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Modeling of quantum cascade lasers for mode-locking and frequency comb generation

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The quantum cascade laser (QCL) exploits optical transitions between quantized electron states in a multi-quantum-well active region. Consequently, the lasing wavelength is not determined by the material bandgap, but can be custom-tailored over a wide range of the mid-infrared and terahertz spectral regions by quantum engineering. For many applications, laser operating regimes are exploited which generate special temporal or spectral waveforms. These include periodic trains of ultrashort pulses as required, e.g., for time-resolved spectroscopy [1], and time-periodic waveforms in general, where the resulting comb-like spectra are widely used in metrology and sensing [2,3].

In QCLs, the dynamics is mediated by a complex interplay of various effects such as coherent light-matter interaction and tunneling, incoherent transport, waveguide dispersion, and spatial hole burning. For an improved understanding of the long-term dynamical operation and for systematic device optimization, a reliable and numerically efficient numerical approach is required. Multilevel Maxwell-Bloch (MB) equations, extended by above mentioned effects, provide a suitable basis [3]. In Fig. 1, two simulation results are exemplarily shown. The QCL-based terahertz comb spectrum in Fig. 1(a) is based on the MB model coupled to carrier transport simulations, resulting in a self-consistent multiscale approach without phenomenological parameters [3,4]. Good agreement with experimental data is found [3]. In Fig. 1(b), the possibility of obtaining passive mode-locking (ML) in QCLs is explored, where pulse formation is enabled by adding a saturable absorber region. This has not yet been experimentally realized in QCLs due to their fast gain recovery. The simulation results indicate that additional pump current modulation at the roundtrip rate, corresponding to hybrid ML, can stabilize the pulsed solution [5]. Above simulations apply the rotating-wave approximation (RWA), which is valid for moderate field strengths and spectral bandwidths. Recent developments, such as octave-spanning QCLs, require going beyond the RWA. The associated significant increase in computational cost can partly be compensated for by highly optimized numerical routines and massive parallelism, as implemented in our open-source GitHub codebase mbsolve [6]. The MB equations are widely used for optoelectronic device simulations beyond QCLs, and are of general relevance as a semiclassical model in computational electrodynamics.

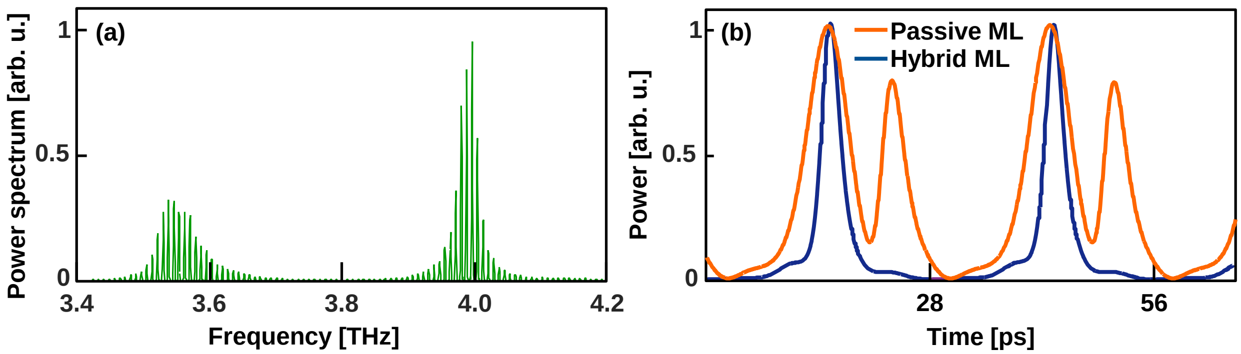

Fig. 1. Exemplary simulation results for (a) frequency comb operation and (b) mode-locked operation of QCLs.

References

[1] C. Y. Wang et al., *Opt. Express* **17**, 12929–12943 (2009)
[2] A. Hugi et al., *Nature* **492**, 229–233 (2012)
[3] P. Tzenov et al., *Opt. Express* **24**, 23232–23247 (2016)
[4] C. Jirauschek and P. Tzenov, *Opt. Quant. Electron.* **49**, 414 (2017)
[5] P. Tzenov et al., *New J. Phys.* **20**, 053055 (2018)
[6] M. Riesch et al., *Opt. Quant. Electron.* **50**, 112 (2018)