# Physical Origin of Frequency Noise and Linewidth in Mid-IR DFB Quantum Cascade Lasers

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# Physical Origin of Frequency Noise and Linewidth in Mid-IR DFB Quantum Cascade Lasers

**L. Tombez[1], S. Schilt[1], G. Di Domenico[1], S. Blaser[2], A. Muller[2], T. Gresch[2], B. Hinkov[3], M. Beck[3], J. Faist[3] and D. Hofstetter[1]**

*1. LTF Laboratoire Temps-Fréquence, Institut de Physique, Université de Neuchâtel, CH-2000 Neuchâtel, Switzerland*
*2. Alpes Lasers S.A., CH-2000 Neuchâtel, Switzerland*
*3. Institute for Quantum Electronics, Department of Physics, ETH Zurich, CH-8093 Zurich, Switzerland*
*Author e-mail address: lionel.tombez@unine.ch*

**Abstract:** Frequency noise and linewidth properties of different mid-infrared DFB-QCLs using buried-heterostructures and ridge waveguides are compared. The physical origin of frequency noise and the impact of the different lasers parameters are discussed.

**OCIS codes:** (140.5965) Semiconductor lasers, quantum cascade; (270.2500) Fluctuations, relaxations, and noise

## 1. Introduction

Since their first demonstration in 1994, Quantum Cascade Lasers (QCLs) have become the most widely used light sources for trace gas sensing and spectroscopy in the mid-infrared molecular fingerprint region. Thanks to the ability to tailor their emission wavelength in order to reach the strong absorption bands of a wide variety of molecules, they opened the way to numerous applications in industrial sensing, safety and environmental sciences. Besides, there has been also a growing interest during last years for QCLs showing high spectral purity and narrow emission linewidth in the field of high-resolution spectroscopy, for instance for comb-assisted spectroscopy in the mid-infrared.

To date, the spectral purity of free-running distributed feedback (DFB) QCLs was studied through frequency noise measurements in several different experimental conditions in the mid-IR wavelength range [1-3], and also in the THz domain [4]. First investigations were performed with a DFB-QCL operated at cryogenic temperature [1] and then with another device at room-temperature [2]. Afterwards, the frequency noise was also investigated with a single laser operated over a wide temperature range [3]. Generally speaking, these studies showed different levels of spectral purity corresponding to linewidths ranging from 500 kHz to 10 MHz depending on the operating conditions and the considered device. In particular, a 10-fold broadening of the linewidth was reported for cryogenic QCLs compared to room-temperature devices [2-3].

However, as various QCLs using different designs, structures and operation conditions have been investigated to date, the identification of the main parameters contributing to the frequency noise generation has been difficult and the underlying physical origin of the noise remained poorly understood. In this paper, we present the frequency noise measurements of a total of four different QCLs emitting at the same wavelength of 4.55 µm. First we compare the frequency noise and its temperature dependence between several lasers using either ridge waveguides or buried-heterostructures. In the second part, we show that the frequency noise generation and the corresponding linewidth broadening are intrinsically linked to electronic fluctuations in the lasers. Finally, the comparison of the different tested devices allow us to discuss the physical origin of frequency noise in QCLs, as well as to assess the impact of the different lasers parameters, such as dimensions and thermal resistance, on the frequency noise generation.

## 2. Experimental results

Frequency noise measurements were performed in the same way as in Refs. [1-4] using a gas cell filled with carbon monoxide (CO) as frequency-to-intensity converter. The laser frequency was tuned to the side of an absorption line, which converts the frequency fluctuations into intensity fluctuations that were subsequently detected with a photodiode and analyzed. The frequency noise of two ridge waveguide and two buried-heterostructure (BH) QCLs at the same wavelength of 4.55 µm was optically measured using a CO line. The measured frequency noise power spectral density (PSD) showed a continuous $1/f$ behavior over all the considered frequency range. The noise component at a Fourier frequency of 3 kHz was extracted from each spectrum in order to assess the frequency noise level. In addition, a complete characterization of the electrical noise of the same QCLs was performed. This was carried out by directly measuring the voltage noise across the QCLs driven by a low-noise current controller.

Fig. 1 shows the temperature dependence of the frequency noise for one of each type of QCLs. First of all, the strong increase reported for the BH-QCL below 200 K in Ref. [3] is not observed for the ridge waveguide QCLs. The frequency noise rather tends to slightly and continuously decrease when the temperature is lowered. The equivalent frequency noise determined from the voltage noise measured across the device and the different tuning coefficients of the lasers is also reported in Fig. 1. In each case, it is in excellent agreement with the frequency noise optically measured using the CO absorption lines. This tends to explain that frequency noise in QCLs is generated through temperature fluctuations resulting from fluctuations of the electrical power dissipated in the device. The corresponding linewidths calculated from the frequency noise PSD are also shown in Fig. 1 and range between a few hundred kilohertz and 10 MHz, showing significant differences between the devices and operation conditions.

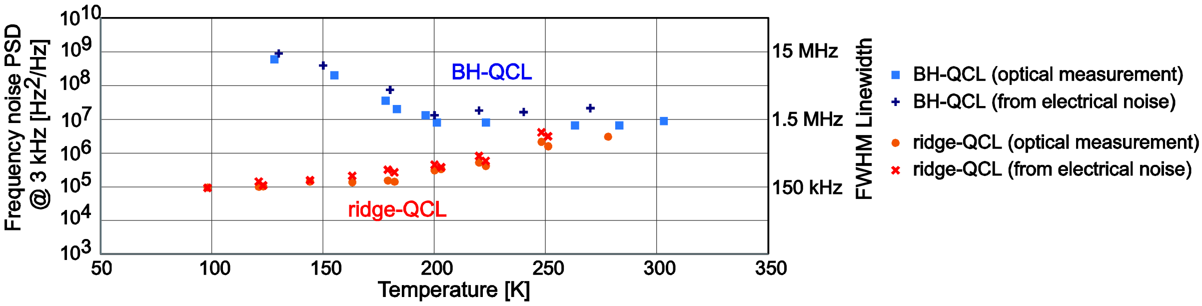


Fig. 1. Frequency-noise PSD at 3 kHz (left vertical scale) and corresponding linewidths for 10ms integration time (right vertical scale) of two 4.55-µm QCLs optically measured and determined from the voltage noise across the lasers junctions. Both methods are in excellent agreement.

In Fig. 2, the frequency noise of a second BH-QCL (labeled as BH-QCL-2) from the same fabrication run is reported along with the BH-QCL-1 of Ref. [3]. At low temperature a similar increase of the frequency noise is observed, with a slightly higher transition temperature. In the high-temperature range, the 4-fold higher frequency noise observed for BH-QCL-2 is a direct consequence of the larger thermal resistance of this device, which makes the laser frequency more sensitive to electrical power fluctuations. From these results and taking into account the different parameters of the tested QCLs, such as the physical dimensions and thermal resistances, we will discuss their impact on frequency noise generation.

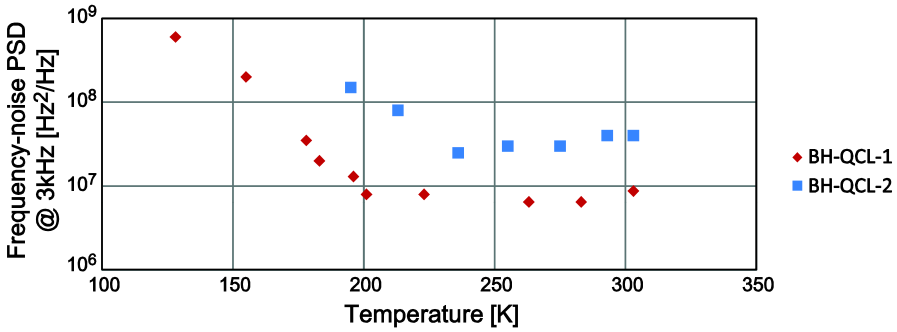


Fig. 2. Frequency-noise PSD of two buried-heterostructure 4.55-µm QCLs from the same fabrication run operated in similar conditions. The higher noise level measured for BH-QCL-2 is a direct consequence of a larger thermal resistance value of this device compared to BH-QCL-1.

## 3. Conclusion

We investigated the frequency noise properties of two types of QCLs and a total of four different devices. A fundamentally different temperature dependence was observed between ridge waveguide and buried-heterostructure lasers. However, we demonstrated in both cases through voltage noise measurements that electrical fluctuations internally generated in the laser structure are closely linked to the observed frequency noise, and therefore to the linewidth broadening. Moreover, these results allow us to discuss the physical origin of frequency noise generation in QCLs and open the way to interesting new opportunities aiming at improving the spectral purity of QCLs.

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