Weih[4], Sven Höfling[3,5]

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Short Abstract Frequency combs are ideal candidates to realize miniaturized spectrometers without moving parts. We present an overview of our current work on ICLs and QCLs ranging from fundamental aspect of their laser dynamics to the realization of monolithic devices. We highlight the similarities and differences between QCLs and ICLs, show how both FM and AM type frequency combs can be realized and discuss why the ICL comb platform is perfect for the realization of miniaturized spectrometers.

Frequency combs consist of a pump laser and a non-linear mechanism that couples the modes. In quantum cascade lasers, the non-linearity of the laser material can be used to generate frequency combs [1]. We show that this concept can be also be applied to ICLs, despite the fact that their laser transition lifetime differs by more than two orders of magnitude [2]. This is possible because the effective upper state lifetime is sufficiently fast under operation. Fig.1a&b show the SWIFTS result for the dominantly frequency modulated (FM) comb state, favored by the ICL and indicates that phase-locking is indeed governed by the same physical mechanism as in QCL combs.

We show that RF injection allows coherent control of QCL and ICL frequency combs. This enables injection locking of the repetition frequency of the FM comb state, which provides an increased stability of the state and the missing knob for the mutual stabilization of two combs via control loops [3]. Even more exciting, the coherent control is not limited to locking a frequency modulated self-starting comb. Detuning the injection frequency far from the natural laser beatnote can completely change the overall behavior of the comb. Similarly to the occurrence of multiple normal modes in coupled oscillators, fundamentally different comb states can be externally enforced. Fig.1c&d show an amplitude modulated (AM) comb state of an ICL enforced by the external modulation (active mode-locking).

A key feature of both QCLs and ICLs is that the very same epilayer structure can also be used to integrate photodetectors on the same chip [4, 5]. The fact that QCLs and ICLs both rely on fast intersubband transport is a great advantage for high bandwidth multi-heterodyne detection. As an example, the on-chip detection capability of ICLs can exceed several GHz electrical bandwidth [2], while providing an excellent noise equivalent power of 2.5 pW/$\sqrt{\text{Hz}}$ at room-temperature. Thus, the ICL technology provides all required properties for monolithic integration and can promote semiconductor based dual-comb spectroscopy from fundamental research to a broadly used sensing platform.

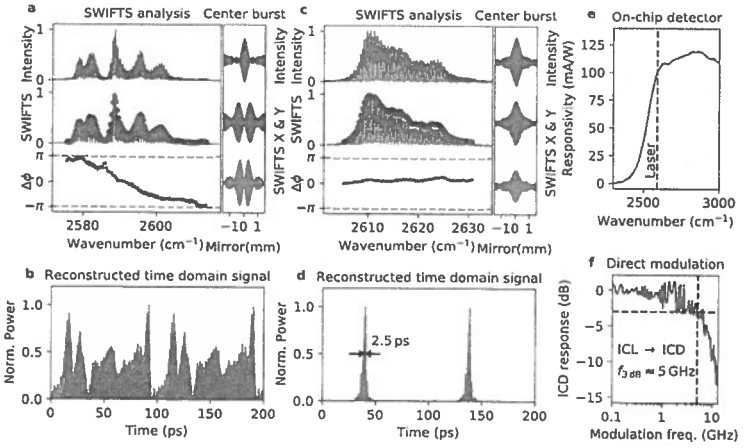

Figure 1: a&b SWIFTS result and reconstructed output signal from the ICL FM comb state. The delta phases, covering the range from $-\pi$ to π, are a clear sign of a dominant frequency modulation with a chirped instantaneous frequency. c&d SWIFTS result of the ICL AM comb state (active mode-locking). e photoresponse of the ICL on-chip detector. f Modulation response of the laser/detector system.

References

[1] 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, no. 7428, pp. 229–233, 2012.

[2] B. Schwarz, J. Hillbrand, M. Beiser, A. M. Andrews, G. Strasser, H. Detz, A. Schade, R. Weih, and S. Höfling, "A monolithic frequency comb platform based on interband cascade lasers and detectors," *arXiv preprint arXiv:1812.03879*, 2018.

[3] 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, no. 2, pp. 101–104, 2018.

[4] B. Schwarz, P. Reininger, H. Detz, T. Zederbauer, A. M. Andrews, S. Kalchmair, W. Schrenk, O. Baumgartner, H. Kosina, and G. Strasser, "A bi-functional quantum cascade device for same-frequency lasing and detection," *Applied Physics Letters*, vol. 101, no. 19, p. 191109, 2012.

[5] H. Lotfi, L. Li, S. M. S. Rassel, R. Q. Yang, C. J. Corrégc, M. B. Johnson, P. R. Larson, and J. A. Gupta, "Monolithically integrated mid-IR interband cascade laser and photodetector operating at room temperature," *Applied Physics Letters*, vol. 109, no. 15, p. 151111, 2016.