Deterministic temporal chaos from a mid-infrared external cavity quantum cascade lasers

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ABSTRACT

Quantum cascade lasers (QCLs) are unipolar semiconductor lasers offering access to wavelengths from the mid-infrared (IR) to the terahertz domain and promising impact on various applications such as free-space communications, high-resolution spectroscopy, LIDAR remote sensing or optical countermeasures. Unlike bipolar semiconductor lasers, stimulated emission in QCLs is obtained via electronic transitions between discrete energy states inside the conduction band. Recent technological progress has led to QCLs operating in pulsed or continuous wave mode, at room temperature in single- or multi-mode operation, with high powers up to a few watts for mid-IR devices. This spectacular development raises multiple interrogations on the stability of QCLs as little is known on their dynamical properties. Very recently, experiments based on optical spectrum measurements have unveiled the existence of five distinct feedback regimes without, however, identifying the complex dynamics dwelling within the QCL. In this article we provide the first experimental evidence of a route to chaos in a QCL emitting at mid-IR wavelength. When applying optical feedback with an increasing strength, the QCL dynamics bifurcate to periodic dynamics at the external cavity frequency and later to chaos without an undamping of relaxation oscillations, hence contrasting with the well-known scenarios occurring in interband laser diodes.

Keywords: Quantum cascade laser, optical feedback, nonlinear dynamics, chaos

1. INTRODUCTION

Quantum cascade lasers (QCLs) are semiconductor lasers based on intersubband transitions within the conduction band, leading to wavelengths ranging from the mid-infrared (IR) up to the terahertz (THz) region.[1] Their compactness and high performances at room temperature make mid-IR QCLs privileged sources for applications such as gas spectroscopy, free-space communications or optical countermeasures. Recently, new interrrogations have arisen on the resistance of QCLs when subject to external optical feedback, especially due to parasitic reflections in the experimental setups. Owing to their very low linewidth enhancement factor, it has been shown numerically that QCLs are expected to be much more resistant to optical feedback.[2] However, it has been demonstrated experimentally that mid-IR QCLs are sensitive to optical feedback, that can lead to significant noise reduction,[3] increase of the emitted power, threshold current reduction, as well as wavelength shift or multimode behavior in distributed feedback (DFB) QCLs.[4]

However, there has been no proof of the appearance of chaos in QCLs so far, even though some instabilities have been observed in the optical spectra for intermediate feedback ratios, defined as the ratio between reinjected and emitted powers. In class-B interband lasers subject to optical feedback, when increasing the feedback ratio, after going through two stable single-mode regimes separated by a bistable one, the laser enters the coherence-collapse regime corresponding to chaos.[5] This transition to chaos always occurs through the undamping of the

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relaxation oscillations,[6] although the chaos by itself can take several forms, such as aperiodic pulsations or low frequency fluctuations (LFF), corresponding to irregular power drop-outs.[7]

In this work, we demonstrate for the first time both experimentally and numerically that a mid-IR QCL can become chaotic when subject to optical feedback, and that the destabilization occurs through a different path than the one typical for interband lasers.

2. DESCRIPTION OF THE EXPERIMENT

The laser under study is a DFB QCL emitting at 5.62 μm. It is constituted of 30 periods of AlInAs/GaInAs between two InP claddings, from a homemade design inspired by Evans *et al.*,[8] as illustrated in figure 3a. The single-mode operation is ensured by a top metal grating[9] with a coupling of $\kappa = 4$ cm^{-1} and a high-reflection coating on the back facet. The laser is 2 mm long over 9 μm wide. The optical spectrum and L-I characteristic curves of the free-running QCL are represented in black in figures 3c and d respectively. The orange plots on the graphs correspond to the QCL characteristics under low optical feedback, with $f_{ext} = 3.2 \times 10^{-2}$.

The QCL is inserted in the experimental setup of figure 3b. After reflection on a mirror, part of the light is reinjected back into the laser. The feedback ratio f_{ext} is controlled with a polarizer, and the external cavity length L_{ext} can be tuned between 20 and 50 cm. The ligth emitted by the QCL under optical feedback is collected on a mercury-cadmium-telluride (MCT) photodiode, and analyzed using an high resolution oscilloscope. The

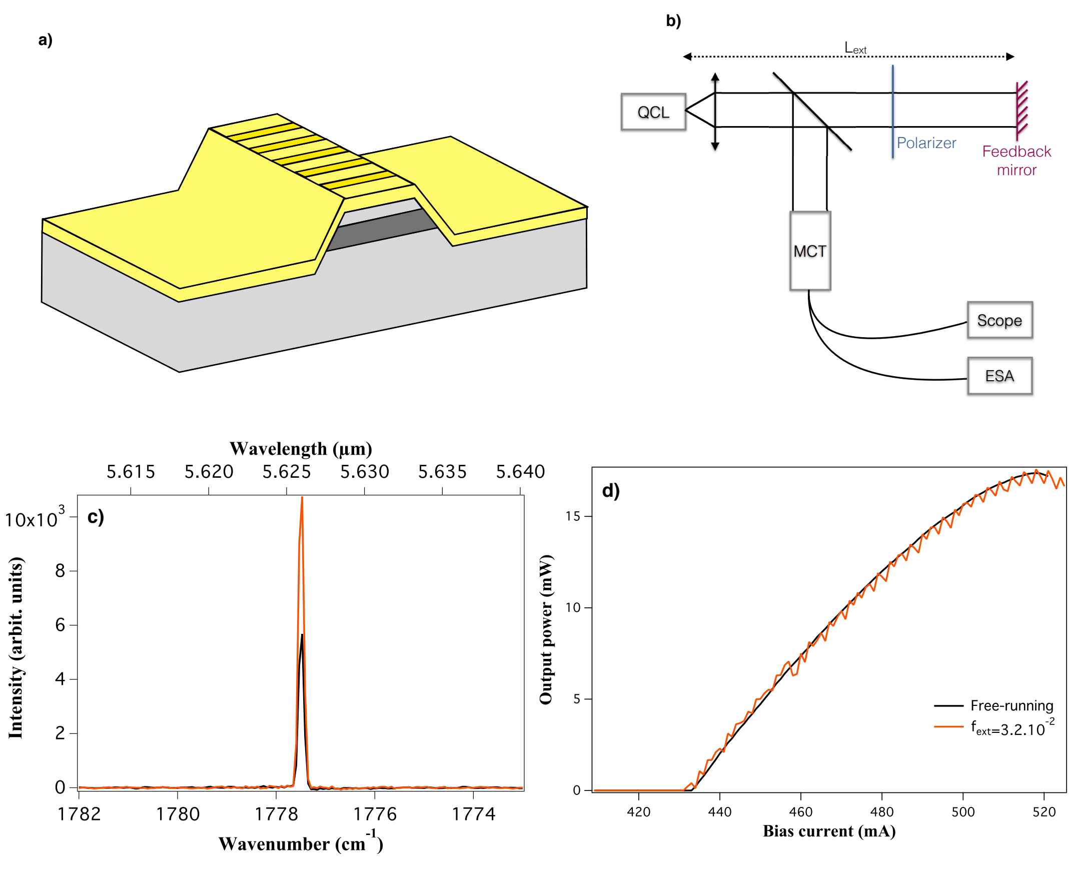

Figure 1. a) Schematic of the QCL. The active area appears in darker gray. b) Experimental setup. c) Impact of optical feedback on the laser spectrum (black: free-running, orange: $f_{ext} = 3.2 \times 10^{-2}$). d) Impact of optical feedback on the QCL L-I curve (black: free-running, orange: $f_{ext} = 3.2 \times 10^{-2}$).

need of a high-bandwith photodetector imposed an pulsed-mode operation of the laser, but pulses as long as 5 μs were considered and only the end of the pulses were used in measurements to avoid thermal fluctuations.

3. DESCRIPTION OF THE NUMERICAL MODEL

The Lang and Kobayashi equations are very well-known to model the impact of optical feedback on a semiconductor laser.[10] These can be written as:[11]

$$\frac{dY}{ds} = (1 + i\alpha)\, Z\, Y \, + \, \eta \; exp(-i\Omega_0 \theta)\, Y(s - \theta) \tag{1}$$

$$T\, \frac{dZ}{ds} = \bar{P} - Z - (1 + 2Z)\, |Y|^2 \tag{2}$$

where Y is the slowly varying envelop of the electric field and Z the carrier number normalized to the value at threshold. Both equations are normalized with respect to the photon lifetime τ_p. T is the carrier to photon lifetime ratio, θ the normalized external cavity roundtrip time, Ω_0 the normalized laser frequency above threshold, $\bar{P}$ = I/I_{th}-1 the bias current over threshold and η the normalized feedback coefficient:

$$\eta = \frac{\tau_p}{\tau_{in}} 2C_l \sqrt{f_{ext}} \tag{3}$$

with τ_{in} the laser cavity roundtrip time. C_l is the coupling strength coefficient at the front facet, whose expression is complex in DFB lasers and depends on facet phases as described in.[12] The value considered here was an average of the different values obtained by considering all possible phases at the facets. Finally α is the linewidth enhancement factor. This parameter, defined as the ratio between the real and imaginary parts of the nonlinear susceptibility, is of prime importance in semiconductor lasers since it quantifies the coupling between the phase and amplitude of the electrical field.[13] Figure 2 shows that depending of the α-factor, the dynamical response of the laser can vary from an always stable behavior for $\alpha = 0.5$ (figure 2a) to a response with multiple occurrences of chaos operations for $\alpha = 3$ (figure 2b). The above-threshold, room-temperature α-factor of the device under study was measured to be $\alpha = 1.7$ using two techniques based on optical feedback, the first one following the evolution of the wavelength of the laser depending on the feedback ratio and the second one exploiting the self-mixing interferogram of the laser under optical feedback with a varying external cavity length.

Table 1 gives all parameters used here for the simulations. The noise level was varied between 10^{-14} and 10^{-7} and does not impact significantly the results.

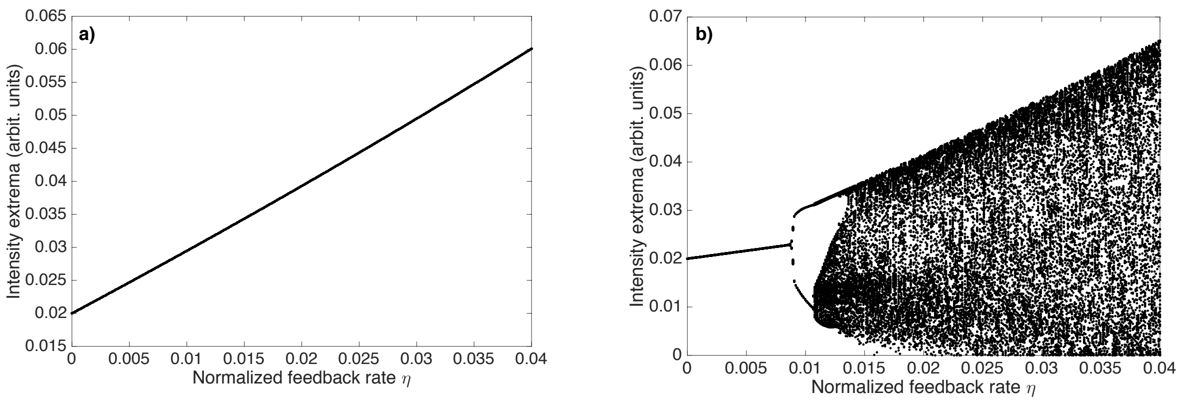

Figure 2. Numerical bifurcation diagrams. a) $\alpha = 0.5$. b) $\alpha = 3$

Parameter	Value
Carrier lifetime τ_c	1.3 ps
Photon lifetime τ_p	4.7 ps
Bias current $\bar{P}$	0.02
External cavity rountrip time θ	492
α-factor	1.7
Feedback phase	$\Omega_0\theta = -atan(\alpha)$

Table 1. Simulation parameters

4. RESULTS AND DISCUSSION

The results of both experiment and simulation are shown in figure 3 for several feedback ratios. When increasing the feedback ratio, the QCL emission is first stable, with only noise (figures 3a and b). Then some oscillations appear, that are at the external cavity frequency (figures 3c and d) and finally the time traces of the QCLs show a second superimposed slow modulation, with a statistical distribution corresponding to LFF (figures 3e and f).

If the appearance of LFF proves that QCLs can indeed become chaotic when subject to optical feedback, the route to chaos observed here is very different from the one that usually occurs in semiconductor lasers. There is no undamping of the relaxation oscillations, confirming the fact that these oscillations do not appear in QCLs, both experimentally and numerically.[14,15] In the case of QCLs, the frequency that appears just after the first Hopf bifurcation is the external cavity frequency whereas in interband semiconductor lasers subject to optical feedabck, this frequency may appear but far above the first Hopf bifurcation, beyond the first chaotic bubble.

A transition at the external cavity for a laser under optical feedback has already been observed for class A lasers. In the case of a HeNe gas lasers, a route to chaos ressembling the one observed here was obtained both experimentally and numerically.[16] Furthermore, a theoretical work looking at the long delay limit of the Lang and Kobayashi equations has shown the same tendency, with a destabilization through oscillations at the external cavity frequency and chaos characterized by LFFs.[17] Therefore, we can conclude that the QCLs under optical feedback may become chaotic by following a class A-like scenario.

5. CONCLUSION

In this work, it has been demonstrated experimentally that mid-IR QCLs subject to external optical feedback may become chaotic and follow a route to chaos similar to that observed in class A lasers, with a destabilization taking place at the external cavity frequency and deterministic chaos characterized by LFFs. Furthermore, these experiments have been confirmed by simulations based on the Lang and Kobayashi equations with parameters adapted to the QCL under study.

The possible appearance of chaos in QCLs has several consequences. First, this leads to a generalization of the use of mid-IR optical isolators in experimental setups and in packaged QCLs in order to avoid parasitic optical feedback on the laser. Especially when using mid-IR optical fibers, unwanted optical feedback may lead to a chaotic behavior of the laser that would prevent its use for single-mode operation, for instance for gas spectroscopy.

On the other hand, a chaotic QCL could be used in new experiments based on chaos, similarly to those existing in the near-IR. We could imagine mid-IR chaotic communications, based on chaos modulation for encryption and synchronized chaos for message transmission,[6] chaotic LIDAR[18] or unpredictible sources for optical countermeasures.

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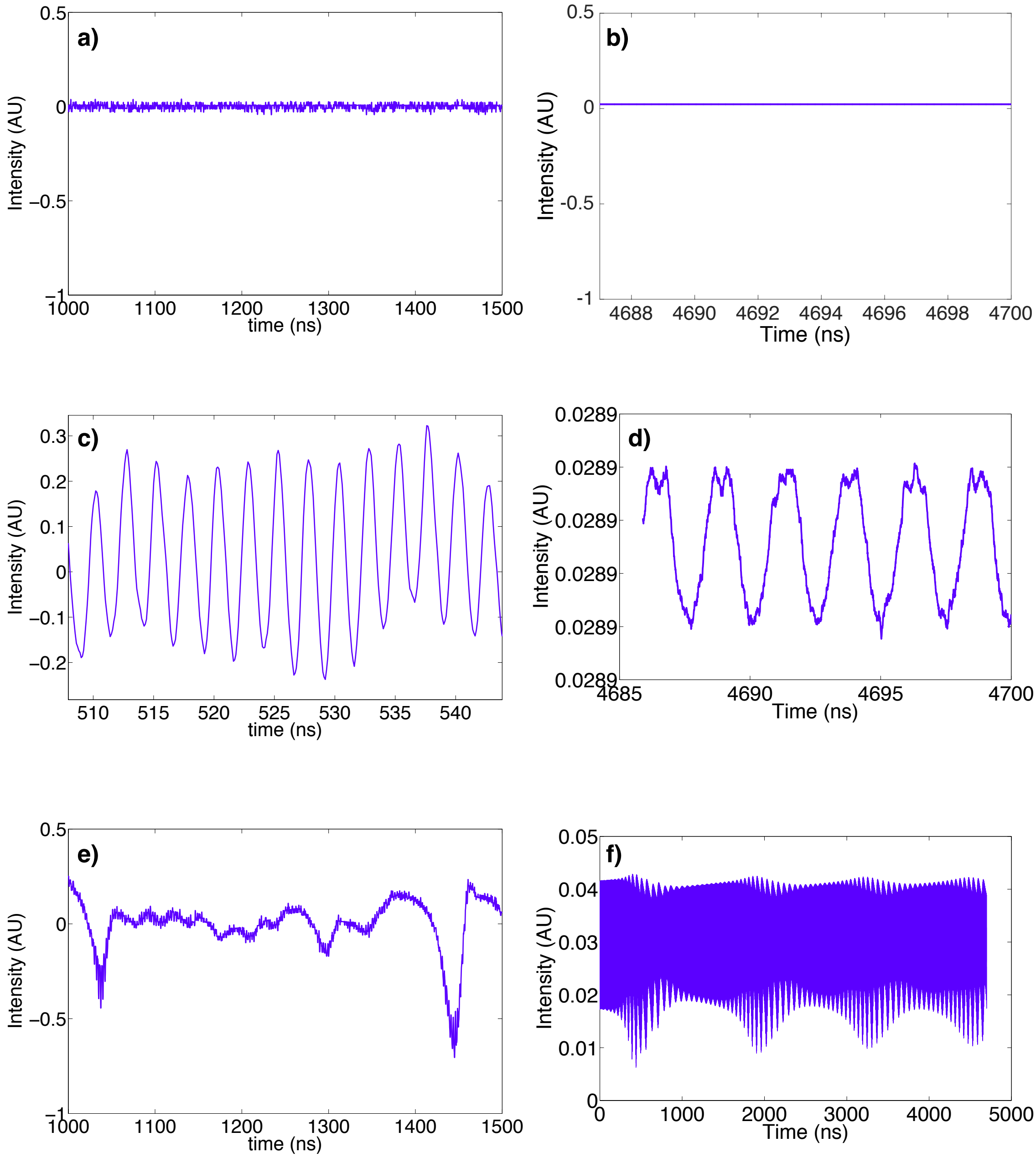

Figure 3. Time traces of the QCL under optical feedback: a,c,e are experimental and b,d,f numerical results. a) $f_{ext} = 0.5\%$. b)$f_{ext} = 0.1\%$. c) $f_{ext} = 1.28\%$. d) $f_{ext} = 1.36\%$. e) $f_{ext} = 2.66\%$. f) $f_{ext} = 2.30\%$.

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