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RF-Injection Control of Quantum Cascade Lasers in the Time-Domain

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Abstract *In this work, we demonstrate control over the time-domain state quantum cascade laser output state using microwave modulation. We demonstrate narrow, pulse-like features with a full-with at half-maximum of 558 fs when isolated, which corresponds to the expected Fourier-transform limited pulse-width. ©2022 The Author(s)*

Introduction

Mid-infrared optical frequency combs act as broadband light sources in the molecular fingerprint region of the electromagnetic spectrum with well-defined mode-positions as well as high mode powers[1]. This makes them ideal sources for spectroscopic applications, especially advanced methods such as dual-comb spectroscopy[2].

Quantum cascade lasers[3] (QCLs) are of major interest as mid-infrared frequency combs due to their compact size and their ability to emit powers as high as 1 W at room-temperature[4],[5]. In addition, their fast gain-dynamics enables their internal optical beating to manifest as current-modulations in the driving-circuit, which can be read out using standard microwave electronics, thus offering a shortcut to probing their mode-spacing and coherence. External injection can be used to couple with the internal modulation to induce injection-locking[6]. When sufficiently high, radio-frequency (RF) injection offers a means for not only stabilizing[7] but also tuning the QCL output state. Modulation-power and -frequency can be chosen appropriately to cause a doubling in the spectral bandwidth or to shift the center-frequency of the spectrum to cover different spectral-regions at high speed[8].

However, a major difference of QCL frequency combs compared with optical frequency combs in the visible and near-infrared spectral regions is the frequency-modulated instead of amplitude modulated nature of the time-domain output. This limits the applicability to non-linear methods or the use of supercontinuum-generation for further spectral broadening. While recently external compression has been used in conjunction with RF-injection for generating pulses as short as 630 fs[9], attempts for using modelocking to directly generate pulses within the device itself have so far only resulted in picosecond pulse-lengths[10].

In this paper, we demonstrate the generation of short pulses on top of a modulated continuum inside the cavity of a Fabry-Pérot QCL caused by strong RF-modulation close to the free-running beatnote frequency.

Methods

The device used for this study is a 4 mm long QCL optimized for low RF-injection losses with a center wavelength around 8.3 µm[11]. To probe the time-domain response of the strongly modulated laser, the direct sampling method asynchronous upconversion sampling[9] (ASUPS) was used. The working-principle and setup are shown in Fig. 1. In a) is a schematic depiction of the sampling of the QCL output with the probe pulses. Due to the low repetition rate of the probe laser compared to that of the QCL, the periodicity of the output from a frequency comb is used to retrieve the signal shape by interleaving the sampling points. Thus any component of the signal which is not periodic at the given frequency is averaged out. In the experiment, as shown in b), the QCL signal is upconverted via sum-frequency generation when it mixes with the probe pulses in the non-linear crystal and is subsequently read out using an avalanche photo diode.

Results

Results from the ASUPS measurement on the QCL are shown in Fig. 2. As can be seen in a), when detuned far enough from the free-running beatnote frequency, the time domain output measured with this method only measures the optical modulation-depth caused by the external current modulation. Any other features are averaged out. However, when approaching the beatnote frequency, injection-locking starts to occur and other coherent features start appearing on top of the underlying modulation. Most prominently a short pulse starts to appear, its phase

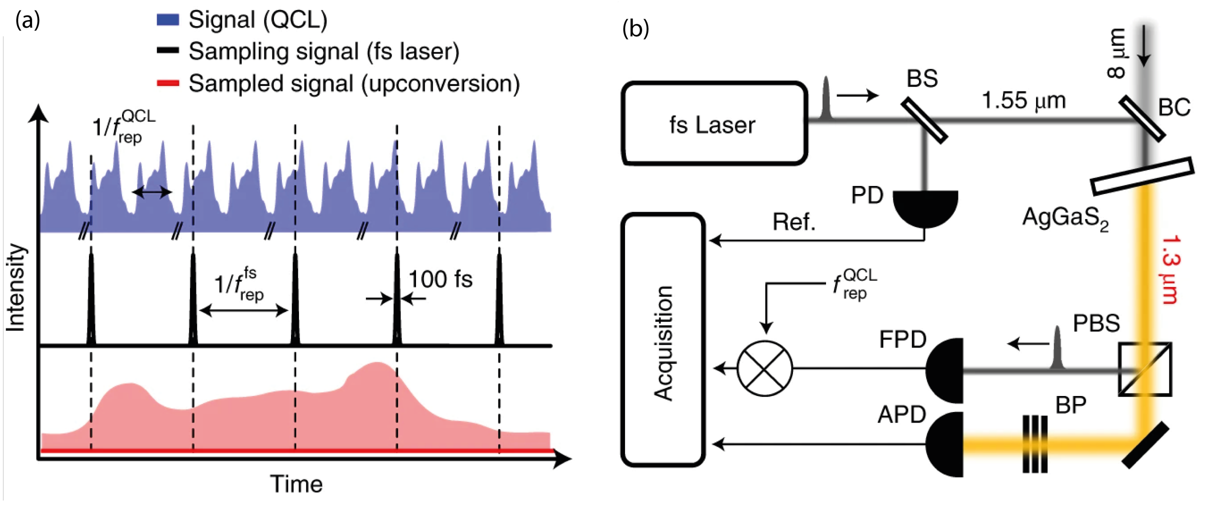

Fig. 1: Schematic depiction of ASUPS, as taken from[9]. a) Underlying principle of the direct sampling of the QCL signal using a pulsed probe-laser. The periodicity of the signal is used obtain the entire signal shape despite the lower repetition rate of the probe. b) Experimental setup for conducting the ASUPS experiment.

relative to the modulation maximum is dependent on the injection frequency. To further corroborate the existence of the pulse as observed in these measurements, a simple spectral filter, consistent of a slit, a grating and a mirror were used to isolate sections of the spectrum and thus reconstruct which spectral components contribute to the formation of the observed feature. The map in b) displays the time-traces as a function of the filter-position, calibrated by complementary measurements with a Fourier-transform spectrometer. The time-frequency relationship reproduces the chirp, which is characteristic for frequency modulated combs. At the transition between the ends of the spectra, a fine trace of signal can be seen persisting throughout the whole spectrum. This position coincides with that found for the pulse when removing the filter, which strongly implies that the entire spectral bandwidth contributes to the formation of the pulse. This matches the measured full-width at half-maximum of 558 fs of the pulse after removing a fit of the sinusoidally modulated background, which is close to the Fourier-limit for the corresponding spectrum with a bandwidth of about 30 cm^{-1}. The zoomed pulse after subtracting the sinusoidal fit is shown in Fig. 2 c).

Conclusions

In this paper we have used the direct sampling method ASUPS to show that strong RF-modulation can be used to induce pulses on top of a modulated background. We have observed that the emergence of these pulses is coupled to the onset of injection-locking and that their relative phase is dependent on the detuning of the modulation frequency. Furthermore, we have used a spectral filter to show that the entire spectral bandwidth contributes to the formation of the pulse and thus a full-width at half-maximum of 558 ps can be found after subtracting a fit of the sinusoidally modulated background.

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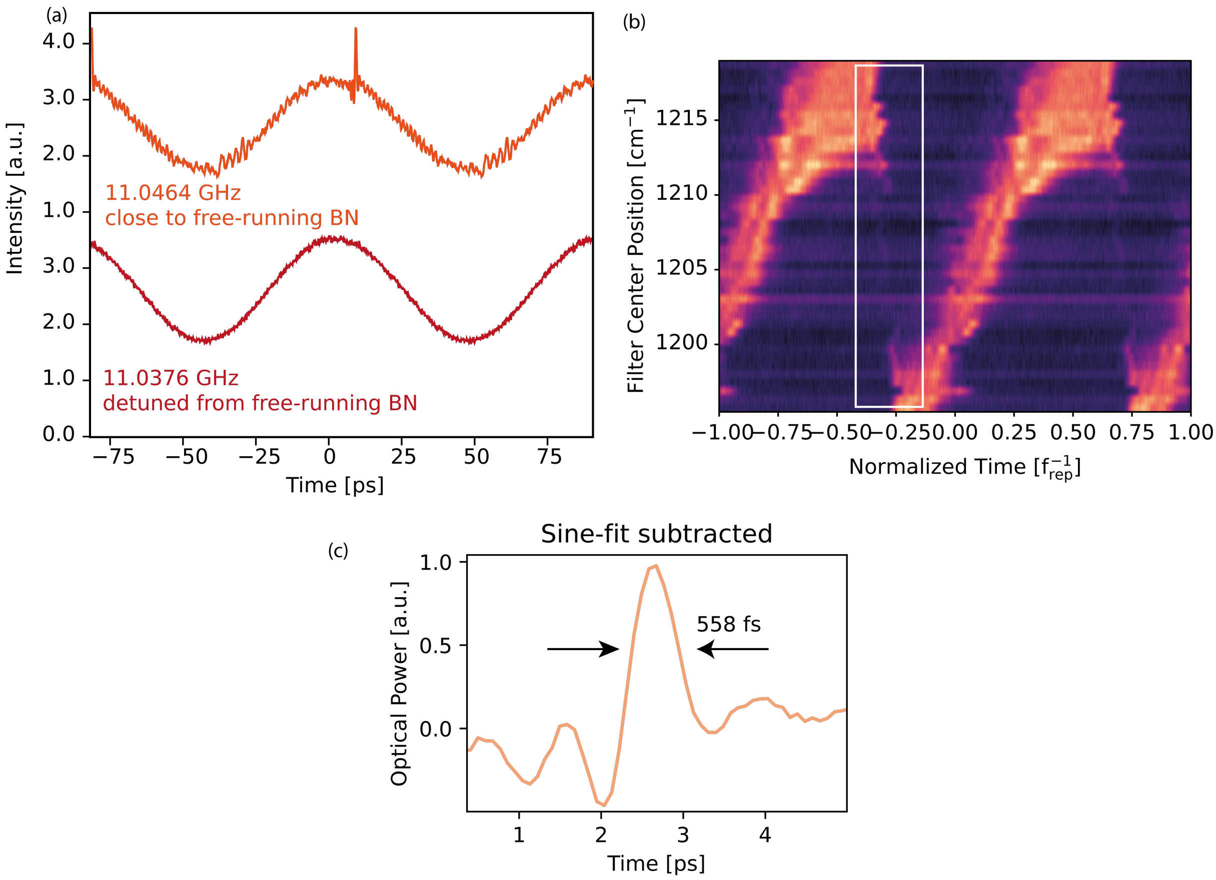

Fig. 2: Experimental Data obtained from ASUPS on a strongly modulated QCL. In (a) the time-trace inside the locking range at 11.0464 GHz is shown compared to a time-trace when modulating outside the locking range at 11.0376 GHz. The graph in (b) displays the time-domain signal after passing through an optical filter as a function of filter position. The white rectangle highlights the position where the spike occurs when the filter is removed. The figure in (c) is a zoom of the pulse in the time-trace, with the arrows highlighting the FWHM of the pulse, which is at 558 fs.

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