On Frequency Comb Formation in Terahertz Quantum Cascade Lasers

***Petar Tzenov***1 ***and Christian Jirauschek***1

*1. Technical University of Munich, D-80333 Munich, Germany*

Their inherently broadband gain and high value of the third order nonlinearity makes quantum cascade lasers (QCLs) ideal candidates for frequency comb generation in the terahertz (THz) and mid-infrared (midIR) spectral ranges. In recent years, it has been demonstrated that free running QCLs can produce broad comb spectra, even without any special endeavour to induce phase-locking of the lasing modes [1]. Unfortunately, such “coherent” regimes of multimode operation seem to span only a very narrow portion of the full dynamic range of the devices, which hinders the practical usability of this technology [1,2].

Group velocity dispersion (GVD) has been largely considered as the main comb degradation mechanism, due to the variation in the cavity-mode distance it introduces. As a consequence, special dispersion compensation mechanisms (DCMs) were developed to suppress this effect, however again with variable success [2,3]. In a recent publication [4], the formation of a population grating, due to the interference of counter propagating waves, i.e. the so called spatial hole burning effect (SHB), together with four wave mixing (FWM), generated by population pulsations, have been identified as the main mode-proliferation processes in QCLs. While the former has been shown to produce a broad and dense, but incoherent spectrum, the latter effect is argued to homogenize the spacing and introduce phase-locking in the lasing modes. Individually, these mechanisms have been well understood, but when considered together, the complex dynamics becomes difficult to analyse. Our submission investigates how the interplay between GVD, SHB and FWM could determine the comb formation, via the numerical solution of the multi-level Maxwell-Bloch equations.

In [5], we outlined a theoretical model for the full time-domain simulation of THz QCLs, and showed that it correctly captures all of the above enumerated effects. Here, we build upon our work to investigate necessary conditions for comb generation with free-running, self-starting THz QCLs. We performed simulations of a typical resonant phonon THz QCL in regimes of strong and weak SHB. Figures 1(a)-(d) illustrate the former case, when SHB is strong and dominates the mode proliferation process, resulting in an incoherent and chaotically varying spectrum. Next, we simulated a free-running laser with asymmetrically chosen outcoupling losses, where the left reflection coefficient was maintained at 100% and the right one was set to 5%. This strengthens the unidirectionality of the emission and thus suppresses SHB. The plots in Figs. 1(e)-(h) show that by only eliminating spatial hole burning we can recover the comb-like stable behaviour of the laser. In this configuration, the physics at play strongly resembles the processes in optically pumped high-Q microresonator combs, and so inspired by the work in [6], we also investigate how the relationships between the first modes that start lasing can determine the nature of the radio-frequency beatnote.



Fig. 1. Simulations of non-comb and comb regime of operation of a THz QC laser in regime of strong SHB (Figs. 1(a)-1(d)) and weak SHB (Figs. 1(e)-(h)). (a), (b) and (e), (f) illustrate the modal phase and power of the ten strongest modes in the lasing spectrum, whereas (c), (d) and (g), (h) display the respective optical spectra and RF beatnotes.

**References**

[1] M. Rösch, et al. "Octave-spanning semiconductor laser," *Nat. Photon.* **9**, 42 (2015).

[2] D. Burghoff, et al. “Terahertz laser frequency combs,” *Nat. Photon.* **8**, 462 (2014).

[3] G. Villares, et al. "Dispersion engineering of quantum cascade laser frequency combs," *Optica* **3**, 252 (2016).

[4] T. S. Mansuripur, et al. "Single-mode instability in standing-wave lasers: The quantum cascade laser as a self-pumped parametric oscillator," *Phys. Rev. A* **94**, 063807 (2016).

[5] P. Tzenov, et al. "Time domain modeling of terahertz quantum cascade lasers for frequency comb generation," *Opt. Express* **24**, 23232 (2016).

[6] T. Herr, et al. "Universal formation dynamics and noise of Kerr-frequency combs in microresonators," *Nat. Photon.* **6**, 480 (2012).