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Regimes of external optical feedback in 5.6 μm distributed feedback mid-infrared quantum cascade lasers

L. Jumpertz,[1,2,a)] M. Carras,[2] K. Schires,[1] and F. Grillot[1]
[1]*Telecom ParisTech, Ecole Nationale Supérieure des Télécommunications, CNRS LTCI, 46 rue Barrault, 75013 Paris, France*
[2]*Alcatel Thales III-V Lab, Campus de Polytechnique, 1 avenue Augustin Fresnel, 91767 Palaiseau, France*

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External optical feedback is studied experimentally in mid-infrared quantum cascade lasers. These structures exhibit a dynamical response close to that observed in interband lasers, with threshold reduction and optical power enhancement when increasing the feedback ratio. The study of the optical spectrum proves that the laser undergoes five distinct regimes depending on the phase and amplitude of the reinjected field. These regimes are mapped in the plane of external cavity length and feedback strength, revealing unstable behavior only for a very narrow range of operation, making quantum cascade lasers much more stable than their interband counterparts. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4897274]

Quantum cascade lasers (QCLs) are unipolar laser diodes that were invented twenty years ago to provide compact mid-infrared sources.[1] The laser effect is based on intersubband transitions inside the conduction band, leading to a large range of achievable wavelengths from the mid-infrared to the terahertz range, depending on the width of the quantum wells in the structure. The electrical-optical conversion efficiency is furthermore increased by using a cascade effect. The structure is indeed constituted of a few tens of periods composed of an active area and an injector zone. Each electron will cross all the active areas, producing each time one photon, and escape to the next injector zone by tunneling effect.[2] The QCL technology evolved quickly and mid-infrared QCLs are now available for continuous-wave (CW) operation at room-temperature with thermoelectric cooling. Therefore, these structures are becoming widely used sources for mid-infrared applications such as gas spectroscopy, optical countermeasures, or free-space communications[3] requiring stable single-mode operation with a narrow linewidth, high output power, and high modulation bandwidth.

The generation of nonlinear dynamics using all-optical schemes such as external optical feedback and optical injection locking has been deeply studied in interband lasers made with bulk, quantum well or quantum dot semiconductor materials.[4–7] External optical feedback consists in reinjecting part of the light emitted by the laser after reflection on a mirror or a fiber extremity.[4–12]

During early research, five distinct regimes of operation were reported for 1.55 μm distributed feedback (DFB) semiconductor lasers under optical feedback based on spectral observations.[4,13]

The influence of both the feedback rate, defined as the ratio between the reinjected power and laser output power, and the external cavity length, i.e., the distance between the laser facet and the external reflector, on the nature of the semiconductor laser's response to optical feedback were investigated. Even small reflections in the percent range were found to affect dramatically the laser stability. Although external optical feedback can be considered as a source of instability in many situations, it can also produce several beneficial effects that can strongly improve laser performance. At the extremes of very weak and very strong optical feedback, linewidth narrowing and noise suppression can occur. This advantage, along with the large gain bandwidth of the semiconductor laser, can produce a highly tunable, narrow-linewidth source with many applications in spectroscopy, metrology, and telecommunications.[4]

However, in the case of QCLs, little is known on the effects of optical feedback on semiconductor materials based on intersubband transitions. Only very few studies are available in the literature, most being theoretical[14,15] or focused on the laser noise evolution.[16,17] The aim of this letter is therefore to experimentally pioneer the impact of optical feedback on mid-infrared DFB QCLs.

The laser diode used for the experiment was designed based on Ref. 18. It is an AlInAs/GaInAs DFB laser emitting at 5.6 μm. The active region consisting of 30 periods was grown by molecular beam epitaxy on InP. The top InP cladding was then grown by metal organic chemical vapor epitaxy. The single-mode operation is obtained thanks to a top metal grating[19] with a chosen coupling efficiency $\kappa = 4\,\mathrm{cm}^{-1}$ over a length of 2 mm, for a width of 9 μm. High-reflective coating (99%) on the back facet favors CW operation at room temperature. To obtain a higher output power all the following measurements were done at 10 °C. Furthermore, let us stress that the temperature fluctuations remain much smaller than 10 mK during the whole experiment and hence do not impact significantly the laser dynamics.[16] The threshold current of the free-running laser was of 433 mA at this temperature for an external efficiency of about 0.23 mW/mA.

The experimental free-space setup used for the optical feedback experiments is depicted in Fig. 1. The laser light is collimated and sent on a beamsplitter with a reflection/transmission ratio of 40/60. Part of the light is reflected on a mirror with an external cavity length that can be tuned from 15 to 95 cm, corresponding to external cavity roundtrip times

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[a)] Author to whom correspondence should be addressed. Electronic mail: louise.jumpertz@telecom-paristech.fr

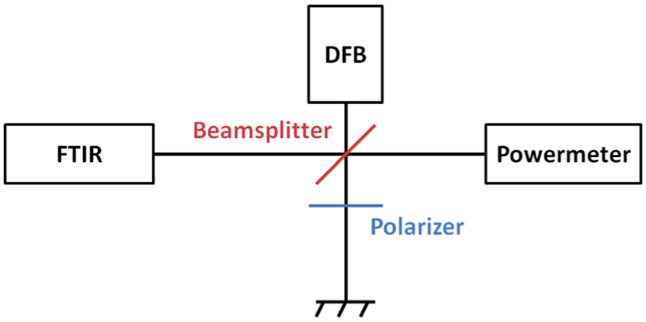

FIG. 1. Schematic of the free-space setup used for experimental feedback experiments.

between 1 and 630 ns, then re-enters the laser. The feedback ratio can be adjusted using a polarizer and is controlled with a power-meter. The remaining half of the laser light is directed toward a detection path. It is either sent in a Fourier transform infrared spectrometer (FTIR) to analyze the optical spectra with a resolution of 40 nm or collected on a detector to obtain the emitted power.

The light versus current characteristic (L-I) of the QCL is plotted in Fig. 2 for several feedback rates. As shown in the inset of Figure 2, a reduction of the laser threshold, up to 4% from 433 mA down to 415 mA at the maximal achievable feedback ratio of 25% is observed. Although the threshold current variation is clearly visible in Fig. 2, the corresponding threshold current density injected into the active region remains roughly constant and equal to about 2.4 kA/cm^2. It has to be noted that the optical output power also significantly increases with the feedback rate. Moreover, undulations appear for high feedback ratios. According to Refs. 20 and 21, this phenomenon can be understood by considering the interferences between the modes of the two cavities. The maximum output power is achieved when the external cavity length is an integer multiple of the effective laser internal cavity length, corresponding to constructive interferences between the modes. On the other hand, when the external cavity length is equal to half an integer of the internal cavity length, the interferences are destructive and the output power reaches a minimum. Therefore, some undulations appear when varying the external cavity length at a fixed bias current. In our situation, the external cavity length is fixed, but the increase of the injection current leads to an increase of the temperature of the active area, and therefore to a modification of the refractive index and of the effective laser cavity length, hence the undulations.

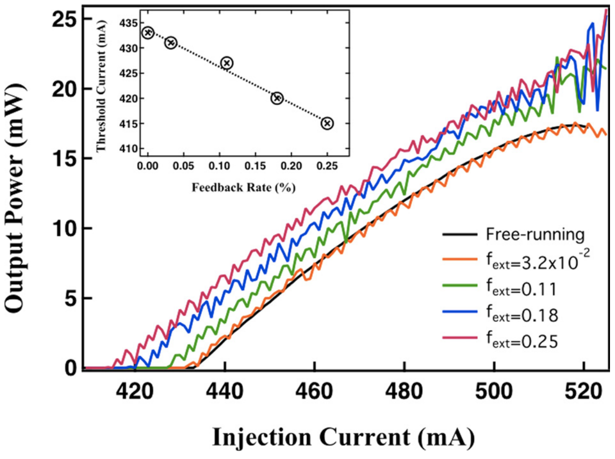

FIG. 2. L-I curves for several feedback rates at constant external cavity length. The inset shows the corresponding threshold current as a function of the feedback rate (the dashed line is for guiding eyes only).

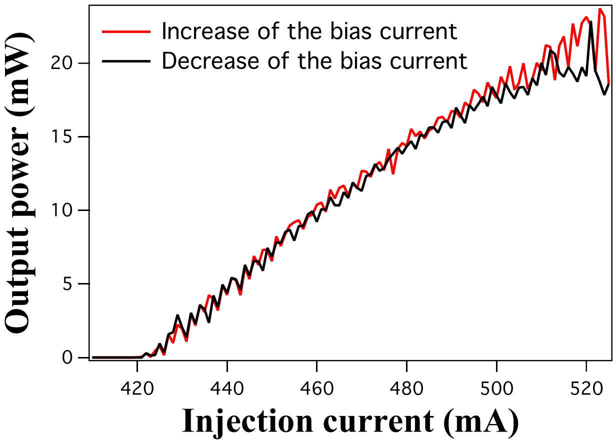

FIG. 3. L-I curves at constant external cavity length showing the hysteresis for a fixed feedback rate of $f_{ext} = 0.18$.

Since the temperature evolution is different when increasing or decreasing the bias current, the L-I curves show some hysteresis, especially for high feedback rates, as illustrated in Fig. 3.

The study of the optical spectra proves that like interband lasers QCLs do exhibit a relative sensitivity to optical feedback. The QCL under study undergoes five regimes with different spectral characteristics when increasing the feedback ratio, as depicted in Fig. 4. The first regime, occurring for very low feedback rates, corresponds to a stable single-mode operation at the free-running DFB wavelength, with a phase-dependent output power. The second regime is also phase-dependent and presents a beating between two adjacent modes of the Fabry-Perot cavity. Then another single-mode regime appears, operating on the first side-mode of the

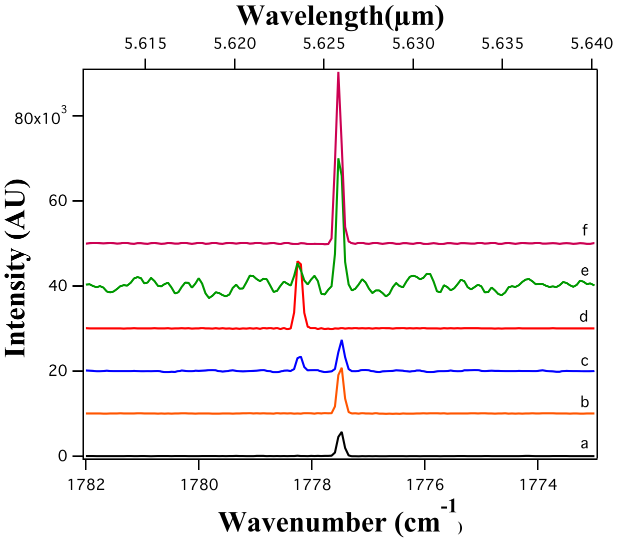

FIG. 4. Spectral signatures of the five optical feedback regimes. The FTIR spectra were measured at constant external cavity length of 13.5 cm and constant bias current of 435 mA. (a) Free-running case. (b) Regime 1, $f_{ext} = 9.1 \times 10^{-4}$. (c) Regime 2, $f_{ext} = 5.1 \times 10^{-3}$. (d) Regime 3, $f_{ext} = 3.2 \times 10^{-2}$. (e) Regime 4, $f_{ext} = 0.13$. (f) Regime 5, $f_{ext} = 0.25$.

Fabry-Perot cavity. The fourth regime exhibits a strong increase of the spectrum pedestal and side-modes, otherwise well suppressed. In interband lasers, these two effects take part in the occurrence of the so-called coherence-collapse regime.[22] Coherence collapse is usually the common name given to describe the complex and irregular dynamics occurring when the laser is operated above threshold in the fourth feedback regime. The main consequence of the coherence collapse regime consists in a drastic reduction of the coherence time leading to an enhancement of the laser linewidth. In the QCL dynamics, it is not yet possible to affirm that this regime is chaos, because we were not able to observe a clear linewidth broadening due to the limited FTIR resolution. A particular feature of QCLs is, moreover, the absence of relaxation oscillations. Relaxation oscillations are observed in most semiconductor lasers and result from the relatively large carrier lifetime compared to the photon lifetime.[23] A slight external perturbation such as external optical feedback is usually enough to induce sustained pulsating intensities.[24–26] As such, the rules of the destabilization and hence the transition towards chaotic operation, which is usually driven through undamped relaxation oscillations in interband semiconductor lasers, certainly follow different routes in case of QCLs. Although no coherence collapse operation has been reported in recent experiments conducted on both THz and mid infrared QCLs,[14] it is important to stress that the onset of the coherence collapse is also strongly dependent on the DFB laser structure, as already pointed out for near infrared emitters.[6,27] Further, investigations are required to determine whether the fourth regime of optical feedback observed in the QCL under study does correspond to the coherence collapse. Finally, for very high feedback levels, the laser enters the extended cavity regime, with single-mode operation and high output power.

The experimental setup is very stable and the measurements are reproducible, which allows us to draw the cartography of optical feedback regimes as a function of the external cavity length and the feedback rate with an uncertainty estimated around 20%. The result is shown in Fig. 5 and can be compared with the cartography for a 1.55-μm DFB laser diode from Ref. 13. The first observation that can be made is that the transitions between two different feedback regimes occur for much higher feedback ratios in QCLs than in interband lasers. However, the transitions between the three lower regimes qualitatively show the same tendency as those observed in interband laser diodes. In Fig. 5, the trend deduced from the optical spectra shows that the range of feedback rates on which regime four occurs is by far much narrower than that typically observed in interband lasers.

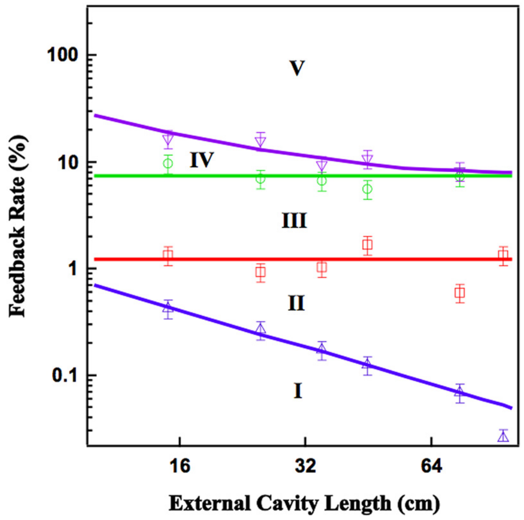

FIG. 5. Cartography of optical feedback regimes as a function of the external cavity length and the feedback ratio. The transitions were deduced from the optical spectra at constant bias current of 435 mA.

This observation that clearly demonstrates the increased range of stability of QCLs in presence of external optical feedback is in agreement with the main conclusions given in Ref. 14. It is also important to note that when the external cavity length is lowered by 10 cm for cavities shorter than 60 cm, the upper limit of the fourth regime is enhanced by a factor of two. It would thus be interesting to extend the measurement in the ultra short external cavity regime to see if this tendency is confirmed, which was not possible with the current experimental apparatus. On the other hand, it is important to notice that for long cavities over 60 cm the range of operation of the fourth regime becomes extremely narrow until the longest achievable external cavity length of 95 cm, for which the QCL was always found stable. In interband lasers, it is known that the onset of the coherence collapse does not depend on the external cavity length as long as the frequency of the external cavity remains much smaller than the laser relaxation frequency. However, once again, no direct comparison is possible at this stage with QCLs for which no relaxation frequency can be defined. While it will be necessary in the near future to confirm whether the fourth regime indeed corresponds to coherence collapse by analyzing electrical spectra, we can already underline that QCLs do exhibit a much higher stability under optical feedback than interband lasers, since the stable and single-mode regimes I, III, and V are much broader. This enhanced stability can certainly be attributed to the ultrafast carrier dynamics within the subbands but also to the reduced linewidth enhancement factor that limits the number of available external cavity modes.[28]

In summary, QCLs present interesting behaviors under external optical feedback, with an evolution of the laser threshold and output power and the apparition of five feedback regimes close to those identified in interband lasers. However, from this experimental investigation, it is proved that QCLs present an increased resistance to optical feedback, exhibiting only a narrow unstable regime that becomes even narrower as the external cavity length increases. These findings are of prime importance for understanding the underlying mechanisms of QCL under external control. As such, further experiments are now necessary to determine whether this unstable regime is indeed the chaotic coherence-collapse regime observed in interband lasers. In future work, the role of the linewidth enhancement factor on the optical feedback sensitivity will be also investigated with different DFB laser structures.

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