Published in Optics Express 28, issue 6, 8200-8210, 2020
which should be used for any reference to this work

Frequency noise correlation between the offset frequency and the mode spacing in a mid-infrared quantum cascade laser frequency comb

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Abstract: The generation of frequency combs in the mid-infrared (MIR) spectral range by quantum cascade lasers (QCLs) has the potential for revolutionizing dual-comb multi-heterodyne spectroscopy in the molecular fingerprint region. However, in contrast to frequency combs based on passively mode-locked ultrafast lasers, their operation relies on a completely different mechanism resulting from a four-wave mixing process occurring in the semiconductor gain medium that locks the modes together. As a result, these lasers do not emit pulses and no direct self-referencing of a QCL comb spectrum has been achieved so far. Here, we present a detailed frequency noise characterization of a MIR QCL frequency comb operating at a wavelength of 8 µm with a mode spacing of ~7.4 GHz. Using a beat measurement with a narrow-linewidth single-mode QCL in combination with a dedicated electrical scheme, we measured the frequency noise properties of an optical mode of the QCL comb, and indirectly of its offset frequency for the first time, without detecting it by the standard approach of nonlinear interferometry applied to ultrafast mode-locked lasers. In addition, we also separately measured the noise of the comb mode spacing extracted electrically from the QCL. We observed a strong anti-correlation between the frequency fluctuations of the offset frequency and mode spacing, leading to optical modes with a linewidth slightly below 1 MHz in the free-running QCL comb (at 1-s integration time), which is narrower than the individual contributions of the offset frequency and mode spacing that are at least 2 MHz each.

1. Introduction

Optical frequency combs (OFCs) generated from mode-locked lasers have been a revolution in time and frequency metrology since their first demonstration 20 years ago by providing a direct and phase-coherent link between optical and microwave frequencies [1–3]. Their emission spectrum is determined by only two radio-frequencies, the constant spacing between the optical modes and the global frequency offset of the comb spectrum. In OFCs generated from ultrafast mode-locked lasers, the mode spacing corresponds to the repetition rate frequency f_{rep} of the pulsed laser train, whereas the global offset frequency is referred to as the carrier-envelope offset (CEO) frequency f_{CEO}, which results from the pulse-to-pulse phase shift occurring between the optical carrier and the envelope of the emitted laser pulses. The repetition rate that can range up to tens of GHz is straightforwardly measured by photo-detecting the laser pulse train

#385849 https://doi.org/10.1364/OE.385849
Journal © 2020 Received 16 Dec 2019; revised 14 Feb 2020; accepted 17 Feb 2020; published 5 Mar 2020

using a high-bandwidth photodiode. On the other hand, the standard method to detect the CEO frequency is the self-referencing scheme, which in the usual implementation requires a coherent octave-spanning spectrum and nonlinear f-to-$2f$ interferometry [1].

A different type of frequency combs has been demonstrated in the mid-infrared (MIR) spectral region that is important for molecular spectroscopy, based on the occurrence of four-wave mixing in the semiconductor gain medium of broadband quantum cascade lasers (QCLs) [4]. These lasers produce a frequency comb in some particular conditions where all emitted modes become equidistant as a result of the parametric four-wave mixing process. QCL combs are very attractive for dual-comb spectroscopy [5–7] in the MIR spectral range that is of particular importance for high-resolution molecular spectroscopy and trace gas sensing. As a result of the very short upper state lifetime of the gain medium, these comb sources do not generate optical pulses, but deliver a fairly constant output power [8] that is associated to a frequency-modulated (FM) spectrum. A recent model proposed by Opacak and Schwarz describes the formation of FM combs with the combined contributions of spatial hole burning, gain saturation and a minimum group velocity dispersion or Kerr nonlinearity due to gain asymmetry [9]. The FM nature of QCL combs has made the self-referencing method not possible so far and no detection of the offset frequency of a MIR QCL comb has ever been reported to the best of our knowledge, even if the full phase stabilization of a THz QCL comb to a CEO-free metrological THz comb was recently demonstrated [10]. For this purpose, the authors investigated the use of two different actuators, which are radio-frequency (RF) injection locking of the comb mode spacing by an external frequency reference signal and the QCL drive current to phase-lock one beat signal with the metrological comb to a reference oscillator. A constant width of the beat notes of around 120 kHz was observed when stabilizing the mode spacing only, while the linewidth of the beat notes increased linearly with the mode number N of the QCL comb when the phase-locked loop only was activated. An alternative approach to stabilize a QCL comb was implemented by Cappelli et al. [11] by phase-locking one mode of the QCL comb to a line of a metrological comb by feedback to the QCL current, reducing the linewidth of all modes below 23 kHz and showing a linear increase of this linewidth as a function of the distance from the locked mode. Simple relations between the QCL comb frequencies and the effective and group refractive indices were presented, showing that the QCL current acts predominantly on the offset frequency. The implemented stabilization scheme removed the common noise between the optical modes of the QCL comb that includes the combined contribution of the offset frequency and of the mode spacing, but no information about the noise of the offset frequency of the free-running QCL comb was assessed. In the recent work of Cappelli et al. [12], the amplitude and phase of the different modes of THz and MIR QCL combs were retrieved by a Fourier-transform analysis of the multi-heterodyne spectrum obtained in a dual-comb setup with a metrological comb. The relative frequency noise between the QCL comb modes was analyzed by implementing a scheme that combines a phase-lock of the mode spacing to an external reference oscillator by feedback to the QCL current, and a noise compensation scheme to remove the common noise between all modes of the multi-heterodyne beat signal with the metrological comb. This scheme removed a large part of the frequency noise of the multi-heterodyne beat signal, but did not reduce at all the noise of the optical modes of the QCL comb.

In this work, we show the first evaluation of the frequency noise properties of the offset frequency of a free-running QCL comb. We refer here to the offset frequency that we label f_0 and not to the CEO frequency f_{CEO}, as this terminology is not well-suited to MIR QCL combs that do not emit pulses. For the same reason, we refer to the mode spacing (or free spectral range) f_{FSR} of the QCL comb spectrum instead of the repetition rate f_{rep} used for mode-locked lasers. But the significance of these two parameters in the frequency domain is the same and they completely determine the frequency of an optical line ν_{N} of index N according to the well-known comb equation $\nu_{\mathrm{N}} = N \cdot f_{\mathrm{FSR}} + f_0$. By analogy to frequency combs generated from mode-locked lasers where f_{CEO} is defined by convention as $f_{CEO} \leq f_{rep}/2$, we consider here the offset frequency as $f_0 \leq f_{FSR}/2$ independently of the underlying physical effect responsible for the comb generation. Hence, N represents the mode number measured from the origin of the frequency axis. Our investigation relies on a dedicated scheme that we have developed to separately characterize the frequency noise of the two characteristic frequencies defining the optical spectrum of the QCL comb, i.e., the mode spacing f_{FSR} and the offset frequency f_0. The measurement involves an electrical scheme that circumvents the standard f-to-$2f$ interferometry method and enables the frequency noise spectrum of f_0 to be indirectly measured, without direct detection of this signal. In addition, the mode spacing can also be detected electrically in QCL combs by extracting the intermode beat signal from the laser current [13]. Hence, we are able for the first time to separately quantify the noise contributions of the two degrees of freedom of the QCL comb to its optical spectrum. We observe a strong anti-correlation between the noise of f_{FSR} and f_0 leading to a much lower frequency noise of the optical mode, similar to our previous observations in different types of ultrafast mode-locked lasers [14–16]. From this result, we assess the position of the fixed point [17] of the QCL comb spectrum.

2. Experimental setup and noise investigation of the free-running QCL comb

The used QCL has a length of 6 mm. Its back facet is high-reflectivity-coated and the device is mounted junction-down. A comb regime was achieved at a temperature of 10°C and at a typical laser current of ~1.7 A. In these conditions, the optical spectrum centered at 1245 cm^{-1} typically extends over 50 cm^{-1} and consists of ~200 lines separated by ~7.4 GHz. This frequency can be detected electrically from the intermode beat signal extracted from the modulation of the injected current in the laser [13]. We used this signal to characterize the QCL comb mode spacing, as it is difficult to detect it optically with a good signal-to-noise due to the lack of high bandwidth detectors in the MIR.

The experimental setup shown in Fig. 1 was implemented to beat one line of the QCL comb (with a mode number $N \approx 5{,}112$) with a low-noise single-mode reference laser in order to measure the frequency noise of one of the comb modes. The mode number N was estimated from the frequency of the reference laser assessed spectroscopically using the position of N_2O absorption lines and the measured mode spacing of the QCL comb. The reference laser is a distributed feedback (DFB) QCL operating at 1256.7 cm^{-1}. It was temperature-controlled and driven by a home-made low-noise laser driver. The DFB-QCL was stabilized to a Mach-Zehnder interferometer to reduce its frequency noise and narrow its linewidth so that the measured heterodyne beat reflects the noise properties of the QCL comb with a negligible noise contribution of the reference laser. The stabilization was realized with a short free-space imbalanced path of about 1 m in a similar way as in our recent demonstration of this approach [18], leading to a linewidth in the 10-kHz range (at 1-s integration time), which is much narrower than the linewidth of the QCL comb presented later.

In addition, this setup enabled us to indirectly assess the frequency noise of the offset frequency f_0 of the QCL comb without directly detecting it by the traditional method of f-to-$2f$ interferometry, but based on an approach that we previously developed and validated using a self-referenced Er:fiber frequency comb [19]. This method was also successfully applied later to perform a detailed investigation of the noise properties of the CEO frequency in a mode-locked semiconductor laser [15] and in a 25-GHz repetition rate diode-pumped solid-state mode-locked laser [16]. It is applied here to a MIR comb to investigate the offset frequency noise in a QCL comb.

Basically, the method consists of suppressing the contribution of the mode spacing f_{FSR} in the frequency noise of an optical line $\nu_N = (N \cdot f_{FSR} + f_0)$ of the QCL comb, measured from the heterodyne beat $f_b = (\nu_N - \nu_{cw})$ with the narrow-linewidth QCL of frequency ν_{cw}. The suppression of the noise of the mode spacing was achieved using an electrical scheme (see

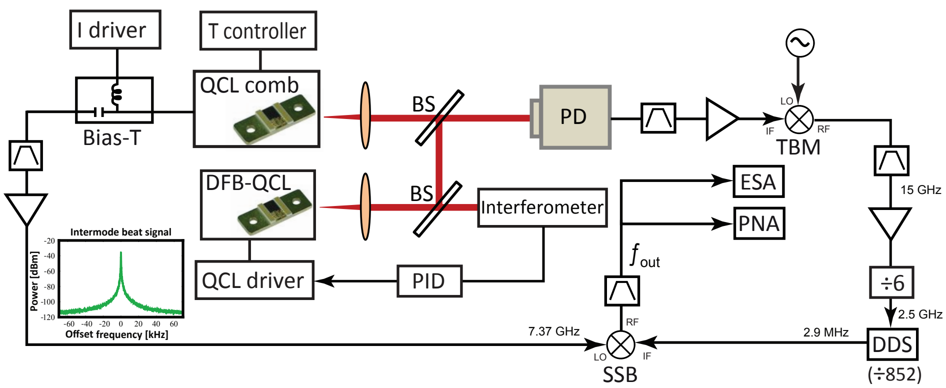

Fig. 1. Scheme of the experimental setup implemented to measure the frequency noise of the unknown free-running offset f_0 of the QCL comb. The frequency noise of f_0 is indirectly measured by separately detecting the mode spacing fFSR by RF extraction (lower branch of the scheme) and the heterodyne beat between one optical line of the QCL comb and a narrow-linewidth DFB-QCL at 1256.7 cm^{-1}. The beat signal is filtered, up-converted and frequency-divided by a large number $N = 5{,}112$ using a frequency pre-scaler (÷6) and a direct digital synthesizer (DDS, upper branch of the scheme). The two signals are then combined (mixed) to remove the noise contribution of fFSR, such that the resulting signal f_{out} is representative of the noise of f_0 only. BS: beamsplitter; PD: photodetector: PID: proportional-integral-derivative servo controller; TBM: triple-balanced mixer; SSB: single sideband mixer; DDS: direct digital synthesizer; ESA: electrical spectrum analyzer; PNA: phase noise analyzer. A representative intermode beat note electrically extracted from the QCL comb with a bias-T is shown on the lower left part of the figure, after amplification. The signal is centered at 7.37 GHz.

Fig. 1) and not optically as with f-to-2f interferometry. For this purpose, the beat signal needs to be frequency-divided by the large integer number N and mixed with the mode spacing f_{FSR} separately extracted from the QCL current with the use of a bias-tee (Marki Microwave BTN2-0018) in order to generate the output signal $f_{out} = f_{FSR} - f_b/N = (\nu_{cw} - f_0)/N$. The noise of this signal is dominated by the contribution of f_0 if the auxiliary laser ν_{cw} has a much lower noise, which is the case here. In order to perform the frequency division by the large number N, the heterodyne beat signal detected at a frequency of ~200 MHz (within the 1-GHz bandwidth of the used photodetector) was first up-converted to ~15 GHz by mixing it with the signal from a synthesizer in a triple-balanced mixer (Marki Microwave T3H-18LS). In this process, the noise contribution from the synthesizer is negligible in comparison to the frequency noise of the beat signal. The up-converted beat signal was then frequency-divided by a factor of 6 in a frequency pre-scaler (RF Bay FPS-6-15), whereas the subsequent division by a factor of 852 was realized by a direct digital synthesizer (DDS, Analog Devices AD9915). The resulting divided signal at ~2.9 MHz was further mixed in a single sideband (SSB) mixer (Marki Microwave SSB-0618LXW-1, lower sideband) with the ~7.37-GHz mode spacing electrically extracted from the QCL, then filtered and amplified. The resulting output signal f_{out} was analyzed with a phase noise analyzer (Rohde-Schwarz FSWP-26). As a result of the implemented scheme, the frequency noise originating from f_0 is the dominant noise contribution in the analyzed signal, which could be measured even if f_0 itself remained unknown.

The frequency noise power spectral density (FN-PSD) measured for an optical mode ν_N of the free-running QCL comb (from the beat signal f_b with the narrow-linewidth QCL) is displayed in Fig. 2. It is compared to the mathematically up-scaled frequency noise spectra separately measured for the mode spacing of the QCL comb and indirectly assessed for f_0 using our experimental scheme. A similar noise spectrum (in both shape and magnitude) is observed for the indirect f_0 signal and for the up-scaled mode spacing $N{\cdot}f_{FSR}$, whereas the noise of the optical line is significantly lower. The corresponding linewidth (full width at half-maximum) calculated from the measured frequency noise PSD using the β-separation line concept [20] is slightly below 1 MHz (at 1-s integration time) for the optical line, whereas it amounts to 2 MHz and 2.5 MHz, respectively, for the individual noise contributions of f_0 and $N{\cdot}f_{FSR}$ if one disregards the influence of the technical noise peaks at 50 Hz and harmonics. As the FN-PSD of f_0 and f_{FSR} is limited by the measurement noise floor at high Fourier frequencies, the $1/f$ trend of these spectra was extrapolated down to the β-separation line for the linewidth estimations. The narrower linewidth of the optical line indicates that the fluctuations of f_{FSR} and f_0 are anti-correlated and partially compensate each other in the optical line. This behavior implies the existence of a fixed point [17,21] in the vicinity of the optical carrier in the spectrum of the QCL comb according to the elastic tape model of frequency combs introduced for mode-locked lasers [22,23]. This fixed point is calculated from the ratio of the FN-PSD of the offset frequency (S_{f_0}) and of the mode spacing ($S_{f_{FSR}}$) as $N_{fix} = \sqrt{S_{f_0} / S_{f_{FSR}}} \approx 4,300$, leading to a fixed frequency of $\sim$1056 cm^{-1} located outside of the comb spectrum. This fixed point results from the dominant noise source in our QCL comb, which is believed to arise from the voltage noise between the QCL terminals as previously observed in single-mode QCLs [24,25], which induces fluctuations of the internal temperature of the gain medium and, thus, produces frequency noise in all comb modes.

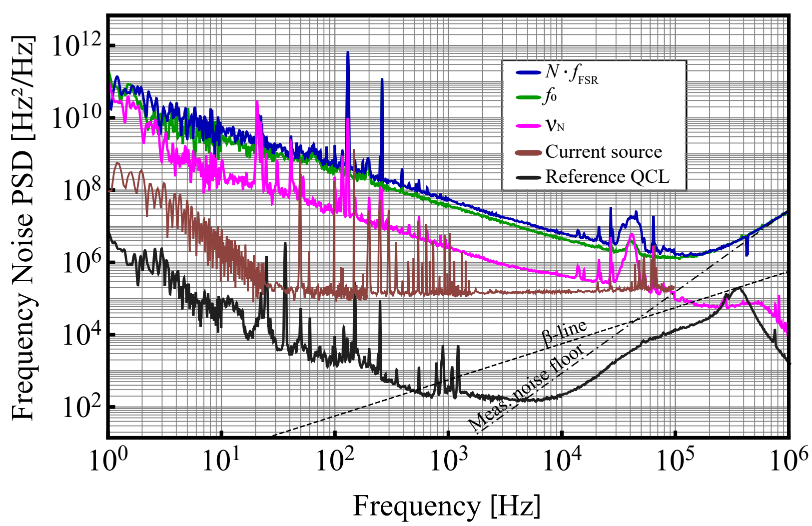

Fig. 2. Frequency noise power spectral density (FN-PSD) separately measured for an optical mode ν_N (pink), for the mode spacing up-scaled to the optical frequency ($N{\cdot}f_{FSR}$, blue) and indirectly assessed for the offset signal f_0 (green). The typical frequency noise spectrum of the reference DFB-QCL locked to the delay line and used to characterize the QCL comb is also displayed (grey, from [18]), as well as the contribution of the current noise of the QCL driver to the comb frequency noise (light brown, obtained by recording the current noise on a resistive load and converting it into an equivalent frequency noise using the measured transfer function discussed in Section 3, here for the optical line ν_N). The measurement noise floor at high frequency is indicated by the dash-dotted line and the β-separation line [20] used to estimate the linewidths by the dashed line.

The degree of correlation between the frequency fluctuations $N{\cdot}\Delta f_{\mathrm{FSR}}$ of the up-scaled mode spacing $N{\cdot}f_{\mathrm{FSR}}$ and Δf_0 of the offset signal f_0 was assessed from the measured FN-PSDs by calculating the sum $\Gamma_\Delta = \gamma_{\Delta f_0\, N\cdot\Delta f_{\mathrm{FSR}}} + \gamma_{N\cdot\Delta f_{\mathrm{FSR}}\, \Delta f_0}$ of the complex coherences $\gamma_{\Delta f_0\, N\cdot\Delta f_{\mathrm{FSR}}}$ and $\gamma_{N\cdot\Delta f_{\mathrm{FSR}}\, \Delta f_0}$ between the frequency variations Δf_0 and $N{\cdot}\Delta f_{\mathrm{FSR}}$ in the free-running QCL comb following the approach presented by Dolgovskiy and co-workers [14]. The complex coherence between two quantities x and y is defined in the general case as $\gamma_{xy} = S_{xy} \Big/ \sqrt{S_x \cdot S_y}$, where S_x represents the FN-PSD of the parameter x and S_{xy} is the cross-spectrum of the parameters x and y. Using the comb equation, the sum of the complex coherences can be obtained from the measured FN-PSDs as (see Ref. [14] for more explanations):

$$\Gamma_\Delta = (S_{f_b} - S_{f_0} - S_{Nf_{\mathrm{FSR}}}) / \sqrt{S_{f_0} \cdot S_{Nf_{\mathrm{FSR}}}}.$$

The calculated value of Γ_Δ displayed in Fig. 3 is close to −2 in the entire considered spectral range, which demonstrates the strong anti-correlation of the frequency noise of $N{\cdot}f_{\mathrm{FSR}}$ and f_0. The value of Γ_Δ close to zero observed at a frequency of ∼20 Hz results from a noise peak present in the FN-PSDs in Fig. 2. This peak is believed to be of technical origin in the experimental setup, we do not believe that it originates from the QCL itself. It is visible in the FN-PSD of ν_N, f_0 and f_{FSR}. As it does not arise from the QCL, this noise is uncorrelated between f_0 and f_{FSR}. This is why the sum of the complex coherence reaches a value close to zero at this frequency. This uncorrelation leads to a noise peak in the FN-PSD of ν_N that is as strong as in the FN-PSD of f_{FSR} in Fig. 2, whereas the FN-PSD of ν_N is much weaker than that of f_{FSR} at other frequencies where a high correlation occurs. The strong noise anti-correlation, combined with the similar amplitude of the FN-PSD measured for $N{\cdot}f_{\mathrm{FSR}}$ and indirectly for f_0, explains the lower frequency noise observed for the optical mode of the QCL comb compared to the individual noise contributions of $N{\cdot}f_{\mathrm{FSR}}$ and f_0. This behavior is very similar to the case of comb spectra generated from ultrafast mode-locked lasers of various types that have been reported previously, such as an Er-fiber [14], a semiconductor mode-locked laser with a repetition rate in the GHz range [15], or a diode-pumped solid-state mode-locked laser (DPSSL) with 25-GHz repetition rate [16], even if the comb formation mechanism is completely different.

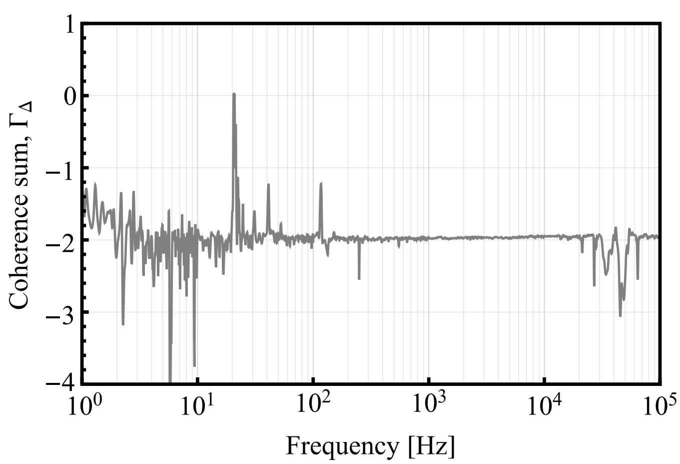

Fig. 3. Frequency dependence of the sum of the complex coherences Γ_Δ between the frequency variations of f_0 and f_{FSR} in the free-running QCL comb. The plot is restricted to 100 kHz, as the noise spectra of f_0 and $N{\cdot}f_{\mathrm{FSR}}$ are limited by the experimental noise floor at higher frequencies.

3. QCL comb transfer functions for current modulation

Frequency combs emitted from ultrafast mode-locked lasers typically make use of two different actuators to separately stabilize their two degrees of freedom, i.e., the repetition rate and the CEO frequency, even if these actuators may not be independent and a cross influence generally occurs between their effect on f_{rep} and f_{CEO} [14]. The cavity length, controlled for instance with a piezo-electric transducer (PZT), is generally used to stabilize the repetition rate, whereas the pump power mainly acts on the CEO frequency. The situation is different for QCL combs that do not have an equivalent knob to the PZT used in ultrafast mode-locked lasers as they are monolithically-integrated, electrically-driven light sources. Different actuators are available to control their emission spectrum, which are the laser current and temperature, but they are strongly correlated. Furthermore, temperature control is fairly slow and does not appear practicable for proper frequency stabilization. Both comb parameters are expected to be affected by the laser average (or DC) current. However, a distinct way to control and lock the mode spacing in QCL combs is by injecting a radio-frequency (RF) current in the QCL at a frequency close to the native mode spacing, which can injection-lock this parameter [26] via the coupled dynamics of the optical field and carrier density in the QCL semiconductor medium [13].

Using the same setup as before to indirectly characterize the offset frequency of the QCL comb, we have separately investigated the effect of a modulation of the laser driving current (baseband component) onto the two comb parameters f_{FSR} and f_0, as well as onto an optical line ν_{N}, by measuring their modulation transfer functions. For this purpose, we modulated the QCL current with a sine waveform with a small amplitude ΔI, ranging between 20 µA and 3 mA depending on the considered measurement, and demodulated the corresponding signals (optical beat, electrically-extracted mode spacing or indirect offset signal obtained using the scheme of Fig. 1) using a frequency discriminator [27] and a lock-in amplifier.

The measured transfer functions are displayed in Fig. 4. They present the same behavior, both in amplitude and in phase, with a flat amplitude response up to ~10 kHz. This limited bandwidth results from the fact that the frequency of the QCL comb modes varies with the laser current mainly due to a thermal effect, as for single-mode QCLs [28]. Even if the QCL current can be modulated much faster (the used current driver has a bandwidth larger than 100 kHz, measured on a resistive load), as well as the output optical power, the effect on the emitted optical frequencies is limited by the thermal dynamics of the QCL. The effect of the QCL drive current was determined to be around 2,550 times larger on the offset frequency ($\Delta f_0/\Delta I \approx 125$ MHz/mA) than on the mode spacing ($\Delta f_{\text{FSR}}/\Delta I \approx 49$ kHz/mA), but the respective contribution of the two parameters to the modulation of the optical line ν_{N} is of the same order of magnitude. Hence, the fixed point for current modulation corresponds to $N_{\text{fix}} = (\partial f_0/\partial I)/(\partial f_{\text{FSR}}/\partial I) \approx 2,550$. A phase shift of 180° is observed between the transfer functions of f_{FSR} and f_0, which indicates that a change of the QCL current produces an opposite effect on these two parameters.

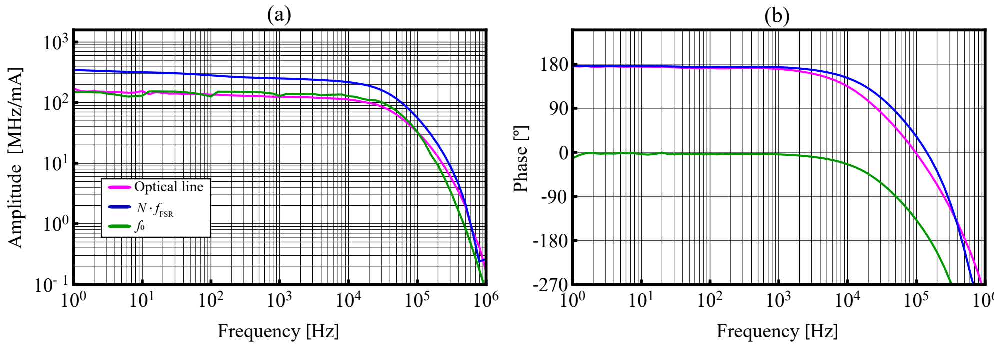

Fig. 4. Transfer function in amplitude (a) and phase (b) of $N{\cdot}f_{\mathrm{FSR}}$ (blue), f_0 (green) and ν_N (optical line, pink) measured for a modulation of the QCL current applied through its driver.

4. Impact of the stabilization of the mode spacing on an optical line

The QCL current can be used to phase-lock the mode spacing to an external RF reference (synthesizer) as schematized in Fig. 5(a). With an achieved loop bandwidth in the range of 30-40 kHz that is limited by the QCL comb transfer function displayed in Fig. 4, the phase noise of the mode spacing is strongly reduced and reaches the noise of the reference oscillator at low Fourier frequencies as illustrated in Fig. 5(b). The mode spacing analyzed here was electrically extracted from the QCL current and its limited signal-to-noise is the reason for the observed noise floor of the measurement in the range of −100 to −110 dBc/Hz.

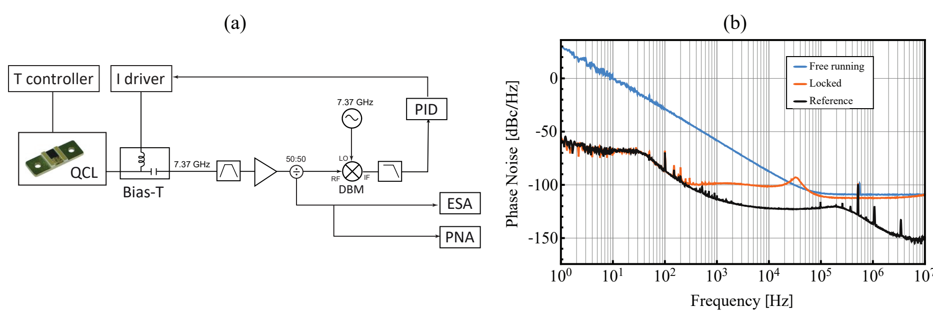

Fig. 5. (a) Experimental scheme used to stabilize the mode spacing of the QCL comb to an external frequency reference at 7.37 GHz by feedback to the QCL current. DBM: double balanced mixer; PID: proportional-integral-derivative servo controller; ESA: electrical spectrum analyzer; PNA: phase noise analyzer. (b) Phase noise PSD of the QCL mode spacing in free-running mode (blue) and phase-locked to an external reference (red). The phase noise of the frequency reference is also displayed in grey.

The impact of the mode spacing stabilization onto an optical comb line was also assessed by analyzing the frequency noise of the heterodyne beat signal f_b between the comb line and the narrow-linewidth QCL. Results are displayed in Fig. 6. They show that while the frequency noise of the mode spacing f_{FSR} is strongly reduced by the stabilization loop, the frequency noise of the optical line ν_N is significantly degraded by the stabilization (by about one order of magnitude). In terms of optical linewidth, it corresponds to a broadening from ~1 MHz for the free-running comb (at 1-s integration time) to 4.5 MHz when the mode spacing is locked. This results from the same reason as analyzed and discussed in details in a similar observation previously made with a 25-GHz DPSSL comb, where stabilizing the repetition rate with the use of a piezo-electric transducer also led to an increase of the frequency noise of the optical lines compared to the free-running case [16].

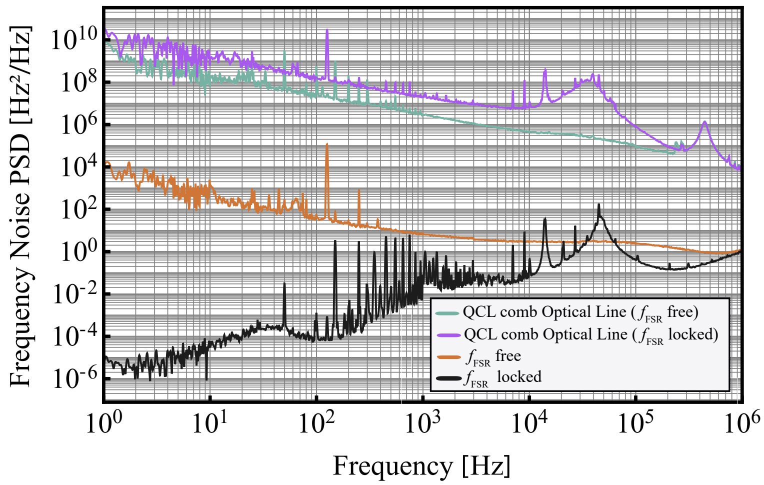

Fig. 6. Frequency noise PSD of an optical comb line (upper traces) and of the mode spacing (lower curves) measured for the free-running QCL and when the mode spacing is phase-locked to an external RF reference. The noise bump occurring in the latter case at ~40 kHz corresponds to the servo bump of the stabilization loop.

As explained before, the noise of f_{FSR} and f_0 partially compensates each other in the optical lines of the free-running QCL as a result of their anti-correlation, which leads to a resulting frequency noise that is lower than the individual contributions of $N{\cdot}f_{\text{FSR}}$ or f_0. When f_{FSR} is stabilized to an external reference, this partial compensation disappears, and the frequency noise of the optical line mainly corresponds to the noise of f_0, as the contribution of f_{FSR} becomes negligible. Therefore, the noise of the optical line increases compared to the free-running case. The reason resides in the fact that the effect of the QCL current on the comb spectrum corresponds to a different fixed point ($N_{\text{fix}} \approx 2{,}550$) than the principal noise source that affects the free-running laser ($N_{\text{fix}} \approx 4{,}300$). Therefore, stabilizing f_{FSR} does not have an effect on f_0, which becomes totally uncorrelated from the locked f_{FSR}, so that the frequency noise of the optical comb line becomes essentially equal to the one of f_0.

5. Conclusion and outlook

We have reported the first noise characterization of the offset frequency in a MIR QCL comb. It was carried out using an electrical scheme that does not require the direct detection of the offset frequency based on a nonlinear interferometry scheme, which is not applicable yet to the unpulsed emission of this type of frequency combs. By means of this scheme, we were able to measure separately the frequency noise of the two parameters of the QCL comb, the mode spacing and the offset frequency. The strong observed anti-correlation between these two signals explains the lower noise and narrower linewidth obtained for the lines of the QCL comb operating around 1245 cm^{-1}, with the presence of a fixed point estimated at 1056 cm^{-1}, as well as the degradation of the frequency noise and linewidth of the optical mode when phase-locking the mode spacing to an external RF reference.

Funding

BRIDGE (CombTrace (20B2-1_176584)); Swiss Space Office (MdP COSMICS); Schweizerischer Nationalfonds zur Förderung der Wissenschaftlichen Forschung (200020_178864).

Acknowledgments

We thank Alpes Lasers SA in Neuchâtel, Switzerland, for providing the DFB laser used in this study to characterize the QCL comb. Experimental results presented in this work are open-access available under DOI: http://doi.org/10.23728/b2share.9ba9521ae2924cd98a2b84f4c8ea3aeb.

Disclosures

The authors declare no conflicts of interest.

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