Optical Frequency Combs from Quantum Cascade Lasers

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In this talk I will discuss how resonant light-matter interaction in the gain medium of quantum cascade lasers (QCLs) gives rise to a rich nonlinear multimode dynamics and a variety of phase-locked multimode regimes, most notably optical frequency combs with separation between the comb lines changing from one to many dozen round-trip frequencies. I will review recent progress in understanding why frequency combs seem to be so ubiquitous in QCLs and their emerging applications.

A standard method of producing frequency combs is based on mode-locked lasers generating ultrashort pulses, which operate mostly in the near-infrared and visible ranges. The mid-infrared (mid-IR) and terahertz (THz) spectral regions, where most chemical compounds have strong spectral fingerprints, hold enormous potential for frequency comb applications. Quantum cascade laser (QCLs) cover most of the mid-IR and parts of the THz spectral regions. Unfortunately, ultrafast gain relaxation in QCLs effectively prohibits ultrashort pulse generation through passive mode locking. Active mode locking schemes are still feasible but they are less convenient and produce pulses of limited peak power.

That is why the realization that strong resonant nonlinearity of the gain transition itself is enough to trigger the self-starting formation of frequency combs in QCLs was such a pleasant surprise. However, unlike the shorter-wavelength combs generated by ultrashort-pulse lasers, in QCLs the underlying periodic modulation is linked to a predominantly frequency-modulated optical wave. Still, the amplitude modulation due to population pulsations is always present to some extent and can be directly measured. This is especially true for the harmonic combs in which the lasing modes are separated in frequency domain by a large number of free spectral ranges. The harmonic combs were found to be self-starting too in all kinds of QCLs. The separation between neighboring lasing modes in the harmonic combs reaches hundreds of gigahertz and even THz frequencies, which implies coherent (sub)picosecond intracavity modulation. Therefore, harmonic QCL combs provide direct link between mid-IR lasing and coherent (sub)THz generation and modulation, which makes them promising as (sub)THz coherent sources and transceivers. Many aspects of the underlying physical mechanisms which give rise to complete suppression of neighboring cavity modes and the harmonic comb formation remain a mystery. Yet another recent puzzle is the formation of frequency combs in ring QCLs that were supposed to be single-mode. It is fascinating how QCLs continue bringing new surprising features to such a well-studied field as fundamental laser dynamics.