Frequency comb generation in ring injection lasers by defect engineering

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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.

Despite decades of studies, the development of optical frequency combs continues at a rapid pace, in terms of both sources and applications [1–2]. Quantum cascade lasers (QCLs) are unique monolithic frequency comb generators combining nonlinearity, gain and detection capability [3] with rapidly emerging applications for dual-comb spectroscopy [4], metrology [5] and microwave photonics [6]. A fundamental 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 resonators, which constitute the simplest form of a standing-wave cavity, coupling modes through reflections from facets (Fig. 1a). Instead, ring QCLs [7] 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 [8]. Thus single-mode operation normally prevails in these lasers (Supplementary Fig. 1a). 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). These sources will further expand QCL frequency comb applications thanks to a higher Q-factor and lower threshold than their Fabry-Perot counterparts, the possibility of high-quality beam generation through outcoupling gratings, efficient microwave generation, and coherent beam coupling by two-dimensional arrays of synchronized lasers.

We fabricated several monolithic ring QCLs [7] whose active region consists of AlInAs/GaInAs/InP layers [10]. The waveguide width is 10 μm, the radius is 505 or 605 μm, emission is around 8 μm and operation is 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). Only a small amount of power is outcoupled from the laser surface (≤ 1 mW), minimizing the external perturbation of the intrinsic states of these lasers. The laser spectral output is measured using a Fourier transform infrared spectrometer and a sensitive photodetector (HgCdTe detector cooled at 77 K). Beat notes produced during frequency comb operation are electrically extracted from the laser chip using a radiofrequency probe connected to a spectrum analyzer [9]. We will concentrate here on the results relative to two representative devices.

The optical spectra of a ring QCL with one defect are shown in Fig. 2a for different values of injection current. Fundamental frequency comb operation is identified by the appearance of a narrow beat tone with sub-kilohertz linewidth at the fundamental beat note frequency of the laser (Fig. 2b). \( f_B \), corresponding to its free spectral range (FSR) given by \( c/(2\pi R n) \), where \( R = 605 \) μm is the ring radius and \( n = 3.4 \) is the effective index of the waveguide. The optical spectrum presents much fewer modes than that of Fabry-Perot lasers fabricated from the same material [10] – an effect that we attribute to...
the small reflectivity of the embedded defect, producing a weak spatial hole burning grating and limiting the gain available to other longitudinal modes. The laser is observed to evolve from single mode to the comb regime, then again to single mode at increasing current. A similar behavior is also seen in space- and time-domain numerical simulations [11] of ring QCLs with a defect (Supplementary Fig. 1b) and is due to an imbalance between the magnitudes of the optical field in the CW and CCW directions.

As previously shown in Fabry-Perot resonators [9], a beat note provides information not only on the frequency locking of a QCL comb but also on the spatial structure of this locking. By placing a radiofrequency probe on the electrode in the vicinity of the waveguide we mapped the beat note power pattern at $f_B$ around the perimeter of the ring (Fig. 2a). Two spatial cycles are observed – a clear indication of the occurrence of standing waves in the ring QCL. The existence of two main peaks is also obtained in the numerical simulations (Fig. 2c). In particular, we notice that the two maxima occur almost symmetrically in the ring with respect to the defect indicating that the defect acts as a pinning point for the dynamic grating that lies at the origin of frequency comb operation.

The ring geometry is particularly interesting for the generation of microwave and sub-terahertz tones from the beating of the comb modes [6]. Due to the absence of light loss through facets, the high optical power accumulates in the ring and is expected to decrease the linewidth of the optical modes [12] and consequently that of the beat tones. Furthermore, rings can be coupled [13] to coherently scale up the beat power. The beat note frequency scales up with the spacing of the comb, thus for sub-terahertz generation a widely-spaced comb is needed.

By embedding two defects separated by an angle of $\approx 40^\circ$ in a ring QCL ($R = 505 \mu m$) acting as pinning points for the optical standing wave, we were able to generate a harmonic frequency comb [14], where the intermodal spacing is a higher harmonic of the resonator FSR and the spacing is 165 GHz (Fig. 3). The generation of harmonic combs in a controlled manner reinforces the existing link between QCLs and Kerr combs [2], where similar states can be generated on demand.

As a final remark, we observed that ring QCLs without any metal opening may switch non-deterministically from single-mode to comb states. The conclusion of our work is that spurious scatterers can be sufficient to trigger multimode operation in a ring QCL, but defect engineering is the key to pin the dynamic grating and control comb operation for the future applications.

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SUPPLEMENTARY DATA

SUPPLEMENTARY FIG. 1. Optical spectra calculated by numerical space- and time- domain simulations as a function of pump for: (a) a perfectly symmetric ring quantum cascade laser; (b) a ring quantum cascade laser with a defect. Pump values are normalized to the lasing threshold, frequencies are normalized to the central frequency of the laser and shown in units of 1 FSR of the laser. Frequency comb operation is obtained only in presence of a defect. The laser parameters used in the simulations are: the reflectivity of the defect is 1%; gain recovery time, $T_1 = 1$ ps; dephasing time, $T_2 = 0.05$ ps; loss = 5 cm$^{-1}$; dipole matrix element of the gain transition, $d = 2$ nm; cavity circumference $2 \pi R = 3$ mm. In a perfectly symmetric ring laser, only field propagating in one direction will survive, and that direction is random from run to run. For a ring laser with a defect, reflection is induced by the defect. We assume that the defect can absorb or generate power so we do not require energy conservation at the defect. We model the reflection using the boundary conditions $E_{CW,+} = t_1 E_{CW,-} + r_2 E_{CCW,-}$ and $E_{CCW,+} = t_2 E_{CCW,-} + r_1 E_{CW,-}$, with $r_1 = 0.1$, $r_2 = 0.1$, and $t_1 = t_2 = \sqrt{0.99}$. 

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