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Lauréline Durupt[1,*], **Olivier Spitz**[1,†], **and Frédéric Grillot**[1,2]

[1]*LTCI, Télécom Paris, Institut Polytechnique de Paris, 19 place Marguerite Perey, 91120 Palaiseau, France*

[2]*Center for High Technology Materials, University of New-Mexico, 1313 Goddard SE, Albuquerque, NM 87106, USA*

[*]*Contact Email: laureline.durupt@telecom-paris.fr*

[†]*Contact Email: olivier.spitz@telecom-paris.fr*

Introduction

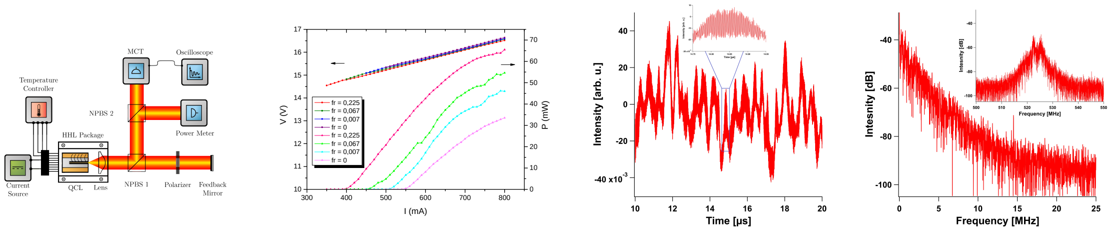
Optical feedback (OF) in quantum cascade lasers (QCLs) has been investigated in order to address private-transmission issues in the mid-infrared domain [1]. By re-injecting part of the emitted light of the QCL into its own cavity, the QCL can operate within five different non-linear dynamics regimes [2]. Among them, low-frequency fluctuations and coherence-collapse dynamics are chaotic waveforms [3] which can be used to hide a secret message within an unpredictable signal. This experimental work focuses on the non-linear dynamics of a HHL-packaged Fabry-Perot (FP) QCL pumped with a continuous bias and emitting at 4 μm. At this wavelength, the message can be transmitted through the atmosphere since two transparent windows have been highlighted in the mid-infrared [4]: the first one between 3 μm - 4 μm and the other one between 8 μm - 12 μm. Previous experimental efforts only dealt with unmounted QCL chips, thus forcing the end-user to own dedicated mounts and mid-infrared optics. This work pushes one step further the opportunities offered by compact off-the-shelf systems emitting in the mid-infrared. We first investigate the effect of OF on the current-voltage characteristics and show a strong threshold reduction, even for low feedback strengths. Then, we study the temporal non-linear dynamics displayed by this FP-QCL when varying the feedback strength and the external cavity length.

1. Experimental setup

Figure 1 (a) depicts the light travel in our experimental setup. The QCL is biased with a continuous wave by a current source. The HHL packaging provides the lens required to collimate the QCL light beam. Above the current threshold, the light emitted by the laser passes through a first beam splitter from which 55% of the light is transmitted into a polarizer and then is reflected back into the laser cavity by a mirror. 45% of the light is reflected towards a second beam splitter where the light is once again split between two paths: 70% of the light is transmitted to be analysed by a Mercury-Cadmium-Telluride (MCT) detector which is connected to an oscilloscope for real-time study, while 30% of the light is reflected and collected by a power-meter to perform the alignment and to record the output power. The laser and the mirror are placed on a rail in order to be able to vary the external cavity length between 15-30 cm, which theoretically corresponds to an external-cavity frequency between 500-1000 MHz. The estimated feedback ratio f_r is the ratio between the back-reflected power that couples inside the laser cavity and the total power emitted by the laser.

2. Results and discussion

Figure 1 (b) shows the light intensity voltage (LIV) characteristics of the QCL under continuous bias. The threshold current is 550 mA when the laser is not subject to OF, which corresponds to



(a) (b) (c) (d)

Fig. 1: (a) Experimental setup: the analysis path, with the MCT detector and the power-meter, is placed above and the external optical feedback path, bounded by the mirror and the QCL's emitting facet, is placed below; (b) LIV characteristics of the HHL-packaged FP-QCL under several feedback ratios and operating at room temperature with a continuous bias. (c) Experimental time trace and (d) fast Fourier transform of the intensity output of the FP-QCL subject to OF and pumped high above threshold with a continuous bias at 293K. The external cavity is 21-cm long in this case. Deterministic chaos can be observed as well as oscillations at the external-cavity frequency.

90 degrees on the polarizer. By increasing step by step the OF, a reduction of the threshold current is observed while the optical power recorded by the power-meter strongly increases. At maximum feedback (0 degree on the polarizer), the threshold current is found to be 405 mA and the recorded output power is nearly doubled.

A high-speed temporal analysis of the optical output illustrates the potential of packaged QCLs for private communications. Indeed, by varying the feedback ratio and the bias current, it is possible to exhibit several chaotic islands with a wide variety of non-linear dynamics. Figure 1 (c) shows a typical time-trace with a low-frequency chaotic contribution and a high-frequency component related to the external-cavity frequency. The corresponding RF spectra are found in Fig. 1 (d). It is relevant to note that these dynamics are easier to find by lowering the temperature and reducing the external-cavity length. Moreover when the latter varies, low-frequency dynamics remain the same while the high-frequency component changes: the values experimentally obtained for an external cavity of 16 cm, 21 cm and 28 cm are respectively 640 MHz, 525 MHz and 435 MHz, which are lower than the theoretical values (935 MHz, 715 MHz and 535 MHz respectively), but follow the same trend. Hence, the results are compatible with our previous findings and the packaging around the QCL under study does not affect the non-linear dynamics performances usually exhibited.

Acknowledgments

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