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Ultrashort pulses from a 8 µm wavelength semiconductor laser

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

[1]**Institute of Solid State Electronics, TU Wien, Gußhausstraße 25, 1040 Vienna, Austria**
[2]**Harvard John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, USA**
[3]**Institute of Ion Beam Physics and Materials Research, Helmholtz-Zentrum Dresden-Rossendorf, Germany**

Abstract: The ultrafast carrier transport in mid-infrared QCLs has so far constituted a seemingly insurmountable obstacle for the formation of short pulses. Here, we demonstrate transformation-limited picosecond pulses generated by 8 µm wavelength QCLs at room-temperature.

The discovery of ultrashort light pulses has triggered numerous breakthroughs in science and technology, including frequency combs[1], high-speed optical telecommunication[2] and refractive surgery in ophthalmology. Nowadays, optical pulses are routinely generated in mode-locked lasers operating in the visible or near-infrared range[3,4]. Currently, large efforts are aimed at bringing ultrafast laser science in the mid-infrared (MIR) region to a similarly high degree of maturity[5]. Methods for the generation of pulses in the molecular fingerprint region beyond 5 µm wavelength have so far relied on non-linear downconversion of near-infrared pulses[6], often limited to sub-mW power levels and tabletop-sized optical setups.

Quantum cascade lasers (QCL) have matured to the dominant mid-infrared laser source and have recently seen a rapid surge in attention for frequency comb generation[9,10]. Microchip-sized and electrically pumped, they are capable of

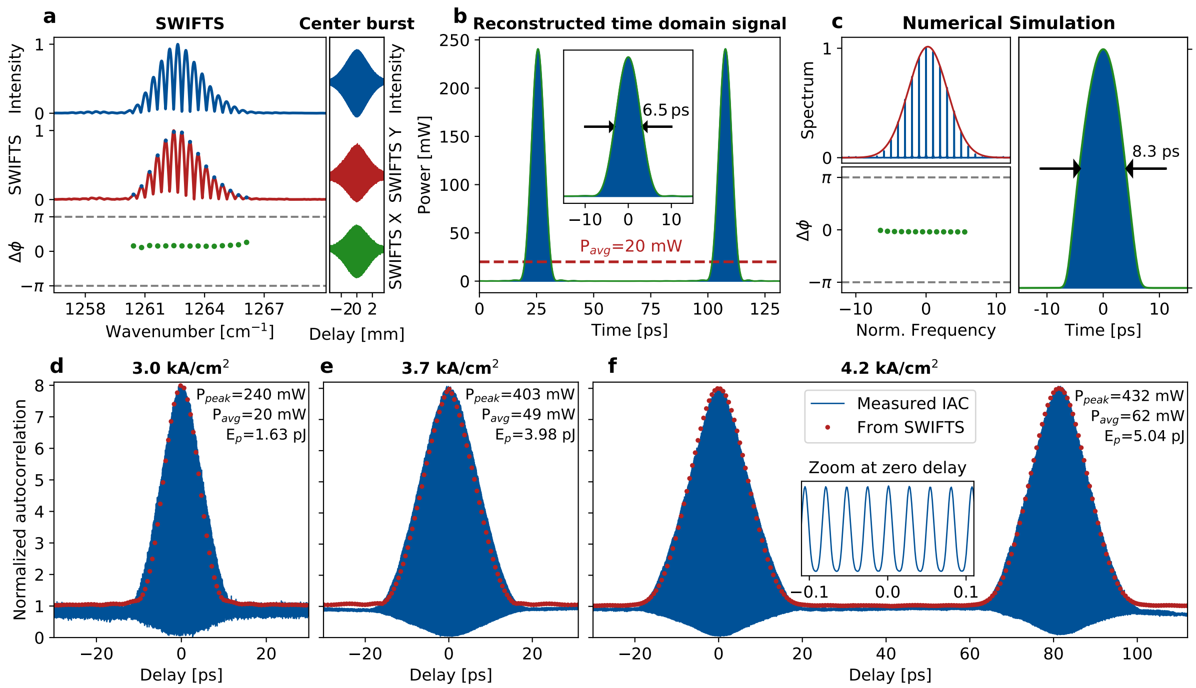

Figure 1 – **Mode-locking of mid-infrared quantum cascade lasers. a**: Characterization of coherence and phases of the mode-locked QCL using Shifted Wave Interference Fourier Transform Spectroscopy (SWIFTS)[7]. While the SWIFTS spectrum shows that the entire spectrum is phase-locked[8], the intermodal differen phases are synchronized almost perfectly in phase. **b**: SWIFTS allows to reconstruct the waveform emitted by the QCL, revealing a train of mode-locked pulses. The individual pulses are 6.5 ps short, which is exactly equal to the transformation limit of the spectrum shown in **a**. **c** Numerical simulation of the mode-locked QCL using a single Master equation derived from the Maxwell-Bloch equations. Both the spectral shape and the pulse width are in excellent agreement with the experimental results. **d**: The interferometric autocorrelation (IAC) of the pulses close to the threshold of the QCL shows a characteristic narrow peak at zero delay and peak-to-background ratio of 8:1. This is widely considered as the smoking gun of mode-locked pulses. Moreover, the measured autocorrelation is in excellent agreement with the SWIFTS reconstruction (red dots), which corroborates both the proof for mode-locking and the pulse width. **e**: IAC at higher current. **f** IAC at rollover, still showing the required 8:1 ratio. At a delay equal to the cavity roundtrip frequency, a second burst appears, which is caused by interference of subsequently emitted pulses. The inset shows the interferometric fringes of the IAC around zero delay.

producing Watt-level average power[11,12]. Tailoring the emission wavelength via quantum engineering allows to unlock the entire mid-infrared region with a single technology[9]. Hence, harnessing high-performance QCL technology for the generation of mid-infrared pulses represents a long-sought milestone in ultrafast laser science. However, the sub-picosecond carrier transport in QCL active regions has so far constituted a seemingly insurmountable obstacle for the formation of short light pulses[13,14,15].

In this work, we report on mode-locking of high-performance mid-infrared QCLs. The light pulses are generated by actively modulating the intracavity loss[16] in a QCL, whose geometry (Fig. 1a) and quantum design were engineered for maximal modulation depth[17]. Both an interferometric radio-frequency technique[7] (Fig. 1a,b) and numerical simulations (Fig. 1c) confirm that the QCL emits a train of 6.5 ps short and transformation-limited pulses around 8 µm - a spectral region so far only explored by downconverted pulses and often limited to sub-mW average power[18]. Furthermore, a well-established technique called 'interferometric autocorrelation' (IAC) (Fig. 1d,e,f) is employed to corroborate both the proof for mode-locking and the pulse width. Mode-locked operation of the QCL is observed over its entire lasing range from threshold to rollover, with peak power in excess of 400 mW and pulse energies up to 5.5 pJ. Further experiments unveil stunning similarities of mode-locking in QCLs to synchronization of coupled oscillators[19] and confirm the existence of multiple synchronization states, both of which can be excited by modulation at their synchronization frequency.

These results prove that QCL technology constitutes a highly promising platform for ultrafast laser science in the mid-infrared region, combining compactness, direct electrical pumping and widely tailorable wavelength. The availability of a semiconductor laser based source for ultrashort optical pulses paves the way towards monolithic supercontinuum generation and potentially octave spanning mid-infrared frequency combs.

References

1. Udem, T., Holzwarth, R. & Hänsch, T. W. Optical frequency metrology. *Nature* **416**, 233–237 (2002).
2. Hasegawa, A. & Tappert, F. Transmission of stationary nonlinear optical pulses in dispersive dielectric fibers. I. Anomalous dispersion. *Applied Physics Letters* **23**, 142–144 (1973).
3. Moulton, P. F. Spectroscopic and laser characteristics of Ti:Al_2O_3. *Journal of the Optical Society of America B* **3**, 125 (1986).
4. Kim, J. & Song, Y. Ultralow-noise mode-locked fiber lasers and frequency combs: principles, status, and applications. *Advances in Optics and Photonics* **8**, 465 (2016).
5. Cao, Q., Kärtner, F. X. & Chang, G. Towards high power longwave mid-IR frequency combs: power scalability of high repetition-rate difference-frequency generation. *Optics Express* **28**, 1369 (2020).
6. Schliesser, A., Picqué, N. & Hänsch, T. W. Mid-infrared frequency combs. *Nature Photonics* **6**, 440–449 (2012).
7. Burghoff, D. *et al.* Evaluating the coherence and time-domain profile of quantum cascade laser frequency combs. *Optics Express* **23**, 1190 (2015).
8. Hillbrand, J., Andrews, A. M., Detz, H., Strasser, G. & Schwarz, B. Coherent injection locking of quantum cascade laser frequency combs. *Nature Photonics* **13**, 101–104 (2018).
9. Faist, J. *et al.* Quantum Cascade Laser. *Science* **264**, 553–556 (1994).
10. Hugi, A., Villares, G., Blaser, S., Liu, H. C. & Faist, J. Mid-infrared frequency comb based on a quantum cascade laser. *Nature* **492**, 229–233 (2012).
11. Schwarz, B. *et al.* Watt-Level Continuous-Wave Emission from a Bifunctional Quantum Cascade Laser/Detector. *ACS Photonics* **4**, 1225–1231 (2017).
12. Jouy, P. *et al.* Dual comb operation of $\lambda \sim 8.2$ µm quantum cascade laser frequency comb with 1 W optical power. *Applied Physics Letters* **111**, 141102 (2017).
13. Gordon, A. *et al.* Multimode regimes in quantum cascade lasers: From coherent instabilities to spatial hole burning. *Physical Review A* **77** (2008).
14. Wang, Y. & Belyanin, A. Active mode-locking of mid-infrared quantum cascade lasers with short gain recovery time. *Optics Express* **23**, 4173 (2015).
15. Wang, C. Y. *et al.* Mode-locked pulses from mid-infrared Quantum Cascade Lasers. *Optics Express* **17**, 12929 (2009).
16. Hillbrand, J. *et al.* Picosecond pulses from a mid-infrared interband cascade laser. *Optica* **6**, 1334 (2019).
17. Schwarz, B. *et al.* A bi-functional quantum cascade device for same-frequency lasing and detection. *Applied Physics Letters* **101**, 191109 (2012).
18. Ruehl, A. *et al.* Widely-tunable mid-infrared frequency comb source based on difference frequency generation. *Optics Letters* **37**, 2232 (2012). URL `https://doi.org/10.1364/ol.37.002232`.
19. Hillbrand, J. *et al.* In-Phase and Anti-Phase Synchronization in a Laser Frequency Comb. *Physical Review Letters* **124** (2020).