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The Effect of Temperature on the Dynamical States of a Time Delayed Mid-infrared Quantum Cascade Oscillator

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Abstract: Carrier-to-photon lifetime ratio is a key parameter in the non-linear dynamics study of quantum cascade lasers under external optical feedback. We experimentally investigate the influence of temperature on this parameter and hence on chaotic behaviors.

OCIS codes: (140.5960) Semiconductor lasers; (140.1540) Chaos; (140.3070) Infrared and far-infrared lasers

1. Introduction

Quantum cascade lasers (QCLs), theoretically demonstrated for the first time in the early 1970s and then experimentally produced since 1994 [1], are semiconductor laser sources based on intersubband transitions. The wide range of achievable wavelengths from mid-infrared to terahertz domain [2] paves the way for multiple applications such as optical countermeasures for defense purposes, particles detection below one per millions, jamming resistant free-space communications and LIDAR remote sensing, all demanding stable single-mode operation with narrow linewidth, high output power and high modulation bandwidth. QCLs are renowned for their higher stability compared to interband laser diodes, in particular when subjected to time-delayed phenomena such as external optical feedback. In laser diodes, optical feedback, ie. reinjection of part of the emitted light after reflection on a mirror, can destabilize the laser and the undamping of the relaxation oscillations may lead to chaotic oscillations. As opposed to interband lasers for which the carrier-to-photon lifetime ratio is around 10^4, QCLs do not exhibit relaxation oscillations [3] owing to the ultrafast intersubband transitions hence keeping the carrier-to-photon lifetime close to 1. Our recent work showed that mid-infrared QCLs operating external optical feedback can experience a route to chaos without undamping of relaxation oscillation [4]. The latter is first observed through a Hopf bifurcation to periodic dynamics at the external cavity frequency and then through a low frequency fluctuation (LFF) pattern. This study goes a step beyond by investigating the direct effect of the carrier to photon lifetime ratio on the QCL temporal dynamics for two different temperatures at 170K and 290K and for various feedback ratios. We believe that this study is of paramount importance for the development of future secured atmospheric transmission line and unpredictable optical countermeasures systems.

2. Device description and experimental apparatus

The QCL under study is a distributed feedback (DFB) laser with a region made of 30 periods of AlInAs/GaInAs grown by molecular beam epitaxy on an InP cladding [5]. Because the laser is biased with a quasi-continuous wave inducing a strong warm-up, one needs to optimize the thermal dissipation of the QCL and this is the reason why it is episide-down mounted with gold-tin soldering on AlN substrate as presented on Figure 1(a).

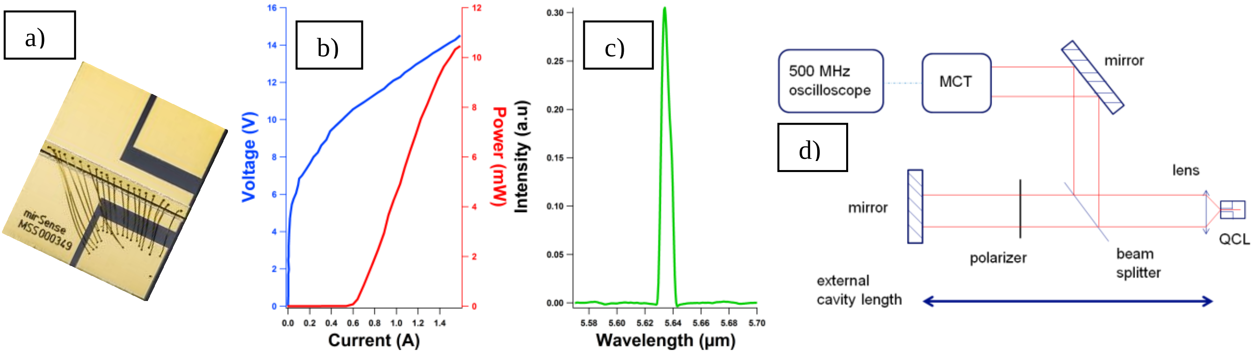

FIG. 1 a) Close up of the QCL under study, the laser is gold-tin soldered to a metal ridge and bonded with gold wires to ensure good electronic and thermal conduction properties. b) LIV and c) optical spectrum characteristics of the free-running DFB QCL operating at room temperature d) experimental apparatus split between the analysis path above and the external optical feedback path below.

Figure 1(b) depicts the light intensity voltage (LIV) characteristics of the free-running QCL under study. The threshold current is of 590 mA for a voltage of 10 V when biased at 293K with a 300 ns pulse at a repetition rate of 100 kHz, standing for a 3% duty cycle. The wall-plug efficiency of this laser at maximum output power is 0.05%. Figure 1(c) shows the optical spectrum retrieved with a Fourier transform infrared spectrometer (FTIR). The optical spectrum is perfectly single mode and the DFB peak is at 5.635 microns. The experimental set up, as presented on Figure 1(d), is made of an analysis path with a high bandwidth Mercury-Cadmium-Telluride (MCT) camera for mid-infrared detection. The camera is linked to a 500 MHz oscilloscope for real time study and acquirements. The external optical feedback path is set with a gold plated mirror and a polarizer, which scales the amount of back reflected light since the QCL wave is TM polarized. The mirror is placed on a rail so that the external cavity length can be varied between 30 cm and 60 cm. This leads to an external cavity frequency between 500 MHz and 250 MHz within the oscilloscope bandwidth. The QCL wave is focused thanks to a mid-infrared lens and a 60/40 mid-infrared beam-splitter shares the light between both paths. The feedback ratios f_r is defined as the ratio between the fed-back power and the total power which is emitted by the QCL.

3. Results and Discussion

Figure 2(a) and Figure 2(b) show the time traces at 170K and 290K when external optical feedback is applied onto the QCL operating under quasi-continuous waves. The temporal dynamics is experimentally recorded for various feedback strengths by changing the angle of the polarizer. In both cases, various dynamical states such as periodic and chaotic oscillations are observed which is in agreement with our prior observations [4]. However, in this work experiments also unveil that the route to chaos of a time delayed QCL is very sensitive to the temperature operation. For instance, at 170K, the LFF chaotic dynamics takes place for a feedback ratio as low as 0.008 while it is observed above 0.019 when the temperature is increased to 290K. Therefore, it becomes possible to control the bandwidth of the chaotic bubble by slowing down the carrier i.e. by engineering the carrier-to-photon lifetime ratio.

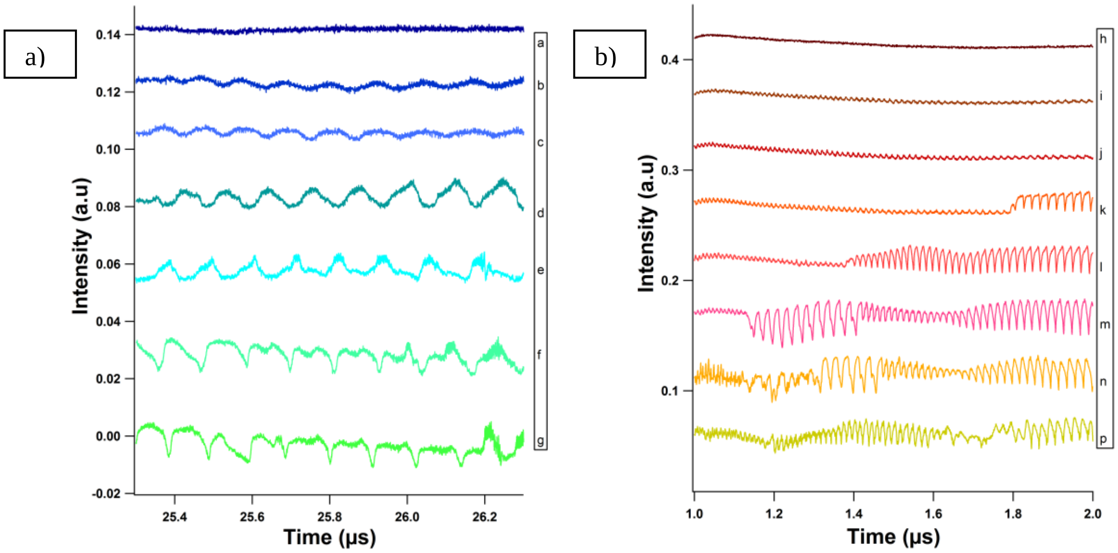

FIG. 2 a) Experimental time traces of the QCL under optical feedback at 170K. a) f_r=0. b) f_r=0.0001. c) f_r= 0.004. d) f_r=0.008. e) f_r=0.038. f) f_r=0.065. g) f_r=0.086; b) Experimental time traces of the QCL under optical feedback at 290K. h) f_r=0. i) f_r=0.002. j) f_r= 0.010. k) f_r=0.019. l) f_r=0.031. m) f_r=0.068. n) f_r=0.119. p) f_r=0.235.

Overall, this work is important to push further the investigation of the nonlinear dynamics of quantum cascade oscillators with the view of controlling and understanding the intersubband dynamics for the development of secured atmospheric transmission lines and unpredictable optical countermeasures systems.

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