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Frequency comb generation in ring injection lasers by defect engineering

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Short Abstract We demonstrate fundamental and harmonic frequency combs in monolithic ring quantum cascade lasers. We show by experiments and simulations that embedding defects in the waveguide is the key to control comb formation in these cavities.

1. Introduction

Quantum cascade laser (QCL) frequency combs [1], first introduced in the context of broadband molecular spectroscopy, have seen drastic development in the last years. A prerequisite for frequency comb operation of QCLs is the occurrence of a standing wave in the laser cavity: its interference pattern is what causes a spatially inhomogeneous distribution of the gain—a phenomenon known as spatial hole burning—allowing multiple modes to lase. It is thus natural that the first demonstrations of frequency combs in QCLs were carried out in Fabry-Perot (FP) resonators, which constitute the simplest form of a standing-wave cavity, coupling modes through reflections from facets (Fig. 1a). Instead, ring QCLs have not yet been exploited for frequency comb generation. In fact, standing waves and spatial hole burning do not spontaneously occur in ring cavities, as these are traveling-wave resonators that do not couple the supported clockwise (CW) and counter-clockwise (CCW) modes. Thus single-mode operation normally prevails in these lasers. Here we show that embedding intentional defects in monolithic ring QCLs allows one to induce standing waves in the cavity, enabling the generation of frequency combs in this type of resonators (Fig. 1b) [2].

2. Results

We fabricated several monolithic ring QCLs with the active region consisting of AlInAs/GaInAs/InP layers with waveguide width of 10 μm, radii 505 and 605 μm, which emit at 8 μm under constant electrical injection at 16°C. Defects are fabricated by opening small windows in the metal contact (10 μm × 30 μm), leaving the waveguide exposed to air. Defects act as scatterers for waves circulating inside the ring (Fig. 1c). As the driving current is gradually increased one can observe the laser to evolve from a single-mode state close to the threshold injection level to a frequency comb state accompanied by the generation of the 400 Hz-wide intermodal beatnote (Fig. 1d). Interestingly, at the highest injection levels the ring laser goes back to a single-mode state—a behaviour also observed in numerical space-time-domain simulations of the ring cavity QCL with a defect. We highlight the

obvious difference of the characteristic optical spectra and spectral evolution of the multimode ring emission with respect to the laser embedded in a FP cavity (Fig. 1a and 1b).

Embedding two defects separated by an angle of ≈ 40° in a ring QCL (R = 505 μm) allows the laser to support harmonic comb generation [3], where optical spectra feature characteristic mode skipping (Fig. 1d) with intermodal spacing being an integer multiple of the cavity free spectral range. Due to inherent insensitivity of the ring laser to optical feedback, harmonic states are highly stable and reproducible as opposed to FP cavity lasers, where alleviating optical feedback is crucial to achieve stable harmonic comb operation. The ability to generate highly-stable harmonic frequency combs with intermodal spacings lying in the sub-THz domain may serve as a building block for a new class of sub-THz carrier generators [4], where the ring cavity geometry allows for scaling up of the beatnote power by synchronous operation of multiple optically coupled QCL ring combs.

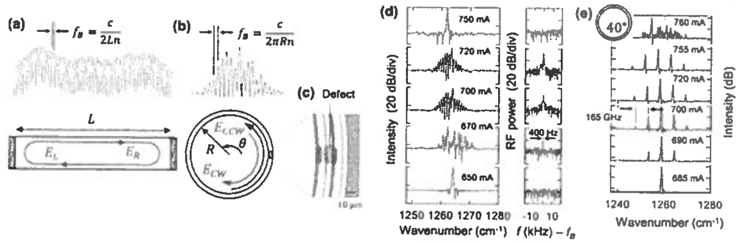

Figure 1: (a) FP cavity QCL with end facet mirrors creating standing waves inside the cavity, allowing for frequency comb operation via SHB. (b) Ring cavity QCL where clockwise and counterclockwise modes are supported and coupled via an intentional defect producing frequency combs whose spectra differ from those of their FP counterparts. (c) Top view microscope image of the defect in the quantum cascade laser waveguide. (d) Spectral evolution of the ring QCL frequency comb with corresponding intermode beatnote spectra. (e) Harmonic frequency comb spectral evolution in a ring QCL.

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