Oscillation paramétrique dans un peigne de fréquence laser à cascade quantique

Third order parametric oscillations in a quantum cascade laser frequency Comb

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Résumé/Abstract

A frequency comb in a quantum cascade laser can appear with two distinct spectral lobes. These two spectral features are switching in time and show strong anticorrelations similarly to parametric phenomena.

Frequency combs (FC) have brought tremendous value to precision instruments in different domains spanning frequency metrology [1], optical clocks [2], broadband spectroscopy [3] and ranging [4]. FCs based on Quantum Cascade Lasers (QCLs), unipolar devices emitting in the mid infrared and terahertz regions of the electromagnetic spectrum, have attracted much attention especially in dual-comb spectroscopy and sensing. Optical combs are generated spontaneously in a QCL cavity thanks to strong resonant third order non-linearity and ultrafast gain dynamics. While QCL FCs have been mostly studied classically, they are nonetheless fundamentally governed by the dynamics of quantized parametric processes, where each longitudinal mode is coupled to every other mode through a four-wave mixing. If the quantum processes can be harnessed, QCL FCs may open the way toward the experimental realization of a multimode quantum resources in a scalable, chip integrated platform. QCL's comb arises from a mode-locking state which differs fundamentally from that of pulsed lasers. The nature of the phase relation has been rigorously investigated through the Shifted Wave Interference Fourier Transform Spectroscopy (SWIFTS) [6], while correlations among spectral lines and noise have not yet been explored.

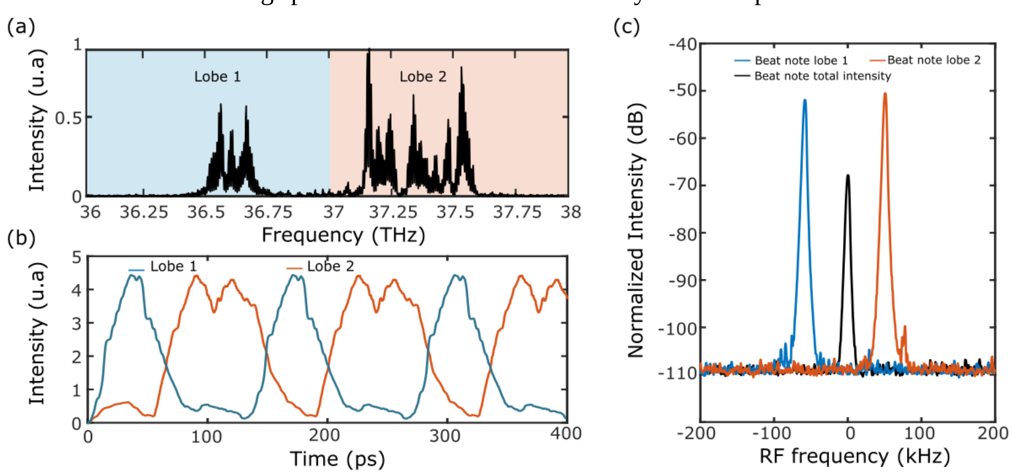

Fig. 1: (a) Optical spectrum of the bilobed QCL (b) SWIFTS reconstructed intensity of each spectral lobes (c) Intermodal beat note of Lobe 1 (blue), Lobe 2 (red) and of the total intensity (black). The three curves are exactly at the same frequency, but have been shifted in the figure for clarity.

Here we demonstrate the presence of strong anti-correlations among two spectral portions of a Fabry-Perot QCL that operates in the FC regime. The laser under study is a standard ridge 6 mm long QCL, operating at 273K in continuous wave at a wavelength of ~ 8.2 µm with maximum output power of 100mW. The recorded optical spectra (Fig.1 (a)) shows two spectral lobes separated in frequency by ~ 0.6 THz. Applying the SWIFTS technique to this FC we were able to reconstruct the temporal evolution of the intensity of each lobe over few round trips of the cavity. The result, in Fig. 1(b), shows a strong antiphase dynamics between the two spectral lobes. The laser action associated to Lobe 1, at low photon energy, is perfectly anti-phased with that of Lobe 2, at higher energy, which means that when Lobe 1 is on the intensity of Lobe 2 is off. This behavior is further confirmed by analyzing the intermodal beatnote of the two lobes, which have been spectrally separated using a diffraction grating (Fig. 1(c)). The normalized intensity of the beatnote is 100 (20 dB) times higher for the separate lobes than for the total spectrum, which is consistent with the much stronger intensity modulation occurring in each individual lobe.

To support this observed temporal pulse switching between high and low frequency components of the comb we address a fully time dependent simulations of QCL comb operation based on the semi-classical Maxwell-Bloch (MB) laser equations. Based on numerical solutions of the MB equations, mode-locking in QCLs and the emergence of a bilobed spectra is found (see Fig. 2). We show that our approach captures the intricate interplay between four-wave-mixing, spatial-hole burning and the refractive index dispersion in free running QCLs.

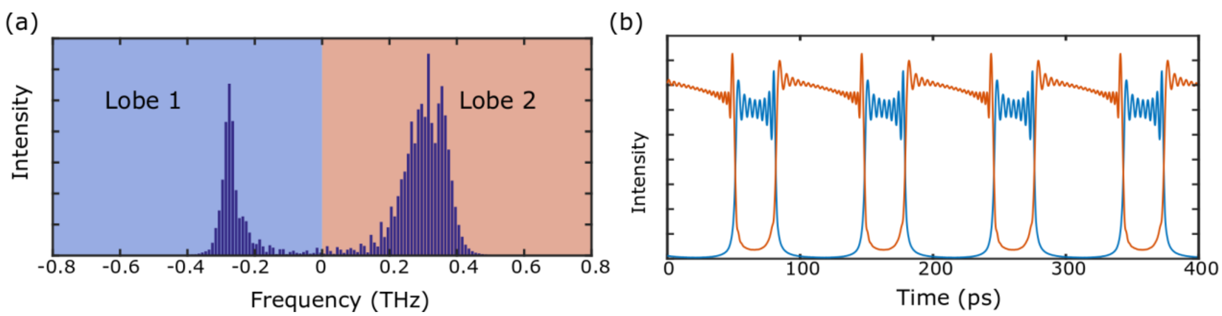

Fig. 2: (a) Optical spectrum of the QCL obtained through numerical integration. (b) Simulations show a switching behavior between the high (Lobe 2) and low (Lobe 1) frequency component of the comb.

The peculiar coherent properties of our device could lead to the generation of squeezed states of light, as it has been already demonstrated in several off-chip platforms, like optical parametric oscillators (OPOs) and optical fibers using four-wave mixing. In such nonlinear parametric processes strong quantum correlations in the intensities are generated between the two "twin" beams, called signal and idler. They occupy well distinct portions of the spectrum. Similarly in our devices the nonlinearities spontaneously generate an optical spectrum that consists of two spectral lobes with strong anticorrelations, reminiscent of the signal and idler twin beams. In the near future the intensity noise correlations of those two lobes will be investigated by comparing their sum to difference. This will be also studied by adding a statistical noise source in the MB equations in order to reproduce theoretically the noise correlations between the two different spectral lobes of the comb.

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