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Active linewidth narrowing of a 8.1 μm Quantum cascade laser to a mid-IR frequency comb

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Abstract— In this work we demonstrate a phase-lock of a single-mode continuous-wave Fabry-Perot quantum cascade laser (QCL) emitting at 8.1 μm to a low-noise mid-Infrared (mid-IR) optical frequency comb. The stability of the comb used as a reference is transferred to the QCL resulting in an integrated residual phase error of 0.4 rad. The laser linewidth is narrowed by more than two orders of magnitude reaching 300 Hz at 1ms observation time, limited by the spectral purity of the mid-IR comb.

Keywords—QCL, phase-noise, linewidth, Phase-lock, Mid-IR

I. INTRODUCTION

High-spectral-purity narrow-linewidth continuous-wave (cw) lasers are crucial for both fundamental research and technological applications in many fields of science, such as atomic, molecular, quantum and optical physics. They play in particular a major role in precision measurement physics, in the development of quantum technologies, and in time and frequency metrology. For these applications, the free-running linewidth determined by the laser short-term stability is often not adequate and active frequency stabilization is required [1].

In this work, we measure the free-running frequency noise power spectral density of an 8.1 μm Fabry-Perot QCL operating in single mode regime and demonstrate coherent phase locking of this source to a tooth of a commercially available low-noise mid-IR optical frequency comb synthesizer (OFCS), by processing a beat-note signal generated directly in a mid-IR photodetector. This allows the spectral performances of the OFCS to be transferred to the QCL without the need to pass the QCL beam through a complex dedicated non-linear optical setup. The locking is achieved with less than 1% of its optical power, keeping the rest of it at disposal for further experiments. Locking to such a low-noise comb results in a linewidth narrowing of the QCL

by of factor of 250, from ~ 100 kHz down to the few hundreds of hertz level [2].

II. EXPERIMENT

The experimental setup is shown in Fig. 1. An offset-free mid-IR OFCS from Menlo Systems, spanning the 7.4 to 9.4 μm spectral window is used as an optical reference. The mid-infrared comb is generated by difference frequency mixing in a non-linear crystal between a low noise 1.5 μm Erbium doped fiber frequency comb and its extension in a wavelength shifting fiber towards the 1.8 μm window. The mid-IR comb delivers an average output power of 2.2 mW, resulting in tens of nanoWatts comb modes. The comb repetition rate, $f_{\text{rep}} = 100$ MHz, is stabilized against a radio-frequency (RF) synthesizer. This corrects the slow frequency drift without affecting the laser linewidth. The QCL is a Fabry-Perot source grown and processed at ETH Zürich. It is typically operated at a temperature of 263 K and delivers up to 45 mW in a continuous wave single mode oscillating at a wavelength of ~ 8.16 μm .

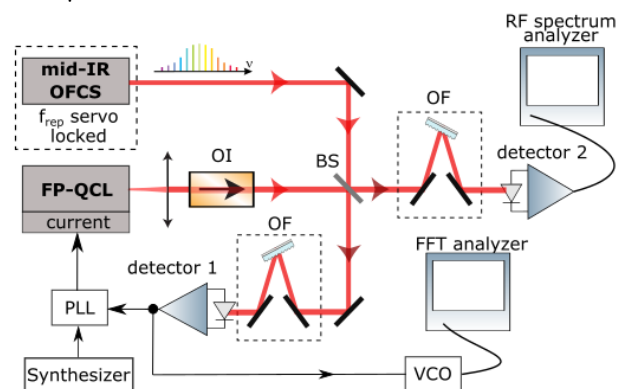


Fig. 1 Experimental setup for measuring the frequency noise of the free-running QCL and for coherently phase-locking it to a low-noise mid-IR OFCS. FP-QCL, Fabry-Perot Quantum Cascade Laser; mid-IR OFCS, mid-

infrared-optical frequency comb synthesizer; BS, beam splitter; OF, optical filtering monochromator build from a diffractive grating with 150 grooves/mm; PLL, phase lock loop; OI, optical isolator; VCO, voltage-controlled oscillator; FFT, fast Fourier transform

The QCL and the mid-IR-OFCS beams are superimposed by means of a 70/30 germanium beam splitter. Both beam splitter outputs are optically filtered with a 50 GHz resolution monochromator, and focused onto an 800-MHz bandwidth mercury-cadmium-telluride (MCT) detector (VIGO System PVI-4TE-10.6). The QCL beam is attenuated and a total power of about only 100 μ W is hitting the detector. The resulting beat-note signals obtained on detector 1 and 2 oscillate at:

$$f_{\text{beat}} = \nu_{\text{QCL}} - n \times f_{\text{rep}} \quad (1)$$

with ν_{QCL} the QCL frequency and $n \sim 370\,000$ the tooth number of the mid-IR-OFCS.

III. RESULTS

The frequency noise power spectral density (FNPSD) of the free-running QCL in Fig. 2 is derived from the beat-note signal f_{beat} measured on detector 1, in open-loop configuration. The latter is fine tuned to 140 MHz with the QCL current to match the frequency range of a tracking oscillator consisting of a voltage-controlled oscillator (VCO) phase-locked to the 140 MHz beat-note signal. The VCO tuning voltage then mirrors the beat-note signal's frequency noise and thus the free-running QCL frequency noise for Fourier frequencies below the system bandwidth of ~ 4 MHz.

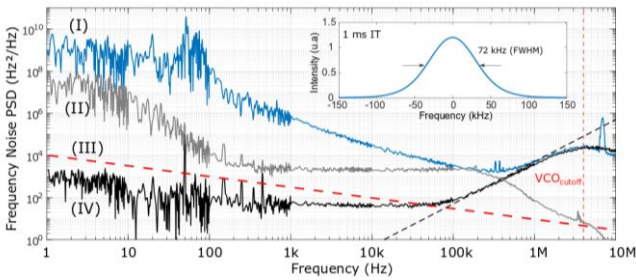


Fig. 2 Frequency noise power spectral density (FNPSD) of the free-running beat note between the 8.1 μ m QCL and the mid-IR comb (blue line (I)). The contributions from the laser driver current noise (grey line (II)) and from the mid-IR OFCS tooth contributing to the beat-note signal (red dashed line (III)) are also plotted for comparison. The black line (IV) corresponds to our noise floor, see text (with the black dashed line corresponding to the contribution from the limited beat-note signal-to-noise ratio of 86 dB/Hz). The tracking oscillator bandwidth is also shown (vertical red dashed line). The inset shows the free-running QCL emission line shape calculated from the measured FNPSD (I) for a 1 ms integration time (IT)

For Fourier frequencies below 300 kHz, the blue curve (I) in Fig. 2 corresponds to the free-running QCL FNPSD, all other contributions being negligible. The level of frequency noise measured is similar to that reported in [3]

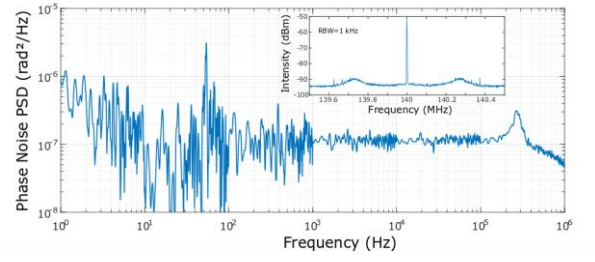


Fig. 3 Phase-noise power spectral density (PSD) of the beat signal between the phase-locked QCL and the mid-IR comb. Inset: Beat signal spectrum between the mid-IR OFC and the phase-locked QCL taken with a RF spectrum analyzer (1 kHz resolution bandwidth, RBW).

As illustrated in Fig. 1, to coherently phase-lock the QCL to a tooth of the mid-IR-OFCS, a phase-error signal is generated by comparing the phase of the filtered and amplified beat signal with a reference signal typically at 140 MHz from a synthesizer. A phase-lock servo loop is used to apply a correction signal directly to the QCL's current.

A significant narrowing of the beat-note signal linewidth is observed and a maximum signal-to-noise ratio of about 55 dB at 1 kHz resolution-bandwidth was obtained, as shown in the inset of Fig. 3. The beat signal spectrum is recorded on a RF spectrum analyzer after detection with a second out-of-loop photodetector (detector 2 in Fig. 1), in order to avoid errors brought by the detection setup and associated electronics. A ~ 250 kHz phase-lock feedback bandwidth can be inferred from the spectral shape. Figure 3 shows the measured phase noise PSD of the beat signal between the Mid-IR-OFCS and the phase locked QCL. A 0.39-rad rms residual phase noise is obtained in a 1 Hz to 1 MHz integration bandwidth, indicating that more than 85% of the power is concentrated in the coherent carrier of the beat signal

This is the signature of a highly coherent phase-lock and of the very good transfer of the mid-IR OFCS spectral features to the QCL. Therefore, this results in a QCL linewidth ultimately set by the mid-IR comb tooth linewidth. Exploiting the OFCS FNPSD displayed in Fig. 2 (dashed red line (III)), we calculate a linewidth of respectively ~ 300 Hz (see above) and ~ 800 Hz at 1 ms and 100 ms integration time, which is 2 to 3 orders of magnitude lower than in the free-running regime. Our phase-locked Fabry-Perot QCL shows a 2 orders of magnitude narrower linewidth compared to a similar work using a 8.6 μ m DFB QCL phase-locked to a home-built 250 MHz mid-IR comb [4].

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