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Citation: AIP Advances **6**, 015212 (2016); doi: 10.1063/1.4940767
View online: http://dx.doi.org/10.1063/1.4940767
View Table of Contents: http://scitation.aip.org/content/aip/journal/adva/6/1?ver=pdfcov
Published by the AIP Publishing

AIP ADVANCES **6**, 015212 (2016)

Measurements of the linewidth enhancement factor of mid-infrared quantum cascade lasers by different optical feedback techniques

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(Received 16 November 2015; accepted 14 January 2016; published online 22 January 2016)

Precise knowledge of the linewidth enhancement factor of a semiconductor laser under actual operating conditions is of prime importance since this parameter dictates various phenomena such as linewidth broadening or optical nonlinearities enhancement. The above-threshold linewidth enhancement factor of a mid-infrared quantum cascade laser structure operated at 10°C is determined experimentally using two different methods based on optical feedback. Both Fabry-Perot and distributed feedback quantum cascade lasers based on the same active area design are studied, the former by following the wavelength shift as a function of the feedback strength and the latter by self-mixing interferometry. The results are consistent and unveil a clear pump current dependence of the linewidth enhancement factor, with values ranging from 0.8 to about 3. *© 2016 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).* [http://dx.doi.org/10.1063/1.4940767]

Quantum cascade lasers (QCLs) are semiconductor laser sources based on intersubband transitions within the conduction band.[1] Due to their compactness and the large range of accessible wavelengths, covering the mid-infrared from around 3 μm up to the terahertz, QCLs have become widely-used mid-infrared sources for applications such as gas spectroscopy, free-space communications and optical countermeasures.[2] Over the past years, various open questions have arisen regarding the dynamical response of such lasers, especially under an external perturbation (optical feedback, optical injection-locking or locking to a microwave reference).[3–5]

In interband lasers, one of the most important parameters governing the dynamical properties of the device is the linewidth enhancement factor (LEF). Also called linewidth broadening factor or α-factor, it was defined by Henry,[6] who showed that this parameter is non-zero in semiconductor lasers. The LEF quantifies the coupling between the phase and amplitude of the electrical field, or similarly the coupling between the gain and the refractive index of a semiconductor laser. This parameter is responsible for the linewidth broadening, resulting in an optical linewidth enhanced by a factor $(1 + \alpha^2)$ compared to the Shawlow-Townes limit,[7] appearance of filamentation in broad-area lasers,[8] or nonlinear dynamics in semiconductor lasers under optical feedback or injection.[9]

The standard method to measure the LEF of a semiconductor laser relies on measurements of the sub-threshold amplified spontaneous emission spectrum and the extraction of the wavelength and gain change as a function of the pump current.[10,11] However, this technique only gives the sub-threshold LEF which can be significantly lower than the above-threshold one. Several other methods have

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therefore been developed, based for instance on optical linewidth measurement, optical injection-locking or high-frequency techniques under modulation.[12]

In QCLs, the lasing transition takes place between two subbands with almost identical curvatures, the gain therefore remains quasi-symmetrical and the LEF is expected to be almost zero.[13] However, prior experimental studies have shown that the α-factor in mid-infrared lasers exhibits non-zeros values, typically ranging from -0.5 to 0.5 for sub-threshold measurements,[14–16] and from 0.2 to 2.5 for above threshold measurements.[17–19]

In this letter, we perform measurements of the above-threshold LEF of mid-infrared lasers using two different methods based on external optical feedback. The first one relies on tracking the wavelength shift of a Fabry Perot longitudinal mode with the feedback strength at a fixed cavity length, while the second one is based on self-mixing interferometry. These investigations provide a comprehensive comparison between the two experimental methods when applied to QCLs.

The lasers under study are Fabry-Perot (FP) and distributed feedback (DFB) QCLs with the same active area, emitting around 5.6 μm. They are based on a custom design inspired by Ref. 20. Devices under study were grown by molecular beam epitaxy on an InP cladding and incorporate 30 periods of the AlInAs/GaInAs structure. A high-reflectivity coating (>95%) on their back-facet enables continuous-wave (CW) operation at 10°C and beyond, while the front facet is left as-cleaved. The single-mode DFB laser is obtained through a top metal grating[21] with a coupling efficiency $\kappa \approx 4$ cm^{-1}.

Figure 1 presents the voltage and output power versus current characteristics at 10°C for the DFB and FP lasers. The DFB laser is 2 mm long and 9 μm wide, its threshold at 10°C is at 425 mA and

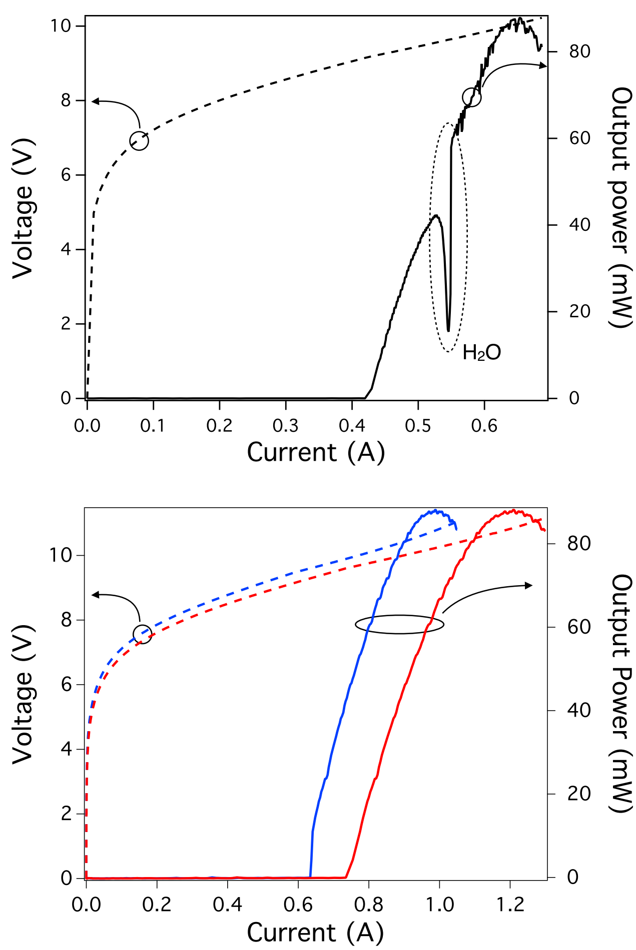

FIG. 1. L-I (right scale) and V-I (left scale) characteristics at 10°C. Top: DFB-QCL. Bottom: FP-QCLs, in blue 3 mm cavity, in red 4 mm cavity.

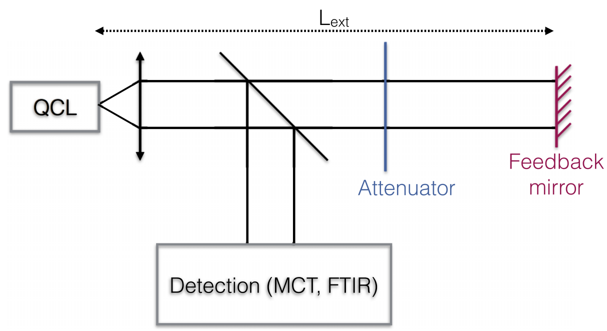

FIG. 2. Apparatus used for both experiments. The optical feedback is either provided by a static mirror or by one mounted on a piezo-electric actuator with a sinusoidal motion.

9.15 V. Its wall-plug efficiency is 1.4%. The dip in the L-I curve around 545 mA for the DFB QCL is a measurement artefact corresponding to a water absorption line in the air between the laser and the power meter. The FP QCLs are 6 μm wide and either 3 or 4 mm long. For the 3 mm-long laser, its wall-plug efficiency is 0.8% and the threshold is at 595 mA with a voltage of 9.50 V at 10°C. In the case of the 4 mm-long laser, the threshold amounts to 744 mA corresponding to a voltage of 9.63 V at 10°C. The threshold current difference between the three lasers mostly originates from their different cavity lengths.

The laser is inserted into a versatile experimental set-up as depicted in Figure 2. The emitted light is split into two paths. The first one is constituted of a feedback mirror and an attenuator, either a polarizer or a neutral density filter. For the self-mixing experiment, the feedback mirror is mounted on a piezo-electric actuator with a sinusoidal motion. The second path is used for detection, with either a Fourier transform infrared (FTIR) spectrometer or a mercury-cadmium-telluride (MCT) photo-detector. The two main experimental parameters impacting the effect of the optical feedback on a semiconductor laser are the external cavity roundtrip time τ_{ext} (related to the external cavity length L_{ext}), and the feedback coefficient k:[22]

$$k = \frac{1}{\tau_{in}} 2C_l \sqrt{f_{ext}} \tag{1}$$

where $\tau_{in} = 2n_g L_{in}/c$ is the internal cavity roundtrip time, with $n_g = 3.2$ the group refractive index, and f_{ext} is the feedback ratio, defined as the ratio between the reflected and emitted powers. C_l is an external coupling coefficient that can be expressed for a FP laser as:[23]

$$C_l = \frac{1 - R_2}{2\sqrt{R_2}} \tag{2}$$

with R_2 the intensity reflection coefficient of the laser facet subject to the delayed field, here $R_2 = 0.3$. In the case of the DFB laser, the expression for C_l becomes more complex and depends on the grating coupling coefficient as well as the complex phase at both laser facets.[23]

The first method used to measure the LEF of the FP QCL is based on the relation between the wavelength shift and the feedback parameters.[22] The phase rate equation of the QCL approximated as a three-level system under optical feedback can be expressed as:

$$\frac{d\phi}{dt} = \frac{\alpha}{2} \left(N_{pd} G_0 \Delta N - \frac{1}{\tau_p} \right) - k \sqrt{\frac{S(t - \tau_{ext})}{S(t)}} sin(\Delta\phi) \tag{3}$$

with S and ϕ the amplitude and the phase of the electric field, respectively, N_{pd} the number of periods in the cascade, G_0 the gain coefficient, ΔN the carrier density difference between upper and lower lasing states, τ_p the photon lifetime in the cavity, and $\Delta\phi = \phi_0 + \phi(t) - \phi(t - \tau_{ext})$, ϕ_0 being the free-running phase.

Considering the previous rate equation under steady state leads to an expression of the LEF given by:

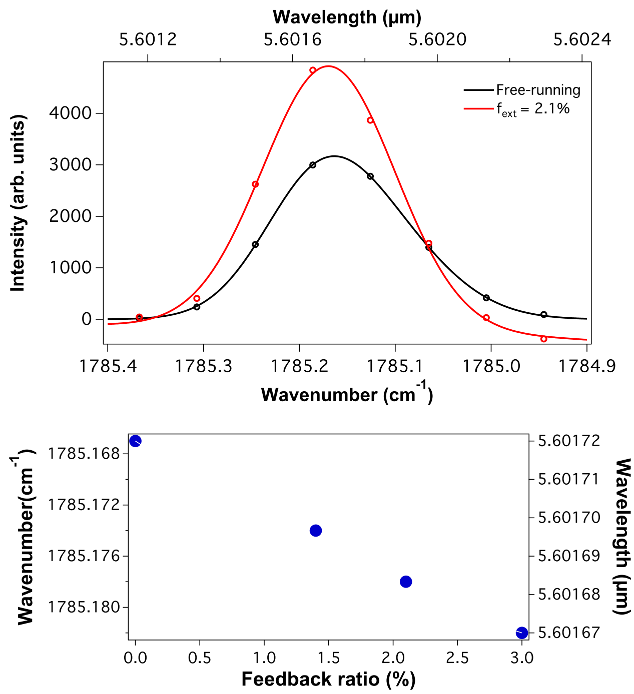

FIG. 3. Top: FTIR spectra of one longitudinal mode of the FP QCL without feedback (black) and with low feedback $f_{ext} = 2.1\%$ (red). The dots correspond to experimental points and the line is the Gaussian fit. Bottom: Wavelength shift of one mode of the FP optical spectrum with optical feedback.

$$\alpha = \frac{\omega_0 - \omega_s}{k cos(\omega_s \tau_{ext})} - tan(\omega_s \tau_{ext}) \tag{4}$$

where ω_0 is the angular frequency of the free-running laser and ω_s is the one in presence of optical feedback. We would like to emphasize that this method works better with FP lasers, where the lasing wavelength is not determined by the Bragg grating. This equation is only valid for low feedback ratios, corresponding to the first regime of optical feedback. In the case of the FP QCLs under study, it corresponds to feedback ratios lower than 3%.[4]

As shown in Figure 3, the wavelength shift of one longitudinal mode taken within the FP spectrum can be tracked using the FTIR spectrometer. To overcome the limited resolution, the spectral peaks were fitted with Gaussian curves. Several measurements were performed with a fixed external cavity length of 15 cm by varying the feedback ratio whithin the low feedback regime, leading to similar results. For the 3 mm FP QCL under study, operated at 10°C and 614 mA, with an external cavity length of 15 cm and a feedback ratio of 2.1%, the LEF was found to be 1.3 ± 0.5. The overall uncertainty value obtained by repeating the measurement mostly originates from the limited FTIR resolution of 0.125 cm^{-1}, the error on the external cavity length of ± 0.1 cm as well as from the uncertainty on the power measurement, due to thermal fluctuations in the room, estimated to be around ± 0.01 mW.

Applying an external feedback on the laser leads to a reduction of the laser threshold even for small feedback ratios.[4] For the 3 mm FP QCL under study, a feedback ratio of 2% results in a threshold reduction from 595 to 583 mA. Such a small amount of backreflection does not impact the LEF, contrary to what may occur under a very short-cavity regime or strong optical injection-locking.[24,25] Further investigations also prove that a modification of the external cavity length from 15 to 25 cm does not change the value of the α-factor. Furthermore, by changing the FP cavity length from 3 to 4 mm, the LEF remains the same within the uncertainty range: for the 4 mm FP QCL, the value was found to be $\alpha = 0.9$ at a pump parameter $P = I/I_{th} - 1 = 0.01$, where I is the bias current.

The second method is based on self-mixing interferometry. When varying periodically the external roundtrip time by applying a sine motion of the feedback mirror at fixed feedback strength, an interferogram is obtained allowing the measurement of experimental parameters such as velocities,

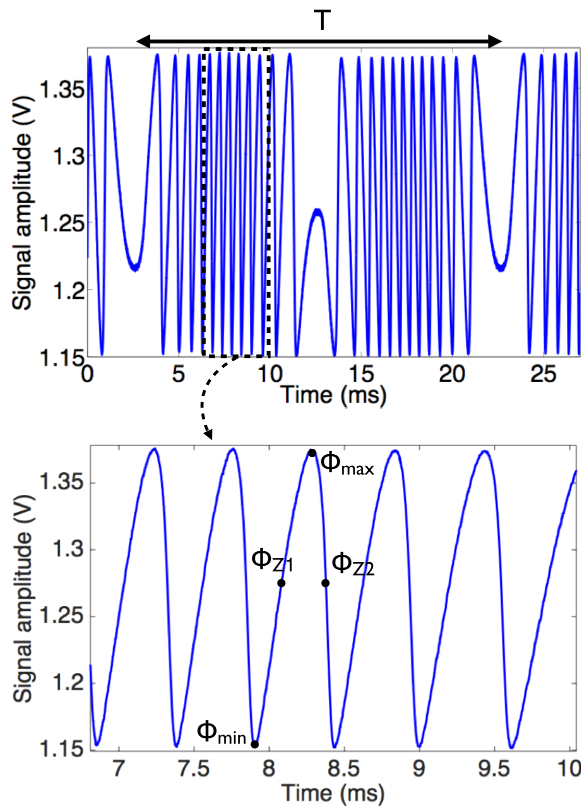

FIG. 4. Self-mixing interferogram for the DFB QCL at 10°C and 470mA.

distances or vibrations.[26,27] The LEF of a DFB laser can then be retrieved from the interferogram as well.[28] This technique can however not easily be exploited to a FP laser due to residual multiple wavelength interferences that lead to a very complex interferometric figure even under low feedback ratios. The self-mixing method has been adapted to the case of very low feedback ratios, becoming therefore well-suited for a DFB-QCL.[17] The positions of two consecutive zeros Φ_{Z1} and Φ_{Z2}, of two consecutive extrema Φ_{max} and Φ_{min} and the period T of the interferogram, as depicted in Figure 4, give access to the α-factor of the laser via the relationship:[17]

$$\alpha = \frac{\Phi_{max} - \Phi_{min} - 0.5T}{\Phi_{Z2} - \Phi_{Z1} - 0.5T} \tag{5}$$

With this method, the values of the LEF have been determined for different pump currents at 10°C. The results presented in Figure 5 for a feedback coefficient around $k = 3 \times 10^8 s^{-1}$, ie. $f_{ext} = 0.01\%$, unveil a clear dependence of the LEF with the pump parameter P, resembling the behavior of the LEF in interband lasers.[29] The α-factor takes values ranging from 0.8 to about 3 when the pump current is increased. These results confirm that the LEF of a QCL can substantially deviate from zero when biasing the laser above its threshold. We would like to point out that these results also show a rather good agreement with the previous value extracted at 10°C for both FP QCLs fabricated from the same wafer hence with similar gain medium. The increase of the α-factor with the pump or the temperature can be attributed to refractive index changes related to the QCL transition which, even though taking place far from the Restrahlen band of the InP ($\lambda = 32\ \mu$m for heavy holes and $\lambda = 28\ \mu$m for light holes), still occurs above the gap ($\lambda = 0.92\ \mu$m).

In addition, in contrast to interband lasers, some studies have suggested that the increase of the LEF with the pump current can be explained by the non-pinning of the carrier density above threshold.[17] The gain compression originating from gain nonlinearities[30] might also have a direct effect on the LEF, which in turn should be considered as an optical power dependent parameter, as

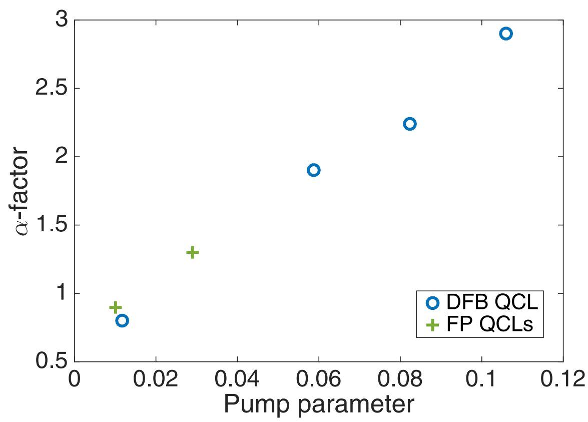

FIG. 5. Measured LEF values at 10°C as a function of the pump parameter P. The blue circles correspond to the self-mixing measurements for the DFB QCL. The green crosses are the values measured from the wavelength shift with optical feedback for the two FP QCLs.

already pointed out for quantum well and quantum dot interband lasers. A number of physical processes such as spectral hole burning, carrier heating, and spatial hole burning are possible candidates for being responsible for gain nonlinearity in semiconductor lasers.[31,32] In particular, spatial hole burning is found to be more dominant in QCLs owing to a lifetime of the gain grating close to the upper state lifetime.[13] As a conclusion, the results depicted in Fig. 5 and showing similarities with interband semiconductor lasers require further study to better understand the effect of gain compression in QCLs and its impact on the above-threshold LEF. From a general viewpoint, the analysis performed in this work shows the good agreement between two optical feedback based techniques for the precise determination of the LEF.

This work is funded by the Direction Generale de l'Armement (DGA). Part of this work was also supported by COST Action MP2014 "TERA-MIR radiation: materials, generation, detection and applications".

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