Linewidth broadening factor and gain compression in quantum cascade lasers

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ABSTRACT

In addition to the phase fluctuation induced by spontaneous emission, instantaneous carrier variations in semiconductor lasers generate coupling between optical gain and refractive index. This coupling between phase and amplitude of the electric field in the optical cavity is driven by the linewidth enhancement factor, which is responsible for the optical linewidth broadening, occurrence of nonlinearities or gain asymmetry, due to the curvature difference between the conduction and valence bands. This key parameter typically takes values between 2 and 6 in interband lasers with quantum well or quantum dot active media. In quantum cascade lasers, since the lasing transition occurs between two subbands of the conduction band that have therefore similar curvatures, the linewidth enhancement factor was expected to be naught. However sub-threshold linewidth enhancement factor was measured taking values from -0.5 to 0.5 and the above-threshold linewidth enhancement factor at room temperature was found between 0.2 and 2.4. In this work, the linewidth enhancement factor of a mid-infrared quantum cascade laser emitting around 5.6 μm is measured using either the wavelength shift under optical feedback or self-mixing interferometry, resulting in values ranging from 0.8 to 3. Furthermore, a strong increase of the linewidth enhancement factor with the pump current was observed, that can be explained by a relatively large gain compression in such structures, of the order of 5×10^{-15} cm^3.

Keywords: Quantum cascade laser, linewidth enhancement factor, optical feedback, gain compression

1. INTRODUCTION

Due to their high performances, mid-infrared quantum cascade lasers (QCLs) have become widely used sources for applications such as gas spectroscopy, free-space communications or optical countermeasures.[1] However, the knowledge of some important device parameters such as the linewidth broadening factor is still limited.

The linewidth enhancement factor (LEF) or α-factor quantifies the coupling between the real and imaginary part of the nonlinear susceptibility, ie. between the phase and amplitude of the electrical field into the laser cavity.[2] The LEF is a non-zero parameter in semiconductor lasers that is responsible for the optical linewidth broadening, enhanced by a factor $(1+\alpha^2)$ with respect to the intrinsic linewidth defined by Shawlow and Townes, for frequency chirp, for filamentation in broad-area lasers or for increased sensitivity to nonlinear perturbations such as optical injection or optical feedback.[3]

In interband laser diodes, the α-factor typically takes values between 2 and 6. The most common method to measure this parameter is to follow the differential gain and wavelength evolution of the amplified spontaneous emission spectrum as a function of the sub-threshold bias current.[4,5] Above threshold, other phenomena such as gain compression or carrier heating impact the LEF, and therefore other measurement techniques have been developed, based for instance on linewidth measurement, optical injection locking or AM/FM modulation.[6]

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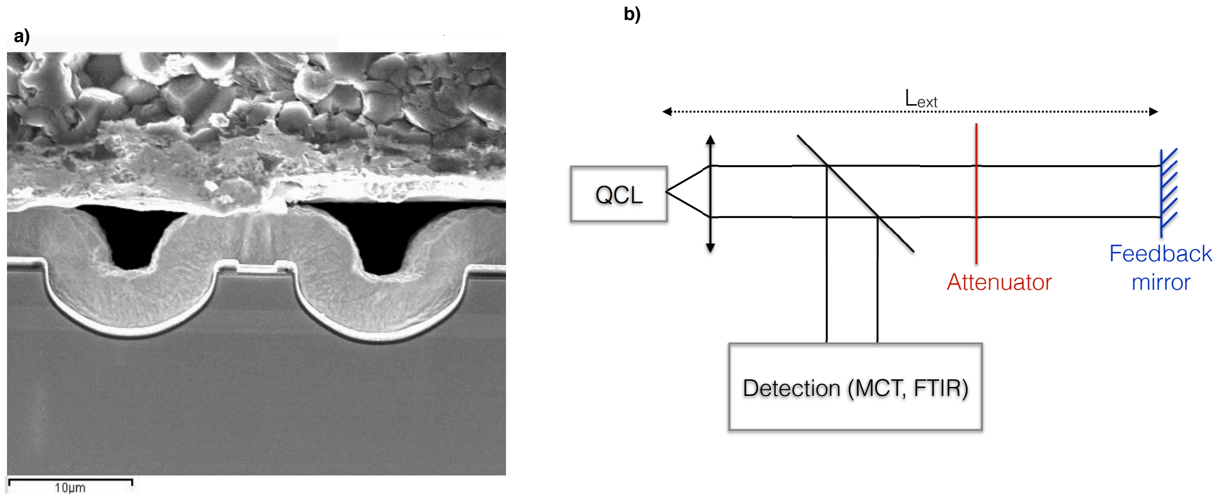

Figure 1. a) SEM picture of the QCL under study. The active area appears in ligther gray. b) Experimental setup.

In the case of QCLs, the LEF was theoretically expected to be null, due to the similar curvatures of the two subbands between which the radiative transition occurs. However, all experiments conducted on QCLs resulted in small but non-zero α-factor. Most LEF measurements were realized at cryogenic temperature and below threshold, leading to values between -0.5 and 0.5.[7] There are only few mesurements performed in actual experimental conditions, ie. at room temperature and above threshold, but those typically result in α-factors between 0.2 and 2.5.[8]

In this work, we propose to evaluate the above-threshold room-temperature LEF of a mid-infrared QCL using two different experimental methods based on optical feedback. The first one relies on the wavelength shift of the Fabry-Perot (FP) spectrum under optical feedback, and the second one on self-mixing interferometry applied to a distributed feedback (DFB) QCL. From these measurements, we then derive the gain compression coefficient of the DFB QCL, that is responsible for the difference between below- and above-threshold LEF.

2. DESCRIPTION OF THE EXPERIMENT

The lasers under study are FP and DFB QCLs originating from the same wafer. The active area consists in 30 periods of AlInAs/GaInAs based on a homemade design inspired by,[9] inserted between two InP claddings (see figure 1a). In the case of the DFB QCL, the single-mode operation is obtained through a top metal grating.[10] The dimensions are respectively 3 mm over 6 μm for the FP and 2 mm over 9 μm for the DFB QCL.

The QCL is inserted in the experimental setup described in figure 1b. Part of the light is reflected on a mirror and injected back into the laser. The feedback ratio f_{ext}, defined as the ratio between reinjected and emitted power, is tuned either with a polarizer or with optical densities. The other feedback parameter is the external cavity length L_{ext}, it is fixed at 15 cm for the wavelength measurement. For the self-mixing experiment, the feedback mirror is placed on a piezo-electric actuator with a sinusoidal motion and the external cavity length varies, creating the interferogram. Finally, the impact of optical feedback on the QCL emission is studied using either a Fourier transform infrared (FTIR) spectrometer or a mercury-cadmium-telluride (MCT) photodiode.

3. LEF MEASUREMENT WITH WAVELENGTH SHIFT

From the steady-state conditions of the rate equation driven the phase of the electric field of a QCL under optical feedback, one can retrieve the well-known equation giving the wavelength variation depending only on the feedback parameters and the α-factor:

$$\omega_s - \omega_0 = -k(\alpha cos(\omega_s \tau_{ext}) + sin(\omega_s \tau_{ext})) \quad (1)$$

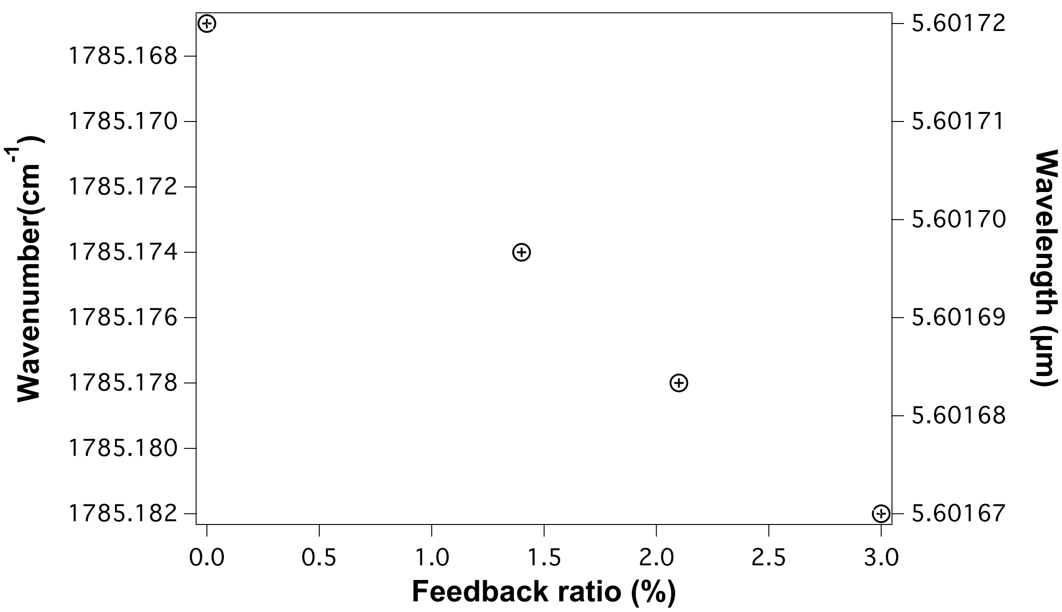

Figure 2. Evolution of the wavelength of one longitudinal mode of the FP spectrum under weak optical feedback.

where ω_0 and ω_s are the angular frequency of the free-running QCL and the QCL under feedback, respectively, τ_{ext} the external cavity roundtrip time and k the feedback coefficient, depending for a Fabry-Perot laser on the internal cavity roundtrip time τ_{in}, on the reflection of the laser front facet R and on the feedback ratio.

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

In the case of the FP QCL, when the laser wavelength is not fixed by a Bragg grating, it is therefore possible to retrieve the LEF from the wavelength shift of one peak of the FP optical spectrum as a function of optical feedback, as represented in figure 2. From these measurements, a value of $\alpha = 1.3 \pm 0.5$ was obtained, when the laser was operated at 10°C close to threshold. This value is consistent with typical LEF values in QCLs. However, the uncertainty is high and can be attributed to the FTIR precision of 0.125 cm^{-1}, and to the uncertainties on the external cavity length of ± 0.1 cm and on the optical power of ± 10 μW.

4. LEF MEASUREMENT WITH SELF-MIXING INTERFEROMETRY

Self-mixing interferometry was first proposed by Donati[11] and enables to measure experimental parameters, such as vibrations, velocities or distances,[12] but also intrinsic laser parameters such as the LEF.[13] This technique was then adapted to very small feedback ratios in order to measure the α-factor of QCLs using self-mixing interferometry.[8] The LEF can indeed be retrieved from the period T, the position of a maximum Φ_{max}, a minimum Φ_{min} and two consecutive zeros Φ_{Z1} and Φ_{Z2} of the interferogram:[8]

$$\alpha = \frac{\Phi_{max} - \Phi_{min} - 0.5T}{\Phi_{Z2} - \Phi_{Z1} - 0.5T} \tag{3}$$

However, this measurement is only valid for single frequency emitters like DFB QCLs meaning that the different wavelengths present in the FP spectrum would interfere negatively with each other hence highly affecting the self-mixing interferogram.

In the case of the DFB QCL under study operated at 10°C, for a feedback coefficient of k = 3 × 10^8 s^{-1} and an external cavity oscillating around 30 cm, the α-factor was mesured at different bias currents applied to

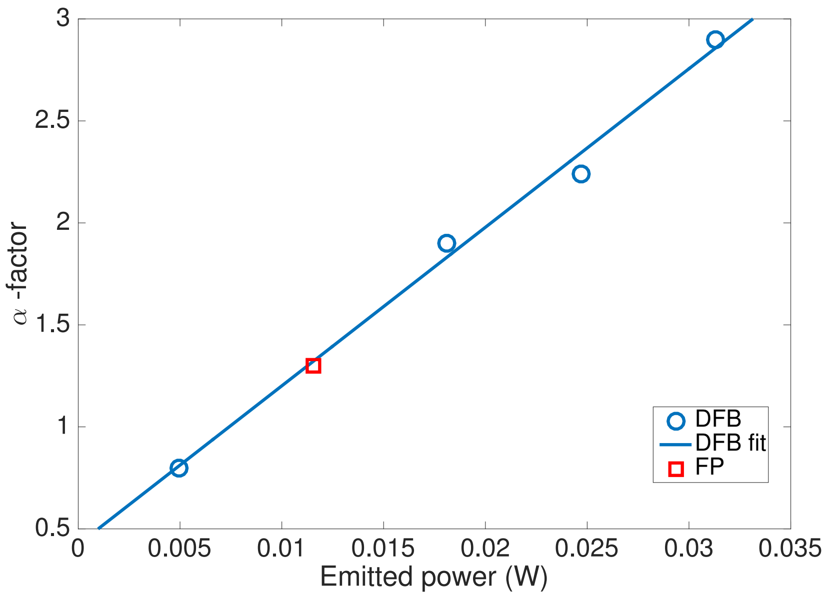

Figure 3. Evolution of the α-factor with the laser output power. The blue circles correspond to the measurements on the DFB QCL with the self-mixing technique and the blue line to the linear fit of these results. The red square corresponds to the LEF measurement of the FP QCL using the wavelength shift with optical feedback.

the laser. Figure 3 represents the evolution of the LEF as a function of the laser output power (blue circles). As shown on the graph, the α-factor increases strongly with the bias current (and hence with the output power), from 0.8 close to threshold up to 2.9. Furthermore, these values are consistent with the one of 1.3 obtained for the FP QCL using the wavelength shift under optical feedback (red square on figure 3).

5. GAIN COMPRESSION

Gain compression in semiconductor lasers e.g the decrease of the gain coefficient with optical intensity originates from gain nonlinearities is caused by processes such as carrier heating, spatial or spectral hole burning.[14] This phenomenon which is known to limit the modulation dynamic of directly modulated transmitters through the adiabatic chirp is also responsible for the bending of the light-current characteristics. Originally introduced to parameterize the effects of nonlinear gain compression in semicondutor lasers,[15] it is quantified by the gain compression coefficient ϵ_S associated with the photon density through the following adiabatically corrected gain expression:

$$g = \frac{g_0}{1 + \epsilon_S S} \tag{4}$$

with g_0 the linear gain and ϵ_S the compression coefficient associated with the photon density. The conversion from ϵ_S to ϵ_P is straightforward, as $\epsilon_S S = \epsilon_P P$. Moreover, the photon density S can be expressed as a function of the output power P as:

$$P = h\nu V v_g \alpha_m S \tag{5}$$

with h the Planck constant, ν the laser frequency, V the volume of the active area, v_g the group velocity and α_m the mirror losses of the laser cavity.

In a homogeneously broadened gain medium, the carrier density and distribution are clamped at threshold, and the change of the effective LEF is mostly due to the decrease of the differential gain from gain compression so that:

$$\alpha = \alpha_0(1 + \epsilon_P P) \tag{6}$$

where α_0 is the LEF at threshold. Since the carrier distribution is clamped, α_0 itself does not change as the output power increases.

In interband lasers, the gain compression coefficient ϵ_S is around 10^{-17} cm^3 for quantum well lasers and 10^{-16} cm^3 for quantum dots lasers.[14,16] The stronger gain compression in quantum dots leads to a much more pronounced increase of the LEF with the pump current, compared to quantum well lasers, as observed experimentally. In QCLs, there are very few values of gain compression coefficient. One can mention the work of Hangauer *et al*, reporting an experimental saturation power, defined as the inverse of ϵ_P, of $P_{sat} = 85$ mW for a 9.6 μm QCL.[17]

In QCLs the α-factor also increases significantly with the bias current, ie. with the laser output power, as shown in figure 3. The LEF values measured on the DFB QCL (blue circles) are fitted linearly (blue line), leading to a threshold value of $\alpha = 0.42$, consistent with sub-threshold measurements in QCLs at room temperature. Furthermore, the fit gives a value of $P_{sat} = 5.4$ mW, corresponding to $\epsilon_S = 4.5 \times 10^{-15}$ cm^3.

This high value of gain compression coefficient in a QCL which is similar to typical values measured in quantum dot transmitters would originate mainly from the strong spatial hole burning, due to an extremely fast gain grating lifetime linked to the upper state lifetime of few picoseconds.[18] Such a high value would moreover explain the strong dependency of the LEF on the bias current, and therefore the difference between the α-factor measured below and above threshold in QCLs.

6. CONCLUSION

The LEF of a mid-infrared QCL structure was measured using two different methods based on optical feedback, either the wavelength shift of one peak of the FP spectrum for low feedback ratios or the analysis of the self-mixing interferogram of the DFB QCL under optical feedback with a varying external cavity length. The obtained α-factor values are consistent between the two methods and range from 0.8 to 2.9 depending on the bias current. This strong increase of the LEF with the pump current originates from gain nonlinearities and especially from gain compression.

By fitting the LEF versus emitted power of the DFB QCL, the gain compression parameter was found to be $\epsilon_S = 4.5 \times 10^{-15}$ cm^3. This value is relatively high compared to the ones usually obtained for interband semiconductor lasers, but such a high gain compression can explain the experimental results of this study as well as the difference between subthreshold and above-threshold LEF that has been noticed in QCLs.

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