Frequency noise and linewidth of mid-infrared continuous- wave quantum cascade lasers: An overview

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Active linewidth-narrowing of a mid-infrared quantum cascade laser without optical reference

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We report on a technique for frequency noise reduction and linewidth-narrowing of a distributed-feedback mid-IR quantum cascade laser (QCL) that does not involve any optical frequency reference. The voltage fluctuations across the QCL are sensed, amplified and fed back to the temperature of the QCL at a fast rate using a near-IR laser illuminating the top of the QCL chip. A locking bandwidth of 300 kHz and a reduction of the frequency noise power spectral density by a factor of 10 with respect to the free-running laser are achieved. From 2 MHz for the free-running QCL, the linewidth is narrowed below 700 kHz (10 ms observation time).

OCIS codes: (140.5965) Semiconductor lasers, quantum cascade; (290.3700) Linewidth.

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Since their first demonstration [1], quantum cascade lasers (QCLs) have opened the way to numerous applications in the field of environmental and biomedical sciences, industrial process monitoring, and defense. Thanks to the ability to overcome the energy bandgap limitations of conventional interband laser diodes and to precisely design their emission wavelengths, QCLs have been demonstrated as very flexible single-frequency light sources in the mid-IR [2] and terahertz [3] optical spectral ranges where many molecules show strong absorption profiles.

The growing interest for high-resolution spectroscopy experiments has pushed scientists to investigate the ultimate limits that these devices can achieve in terms of frequency stability. Frequency noise and linewidth properties of free-running QCLs were investigated in various experimental setups in the mid-IR with distributed feedback (DFB) [4,5] and external cavity configurations [6], as well as in the terahertz domain [7]. Moreover, different active frequency-stabilization experiments for linewidth narrowing have been reported. Generally, a frequency-sensitive element is used to sense the fluctuations of the laser frequency and generate an error-signal that is usually fed back to the QCL injection current. Several methods were demonstrated using high-finesse optical cavities [8], Doppler-limited [9] and more recently Doppler-free molecular resonances [10], as well as by phase-locking a QCL to an optical frequency comb [11] and a mid-IR CO_2 laser to a remote near-IR ultra-stable frequency reference [12]. The frequency noise can be reduced by several orders of magnitude and emission linewidths below 1 kHz have been demonstrated.

In this Letter, we present a different approach for frequency noise reduction and linewidth-narrowing of a 4.55 μm QCL that does not involve any optical frequency reference. Following the observation that frequency noise in DFB QCLs arises from electrical power fluctuations due to the electronic transport in the devices [13,14], in this work we assess and experimentally demonstrate linewidth narrowing using only the voltage fluctuations across the QCL as an error signal for a feedback loop. This error signal is generated without measuring the actual fluctuations of the QCL optical frequency. A similar approach aiming at using the voltage noise (VN) measured across a near-IR laser-diode in order to implement an electrical feedback to reduce the phase noise was proposed [15] but never demonstrated to the best of our knowledge. We show here a reduction of the frequency noise power spectral density (PSD) of one order of magnitude within the bandwidth of the feedback loop (>100 kHz).

The laser used in our experiment is a 4.55 μm buried-heterostructure DFB QCL provided by Alpes Lasers. The stabilization scheme is shown in Fig. 1. The QCL is mounted on a Peltier-cooler operated at 20°C and an output power of 10 mW is obtained at an injection current of 260 mA (the threshold current is $I_{th} = 220$ mA). A low-noise current source is used to drive the QCL with a current noise lower than 1 nA/$\sqrt{\text{Hz}}$ in order to avoid any linewidth broadening resulting from technical noise [16]. In these conditions, the contribution of the injection current noise to the frequency noise is negligible and the fluctuations of the QCL laser frequency are intrinsic to the device, as shown in [4,5]. In our scheme, the VN

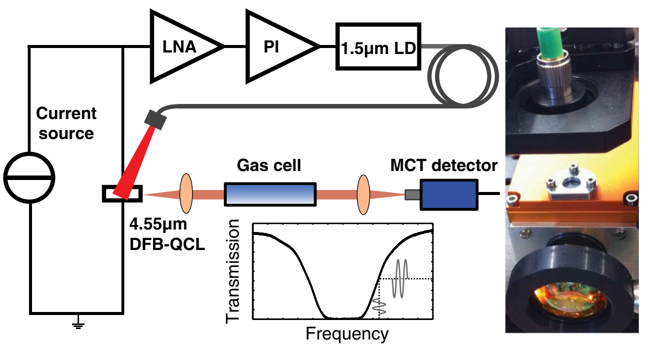

Fig. 1. Experimental setup. The VN across the QCL junction is amplified by a low-noise high-Z voltage-amplifier, processed through a PI controller and fed back to the QCL temperature using a fiber-coupled 1550 nm laser diode illuminating the top of the QCL chip. At the same time, the optical frequency of the QCL is analyzed using a ro-vibrational absorption line of carbon-monoxide acting as a frequency-to-intensity converter. On the right, a picture of the experimental setup shows the cover of the laser housing where a window was installed in order to illuminate the QCL with the near-IR radiation.

across the QCL junction is sensed and used to apply fast corrections to the QCL internal temperature. The voltage fluctuations are first amplified by a high-impedance low-noise voltage preamplifier (gain of 60 dB and specified bandwidth of 1 MHz) and then by a proportional–integral (PI) controller in order to generate a correction signal. The fast control of the QCL temperature is implemented here with a 1.55 μm diode laser (6 mW output power) illuminating the top of the QCL chip. A small fraction of the near-IR radiation on the order of 10% is indeed absorbed by the upper layers of the QCL structure, which produces a localized heating. By modulating the output intensity of the near-IR laser diode, the temperature of the QCL active region is therefore also modulated. The correction signal generated from the voltage fluctuations is sent to the modulation input of the 1550 nm laser driver in order to act on the temperature of the QCL. At fixed current, the voltage across the QCL depends on temperature (~10 mV/K for the present QCL) and the loop therefore stabilizes the voltage by acting on the QCL temperature and the associated electrical conductivity. It is important to note that the stabilization of the QCL voltage is independent of the injection current, which is kept constant. Fast all-optical wavelength-modulation of a cryogenic Fabry–Perot QCL was also demonstrated using front-facet illumination with a femtosecond Ti:sapphire laser [17]. In this case, a different mechanism was responsible for the QCL frequency shift, which was not thermal but attributed to the generation of free carriers.

At the same time, the optical frequency of the QCL is monitored and analyzed using a 10 cm gas cell filled with pure carbon-monoxide (CO) at a pressure of 2 mbar. As shown in Fig. 1, the QCL frequency is tuned to the flank of the absorption line, which acts as a frequency-to-intensity converter. At this point, the fluctuations of the laser frequency are converted into intensity fluctuations that are detected with a fast photodiode (100 MHz bandwidth), which gives a voltage proportional to the QCL optical frequency. Similar experimental setups were used for frequency noise characterization of free-running QCLs [4,5,16].

Figure 2 shows simultaneous recordings of both the QCL voltage and relative optical frequency versus time (in a 10 kHz bandwidth), first in free-running and then locked conditions. When the feedback loop is inactive ($t < 2$ ms), a clear correlation between the fluctuations of the QCL voltage and optical frequency can be observed (correlation coefficient $\rho = 0.9$). It is important to remember that the contributions of the current-driver noise are negligible and the fluctuations reported in Fig. 2 are generated in the QCL structure itself. Once activated ($t > 2$ ms), the feedback loop efficiently reduces the VN (error signal) by acting on the temperature of the QCL. At the same time, a significant reduction of the fluctuations of the optical frequency is also observed. In terms of frequency noise PSD, a 10-fold reduction is achieved within the bandwidth of the control loop, which is about 300 kHz in the present case from the observed servo bump (Fig. 3). From the frequency noise PSD, the FWHM linewidth is estimated to be narrowed from 2 MHz down to ~700 kHz over a 10 ms timescale [18]. Whereas the improvement might appear modest at first glance compared to the linewidth narrowing achievable with high-finesse cavities or molecular resonances, one must highlight that in our case the frequency noise reduction is achieved without any frequency reference and optical detection. Therefore, it has the potential to be completely electrically integrated and very compact. We verified that the near-IR laser light that illuminates the QCL does not degrade its free-running spectral properties. Indeed no change of the frequency noise PSD was observed when the near-IR beam illuminates the QCL (lock off) compared to the noise observed in absence of near-IR illumination. Moreover, the QCL intensity noise was measured in each configuration by detuning the laser from the absorption line. In each case, the intensity noise lies several orders of magnitude below the frequency noise contribution and does not affect any of the measurements.

The servo-bump in the frequency noise PSD indicates that a loop bandwidth on the order of 300 kHz is achieved, which is on the same order of magnitude as obtained in [10] for the stabilization of a QCL to a sub-Doppler molecular transition. The dynamic responses of the

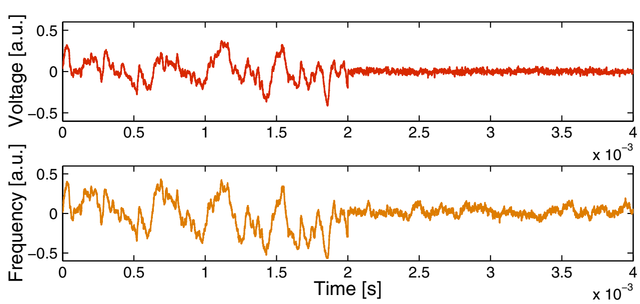

Fig. 2. Simultaneous recordings of the QCL voltage (upper frame) and optical frequency (lower frame) with a 10 kHz bandwidth. When unlocked ($t < 2$ ms), a clear correlation between the voltage and frequency fluctuations is observed. Once enabled ($t > 2$ ms), the loop efficiently reduces the voltage fluctuations by acting on the QCL temperature and a reduction of the QCL frequency-noise is also observed.

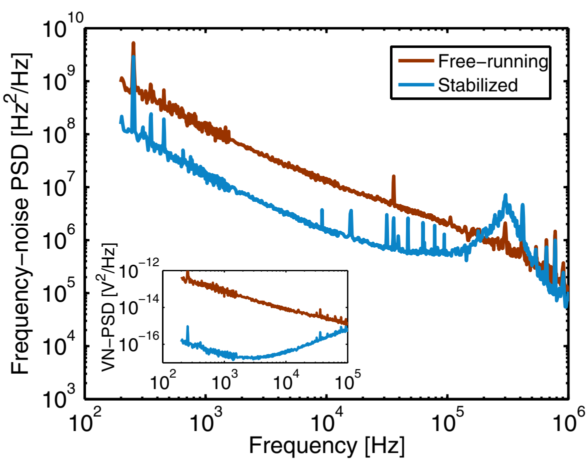

Fig. 3. Frequency noise PSD of the free-running and stabilized QCL. When the locking loop is enabled, a reduction of the frequency noise PSD by a factor of 10 is achieved. The bump observed at 300 kHz is due to an oscillation in the feedback loop. Inset: free-running and stabilized PSD of the VN across the QCL. A strong reduction of up to 3 orders of magnitude is achieved in the bandwidth of the feedback loop.

QCL voltage and optical frequency to a modulation of the intensity of the near-IR radiation are plotted in Fig. 4. The effect of the near-IR laser driver and voltage-preamplifier was taken into account so that the dynamic responses reflect the thermal response of the QCL itself. Modulation bandwidths of a few hundreds of kHz are measured. The frequency responses are governed by the thermal dynamics in the QCL structure. A slight roll-off is indeed observed in the magnitude diagram above 100 Hz. This behavior is similar to the one reported and modeled for ridge-waveguide continuous-wave DFB QCLs under direct current modulation and attributed to the thermal dynamics in the QCL structure [19]. The phase response of the QCL voltage combined with the other elements of the loop (voltage preamplifier and near-IR laser driver) is also shown (dashed line). Above 100 kHz, an important additional phase-shift is introduced by both the current driver of the near-IR laser and the voltage-preamplifier, despite specified bandwidths of 1 MHz and flat measured magnitude responses. The overall phase-shift becomes close to −180° at ~300 kHz (dashed line in the phase response of Fig. 4), which is consistent with the obtained feedback-loop bandwidth. The bandwidth limitation is therefore not exclusively due to the QCL thermal response and a faster feedback loop (close to 1 MHz) could probably be obtained by using a voltage-preamplifier and a 1550 nm laser diode driver introducing a lower phase-shift above 100 kHz.

The VN and therefore also the fluctuations of the electrical power dissipated in the QCL are efficiently reduced by the feedback-loop in the considered frequency range, as shown in the inset of Fig. 3. At a Fourier frequency of 3 kHz, the VN is reduced from $2.25 \cdot 10^{-14}\ \mathrm{V^2/Hz}$ ($150\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$) down to $2.5 \cdot 10^{-17}\ \mathrm{V^2/Hz}$ ($5\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$). However, residual $1/f$ frequency noise is still clearly observed both in the time domain (Fig. 2) and in the PSD (Fig. 3). This residual noise can be attributed neither to the QCL intensity noise, which lies an order of magnitude below as mentioned before, nor to the noise of the current driver that would set a white frequency noise floor of about $10^6\ \mathrm{Hz^2/Hz}$. This residual frequency noise probably reveals the contribution of another noise source and the occurrence of residual temperature fluctuations, although the electrical power dissipated in the device is stabilized. These residual temperature instabilities could arise from fluctuations of the intracavity optical power dissipated by the waveguide losses. Another possible explanation might be related to the fact that the sensed voltage is an average image of the electronic transport all along the QCL active region, whereas the temperature corrections are applied on top of the structure and can lead to an inhomogeneous temperature distribution in the active region. Frequency noise can be produced locally in the active region through local temperature fluctuations, whereas the voltage is a global measurement of the noise throughout the QCL active region and can very likely not completely describe the noise generation processes. This observation agrees with the correlation coefficient of 0.9, which was experimentally measured in free-running regime and tends to confirm that the two quantities are not entirely correlated. More experimental work will be necessary in order to confirm these hypotheses and figure out how to improve the performances of the stabilization scheme.

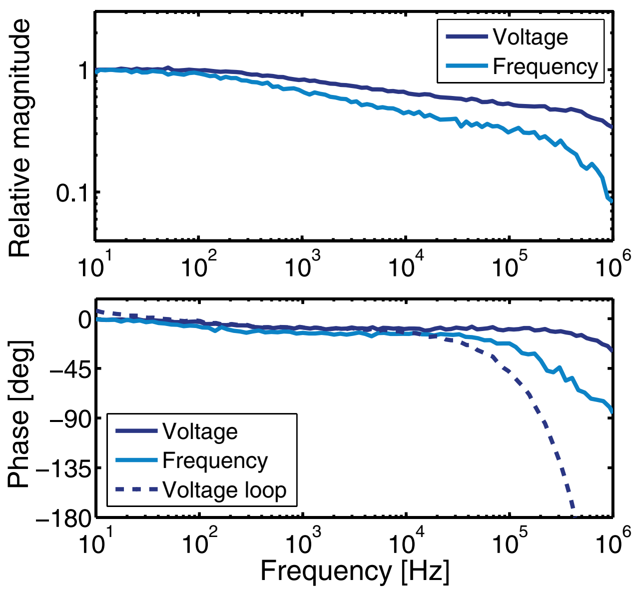

Fig. 4. Dynamic response of the QCL voltage and optical frequency when the intensity of the near-IR radiation illuminating the QCL is modulated. The slight roll-off observed in the magnitude diagram above 100 Hz is due to the thermal dynamics in the QCL structure. Above 100 kHz, an important phase shift is introduced by the voltage-preamplifier and the near-IR laser driver. The overall phase (dashed line) at 300 kHz becomes close to −180° and explains the servo-bump and bandwidth limitation of the feedback loop.

To conclude, we have demonstrated in this work the frequency noise reduction of a mid-IR DFB QCL without using any optical frequency reference. In our scheme, the VN across the QCL is sensed and fed back to the active region temperature via a 1550 nm laser diode illuminating the top of the QCL, which compensates the fluctuations of the electrical power dissipated in the structure. The optical frequency of the QCL was analyzed at the same time using a molecular absorption line and a reduction of one order of magnitude of the frequency noise PSD was achieved within the loop bandwidth. Although an external near-IR laser beam was used in this Letter, the fast control of the QCL temperature could be potentially implemented with an integrated element placed close to the active region, such as a microheater. This would lead to an all-electrical scheme for active linewidth-narrowing of a QCL. This technique could also possibly be applied to other kinds of semiconductor lasers and triggers new developments of low-noise integrated light sources.

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