Published in
Optics Letters 36, issue 16, 3109-3111, 2011
which should be used for any reference to this work

Frequency noise of free-running 4.6 μm distributed feedback quantum cascade lasers near room temperature

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The frequency noise properties of commercial distributed feedback quantum cascade lasers emitting in the 4.6 μm range and operated in cw mode near room temperature (277 K) are presented. The measured frequency noise power spectral density reveals a flicker noise dropping down to the very low level of $<100\,\mathrm{Hz}^2/\mathrm{Hz}$ at 10 MHz Fourier frequency and is globally a factor of 100 lower than data recently reported for a similar laser operated at cryogenic temperature. This makes our laser a good candidate for the realization of a mid-IR ultranarrow linewidth reference.

Narrow linewidth lasers exhibiting high spectral purity have important applications in various fields such as coherent optical communications or high-resolution spectroscopy. In time and frequency metrology, ultranarrow linewidth lasers are commonly used as a local oscillator in optical clocks, as well as in microwave photonics for all-optical generation of ultralow phase noise microwave signals. We are particularly interested in this latter application, which has been demonstrated in the past, most often based on near-IR (NIR) lasers [1], but also with a mid-IR (MIR) gas laser [2]. Laser linewidth narrowing down to the hertz level can be achieved by frequency stabilization to a properly designed and isolated high-finesse cavity using an appropriate feedback loop [3]. To be feasible with a reasonable loop bandwidth, a laser with a sufficiently low free-running frequency noise is generally used, such as an extended cavity diode laser or a fiber laser in the NIR.

In view of the realization of an ultrastable MIR laser for ultralow noise microwave generation, we investigated the frequency noise properties of quantum cascade lasers (QCLs). Indeed, due to their small Henry's linewidth enhancement factor α_e [4,5], these lasers are expected to have a low white frequency noise, or narrow intrinsic linewidth described by the Schawlow–Townes limit. This results from the fact that refractive index fluctuations at the lasing wavelength are almost nonexistent. However, much higher frequency noise may be present at low Fourier frequencies due to flicker noise. For our targeted application, it is important to assess the complete frequency noise spectrum of QCLs. More specifically, we are interested in the use of distributed feedback (DFB) QCLs, which are simpler, more compact, and reliable than their extended cavity counterparts. For practical reasons, especially for out-of-the-lab applications, QCLs operated at room temperature are also preferable to cryogenic devices.

QCL spectral properties have been reported in the past, but most often expressed in terms of linewidth. In contrast, the frequency noise power spectral density (PSD) provides much more information about the nature of the frequency noise, which is necessary to evaluate the feedback bandwidth needed for significant linewidth narrowing [6]. QCL frequency noise properties are poorly known and data have been reported by a few research groups only, but exclusively for cryogenic temperature devices so far [7–9] and especially for spectroscopy-related applications. Here, we have investigated the noise properties of commercial single-mode MIR QCLs (Alpes Lasers SA, Switzerland) emitting in the 4.6 μm wavelength range and operated in cw mode near room temperature (268–298 K range). In order to minimize the contribution of the current driver to the laser frequency noise, a homemade ultralow noise current source ($<350\,\mathrm{pA/Hz}^{1/2}$) was used.

The laser frequency noise was measured using the side of a molecular absorption line as a frequency-to-intensity converter in a standard single-pass direct absorption spectroscopy, as previously used in [7,8]. Working in a high absorption regime enables a slight increase of the conversion factor. For this purpose, a 1 cm long gas cell filled with pure carbon monoxide (CO) at a total pressure of 20 mbar was used and the laser was tuned to the flank of the R(14) rovibrational transition in the fundamental vibration band of CO at $2196.6\,\mathrm{cm}^{-1}$ (Fig. 1). A liquid-nitrogen-cooled HgCdTe photovoltaic detector with 20 MHz bandwidth was used to detect the transmitted light. The linear range of the absorption line flank is about 100 MHz broad, leading to constant discriminator sensitivity for all Fourier frequencies considered here, and the measurement was limited by the detector bandwidth only. The measured frequency noise PSD reveals the presence of flicker noise up to 10 MHz, with a noise level of $2\cdot 10^8\,\mathrm{Hz}^2/\mathrm{Hz}$ at 100 Hz and below $100\,\mathrm{Hz}^2/\mathrm{Hz}$ at 10 MHz (Fig. 2). Also shown in Fig. 2 are the contribution of the laser intensity noise (measured with the laser tuned out of resonance) and the contribution of the laser driver (obtained by combining the driver's current noise spectrum with the dynamic response of the laser). The laser dynamic response (change of the laser frequency for drive current modulation) shows a DC tuning coefficient of ≈900 MHz/mA and a low-pass behavior with a

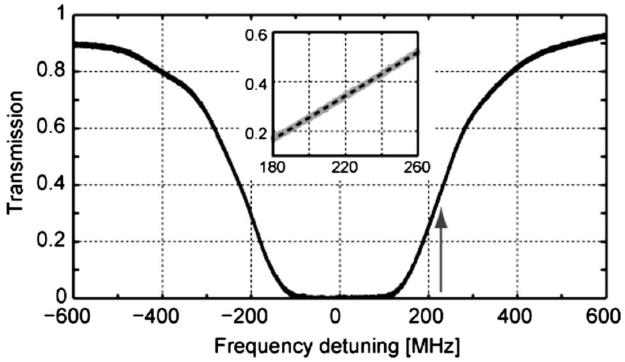

Fig. 1. Measured CO absorption profile used as a frequency discriminator (99.9% CO, 20 mbar, 1 cm path length). X axis is the detuning from the line center (2196.6 cm^1). The arrow represents the laser operating point. Inset: zoom on the linear region and linear fit (dashed line).

–3 dB bandwidth around 100 kHz (Fig. 3), limited by the laser only as the bandwidth of the current source is larger than 10 MHz. Figure 2 shows that neither the laser intensity noise nor the laser driver contributions limit the measured frequency noise at Fourier frequencies below 100 kHz, which can thus be attributed to the laser itself. The cutoff observed in the contribution of the laser driver above 100 kHz corresponds to the bandwidth of the laser dynamic response (Fig. 3). At higher Fourier frequencies, the measurement is affected by additional technical noise, also present in the intensity noise spectrum. This excess noise is believed to be induced by the current driver, whose noise contribution was evaluated on a resistive load, while it can behave differently on the QCL capacitive load, especially at high frequencies. Despite this excess technical noise, the laser frequency noise decreases significantly up to 10 MHz. Moreover, the general trend seems to change from the $1/f$ slope observed at low frequency into a steeper slope in $1/f^{3/2}$ above 10 kHz. However, one cannot exclude that an even steeper behavior in $1/f^2$ as observed in [7] is hidden in the noisy high-frequency part of the spectrum. We also characterized a second laser from the same fabrication run and used the resonance of a Fabry–Perot analyzer as a frequency discriminator instead of the CO absorption line. Both experiments yielded very similar results.

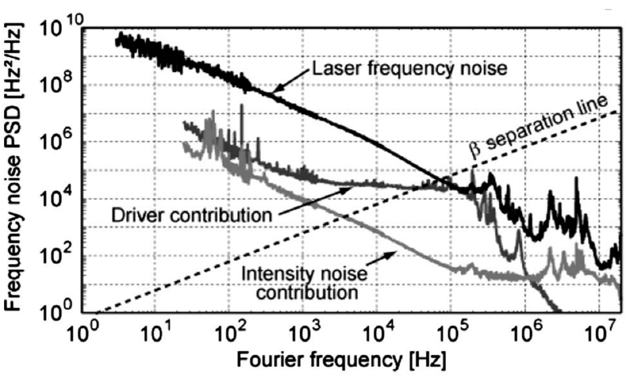

Fig. 2. Frequency noise PSD of a 4.6 μm DFB QCL ($T_{\text{op}} = 277$ K, $I_{\text{op}} = 350$ mA, $P_{\text{op}} = 6$ mW). The contributions of the laser intensity noise and laser driver current noise are also plotted as well as the β separation line that is relevant for the determination of the laser linewidth [6].

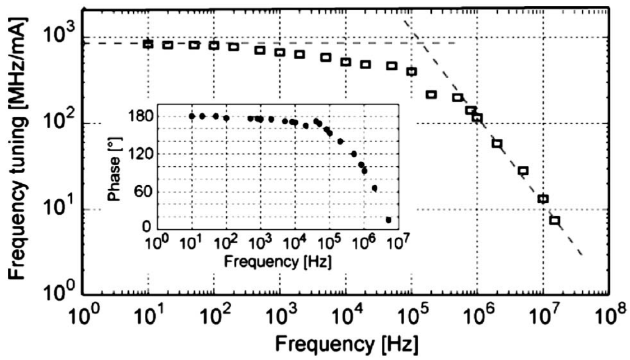

Fig. 3. Dynamic response (magnitude and phase) of the laser frequency tuning for drive current modulation.

As our main goal was to estimate the feedback bandwidth that is required to narrow the QCL linewidth, the noisy part of the frequency noise spectrum above 100 kHz is not of prime importance in this context, as it lies below the β separation line shown in Fig. 2, which is relevant for the determination of the linewidth [6]. Therefore, this spectral region does not contribute to the laser linewidth. One can notice that the laser white frequency noise is not reached below 10 MHz in such a way that only an upper limit of $S_w = 100\,\text{Hz}^2/\text{Hz}$ can be inferred for the white noise level. This level determines the laser intrinsic linewidth, for which an upper limit of $\Delta\nu = \pi S_w \approx 300$ Hz is obtained. However, it is important to note that while the intrinsic linewidth is a fundamental limit, the real laser linewidth, observed on a reasonable time scale, is strongly broadened by the $1/f$ noise. The laser FWHM linewidth can be calculated from the frequency noise PSD as shown in [6]. Because of $1/f$ noise, the linewidth depends on the observation time τ and diverges for $\tau \to \infty$. Therefore, a specified linewidth must always be reported with the corresponding observation time in the presence of flicker noise. The inset in Fig. 4 shows the calculated linewidth for a range of observation times being relevant in these measurements. For instance, a FWHM linewidth of 550 kHz is obtained for 5 ms observation time. This value is in good agreement with the spectral width of the heterodyne beat signal between two identical QCLs measured in a complementary experiment. As shown in Fig. 4, a total beat signal FWHM of the order of 1 MHz is obtained for an observation time of 4 ms. Since the line shape of the beat

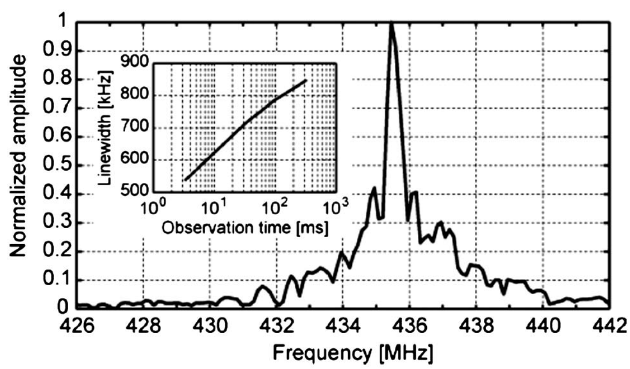

Fig. 4. Measured heterodyne beat spectrum of two identical 4.6 μm room-temperature QCLs with 4 ms sweep time. Inset: calculated FWHM linewidth as a function of observation time.

signal corresponds to the convoluted line shape of two nominally identical QCLs, this result agrees very well with the theoretical estimation based on the measured frequency noise PSD. The frequency noise spectrum also shows that a feedback bandwidth of hundreds of kilohertz appears sufficient to significantly narrow the linewidth of the room-temperature QCL, which is straightforwardly achievable by a standard servo controller and compatible with the laser frequency response shown in Fig. 3.

Interestingly, the frequency noise PSD measured in our room-temperature DFB QCL is generally a factor of 100 lower than the one recently reported by Bartalini *et al.* [7] for a similar laser (4.3 μm DFB QCL from Alpes Lasers SA), but operated at cryogenic temperature (around 80 K). In terms of linewidth, this difference corresponds roughly to a factor of 10. This significant difference is surprising at first glance as semiconductor lasers are generally expected to have better performances at low temperature (e.g., in terms of threshold current or optical power). We should point out that none of these results was limited by the laser driver. Even if the lower frequency noise of our QCL has no clear explanation yet, we believe that it results from its room-temperature operation through two possible effects. The first one is related to the excess voltage commonly observed in the I-V curves of cryogenic QCLs. Indeed, I-V curves measured at different temperatures [10] tend to show that a higher voltage is observed in cryogenic devices compared to room-temperature lasers, which could indicate less efficient contacts or junctions, leading to extra noise that is absent in our room-temperature-operated QCLs. A further important point is the magnitude of the specific heat of the QCL constituent materials. Based on a Debye temperature of 422 K for InP and 322 K for both InGaAs and InAlAs [11], we estimate that the specific heat of our device is at least a factor of 3 higher than for an identical QCL at 77 K. Since the output frequency of the laser mainly depends on changes of the effective optical path length due to temperature variations, this additional thermal inertia could by itself explain part of the lower frequency noise PSD observed here. On the other hand, our results are of the same order of magnitude as those reported by Myers *et al.* [8], even though their laser was emitting at a considerably longer wavelength of 8.3 μm and operated at 77 K. Longer wavelength QCLs were already reported to have lower frequency noise than similar shorter wavelength lasers operated at the same cryogenic temperature [9]. Further experimental and theoretical investigations that we plan to perform in the near future are required to understand the origin of the lower frequency noise observed in our room-temperature QCL.

In conclusion, we have presented, for the first time to our knowledge, frequency noise measurements of 4.6 μm QCLs operated in cw mode near room temperature (277 K). These results do not only complement previous data reported for cryogenic devices, but they also show the lowest frequency noise (and thus the narrowest linewidth) observed for a free-running QCL in this spectral range. The obtained noise level is very promising for the future realization of a QCL-based ultrastable MIR reference for time and frequency metrology. Indeed, the measured frequency noise indicates that a high reduction of the laser linewidth can be obtained by frequency-stabilization to an ultrastable optical cavity with a moderate feedback loop bandwidth of the order of 100 kHz for a DFB laser without the need for an external cavity configuration.

This research is supported by the Swiss National Science Foundation (SNSF), the Swiss Confederation Program Nano-Tera.ch scientifically evaluated by the SNSF, and was initiated by the Gebert-Ruef Foundation in Basel, Switzerland. We would like to thank Prof. Sigrist and M. Gianella from ETHZ for providing the gas cell, Prof. Gianfrani (Uni Napoli II) for the advice concerning the current driver, and Stéphane Blaser (Alpes Lasers) for fruitful discussions and information about the lasers.

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