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Castle of Mauterndorf
A-5570 Mauterndorf
Province of Salzburg, Austria
www.jku.at/hfp/mauterndorf
winterschool@jku.at

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Actively mode-locked mid-infrared quantum cascade laser

Johannes Hillbrand[1,2], Nikola Opacak[1], Marco Piccardo[2], Harald Schneider[3], Gottfried Strasser[1], Federico Capasso[2], Benedikt Schwarz[1,2*]

[1]*Institute for Solid State Electronics, Technische Universität Wien, Austria*
[2]*John A. Paulson School of Engineering and Applied Sciences, Harvard University, USA*
[3] *Institute of Ion Beam Physics and Materials Research, Helmholtz-Zentrum Dresden, Germany*

Mode-locking of mid-infrared quantum cascade lasers (QCL) remains challenging to date due to their ultrafast gain dynamics. We report on active mode-locking of mid-infrared QCLs resulting in the emission of intense picosecond pulses. We investigate the temporal dynamics of the QCL using both linear and quadratic autocorrelation techniques. Both methods confirm independently that the QCL emits a train of isolated pulses.

The majority of semiconductor lasers relies on interband transitions to create optical gain. In such lasers, the upper-state lifetime is generally much longer than the cavity roundtrip time. As a consequence, the longitudinal cavity modes of most interband lasers can be mode-locked by introducing a fast saturable absorber in the cavity or by modulating the gain or losses at the roundtrip frequency resulting in the emission of short pulses. In contrast to this, the optical gain in quantum cascade lasers (QCL) is provided by intersubband transitions. This has important consequences for the temporal dynamics of the QCL. Due to fast intersubband scattering and tunneling, both the upper-state lifetime and gain recovery time of mid–infrared (MIR) QCLs are typically orders of magnitude shorter than the cavity roundtrip time. Hence, the QCL acts as a fast saturable gain. In contrast to a fast saturable absorber, the fast QCL gain dynamics are highly unfavorable for the formation of short pulses. As a consequence, mode-locking of MIR QCLs remains challenging to date. A possible solution is to increase the upper-state lifetime artificially by designing a very diagonal optical transition [1]. However, the necessary modifications of the laser design strongly degrade its overall performance and mode-locking was only observed close to lasing threshold with relatively small peak powers.

Here, we demonstrate active mode-locking of a MIR QCL without requiring a long upper-state lifetime. The investigated QCLs are two-section devices (Fig. 1), which allow efficient RF injection [2]. The electronic bandstructure of the QCLs was optimized to enable high modulation depth. When the frequency of the injected RF signal is close to the roundtrip frequency, the spectrum of the QCL consists of a single lobe with a Gaussian envelope and the interferometric autocorrelation shows a ratio of 8:1 between peak and background, which proves unambiguously that the QCL operates in the mode-locked regime (Fig. 2). The average power in the mode-locked regime can be as high as roughly half of the maximum average power of the QCL at the thermal rollover. Our results demonstrate that QCLs provide a platform for compact generation of mid-infrared picosecond pulses.

[1] Wang et al. "Mode-locked pulses from mid-infrared quantum cascade lasers." *Optics Express* 17.15 (2009): 12929-12943.

[2] Hillbrand et al. "Coherent injection locking of quantum cascade laser frequency combs." *Nature Photonics* 13.2 (2019): 101-104.

Corresponding author: email: benedikt.schwarz@tuwien.ac.at

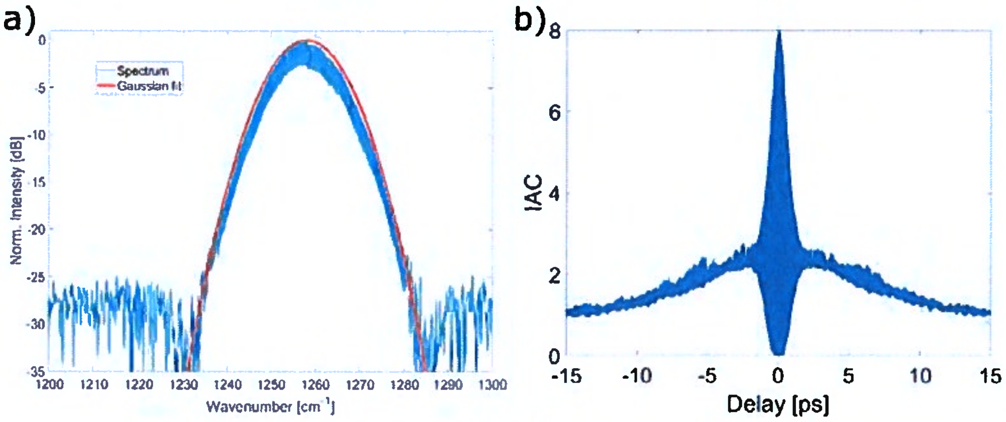

Figure 2: a: spectrum of the QCL in the mode-locked regime. B: interferometric autocorrelation (IAC) of the QCL recorded using a two photon quantum well infrared photodetector.

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