Extreme events in mid-infrared quantum cascade lasers : from randomness to advanced controllability

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O. Spitz[1,2*], A. Herdt[3], J. Wu[4,5], M. Carras[2], C. W. Wong[4], W. Elsäßer[3] and F. Grillot[1,4,6]
[1]*LTCI, Télécom Paris, Institut Polytechnique de Paris, 46 rue Barrault, 75013 Paris, France*
[2]*mirSense, Centre d'intégration NanoInnov, 8 avenue de la Vauve, 91120 Palaiseau, France*
[3]*Technische Universität Darmstadt, Schlossgartenstraße 7, D-64289 Darmstadt, Germany*
[4]*Fang Lu Mesoscopic Optics and Quantum Electronics Laboratory, University of California Los Angeles, CA, USA*
[5]*College of Electronics and Information Engineering, Southwest University, Chongqing, China 400715*
[6]*Center for High Technology Materials, University of New-Mexico, 1313 Goddard SE, Albuquerque, NM, USA*
**E-mail: olivier.spitz@telecom-paristech.fr*

Abstract: We experimentally generate rogue waves in a mid-infrared quantum cascade laser with external optical feedback. These giant pulses become controllable when adding a low-amplitude periodic perturbation. This paves the way for applications where mid-infrared bursts can be of prime importance such as optical neuromorphic clusters and countermeasure systems.

1. Introduction

'Rogue waves' describes extreme and rare events with reference to the 'freak' waves observed in the ocean [1]. Optical rogue waves were first demonstrated twelve years ago in the context of super-continuum generation in optical fibers [2] and have since been observed in a wide variety of configurations such as semiconductor lasers [3]. However, the randomness of such events is not always compatible with applications. Experiments have been carried in semiconductor lasers to predict these events [4] or even trigger them [5]. In such case, the term 'rogue waves' is turned to 'extreme events'. The criterion to indicate an extreme event compares the amplitude of the extreme event with the average of the global signal (μ). Any event whose amplitude is larger than μ plus six times the standard deviation (σ) is considered as an extreme event ($\mu \pm 6\sigma$) [5]. We experimentally show that mid-infrared quantum cascade lasers (QCL) under optical feedback (OF) can emit rogue waves. We further prove that adding a sine wave modulation or an asymmetric square low modulation can lead to controllable extreme pulses.

2. Device description and experimental apparatus

The QCL under study (Fig. 1 a) and b)) is a distributed feedback (DFB) laser which needs to be cooled down at cryogenic temperatures to be pumped with a continuous bias. At the temperature of 77K, the QCL has a current threshold of 331 mA and emits up to 50 mW optical power when pumped at 950 mA. It emits single mode at 5.45 µm as shown in the optical spectrum of Fig. 1 c) retrieved with a Fourier transform infrared spectrometer.

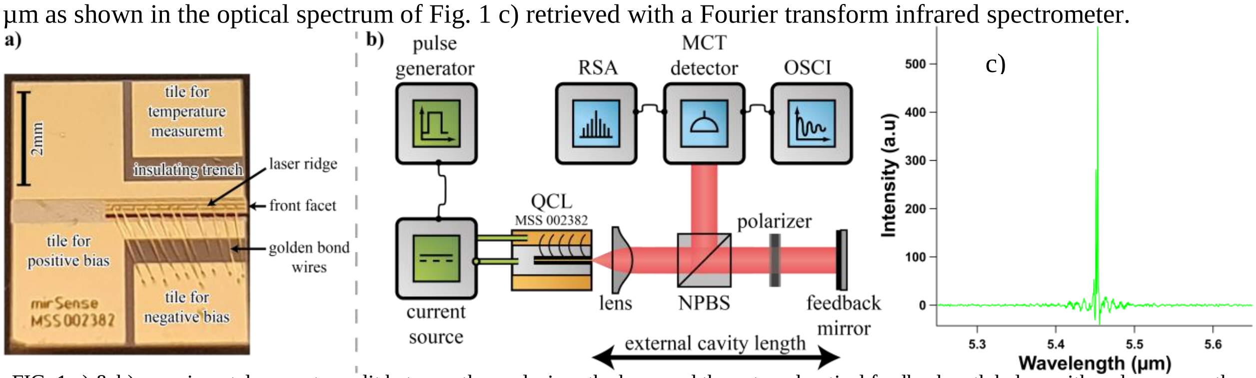

FIG. 1 a) & b) experimental apparatus split between the analysis path above and the external optical feedback path below with a close-up on the QCL under study; c) optical spectrum characteristics of the free-running DFB QCL operating at 77 K under a continuous bias of 340 mA

OF is applied with a gold plated mirror which defines the external cavity. This cavity is 27 cm long and a mid-infrared beam-splitter is placed between the QCL and the mirror. The wave reflected by the beam-splitter hits a 1-GHz bandwidth detector (Vigo PEM Mercury-Cadmium-Telluride) working at room temperature. This detector is linked to a low-noise amplifier (RF BAY, Inc LNA-545) with a 500 MHz bandwidth. The electric signal exiting the amplifier is analyzed using both a real-time oscilloscope at one giga samples per second (Atten ADS112CAL) and a RF spectrum analyzer (Agilent Technologies CXA N9000A), the latter being used to optimize the alignment of OF. The QCL is powered with a low-noise current source (Wavelength Electronics QCL2000 LAB) and the continuous bias delivered by the source can be modulated with an external signal from a waveform generator (Rigol DG1022Z).

3. Results and Discussion

The QCL is continuously biased at 600 mA and by applying OF, low frequency fluctuations emerge [6].Tilting a bit the feedback mirror to slightly misalign the OF [7] may trigger rogue waves as shown in Fig. 2 a). The dashed green line in Fig. 2 a) corresponds to the ($\mu + 6\sigma$) criterion and shows that the spikes with large amplitude are extreme events because the maxima of these spikes are above the dashed green line. However, these events randomly appear and cannot be predicted. Adding a low amplitude external modulation triggers the extreme events for a specific phase shift of the modulation signal. Figure 2 b) and c) show that extreme events only appear at the maximum of the sine wave in the case of a sine modulation with amplitude of 1% of the DC bias. In this case, the success rate is low, around 10%, but extreme events can be predicted in a time interval. By tuning the external modulation, it is possible to increase the rate of extreme events. In the case of Fig. 3, a square wave modulation with a duty cycle of 20% and amplitude of 1% is added to the DC bias. Once again, extreme events only appear for a specific phase shift, corresponding to the pulse-up, but they are now triggered with a success rate of 47%. This rate is similar to that predicted in simulations with laser diodes [5]. Further analysis is required to thoroughly determine the optimal parameters to control these pulses. We thus reported a method to control the likelihood of extreme events through a periodic perturbation, which allows envisioning applications based on sudden mid-infrared bursts.

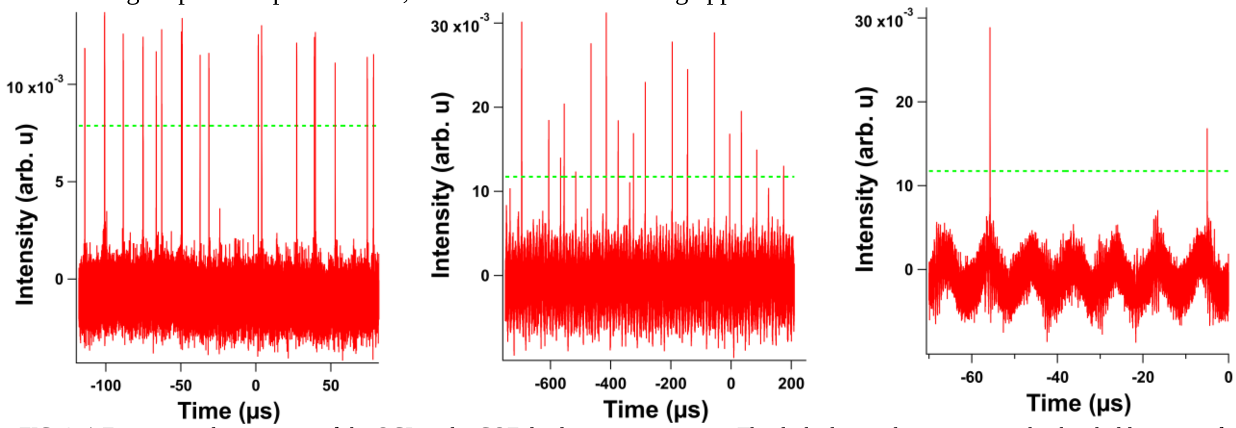

FIG. 2 a) Experimental time traces of the QCL under COF, leading to rogue waves. The dashed green line represents the threshold criterion for extreme events; b) same configuration but with a low-amplitude external sine modulation; c) close-up on the sine pattern with two extreme events

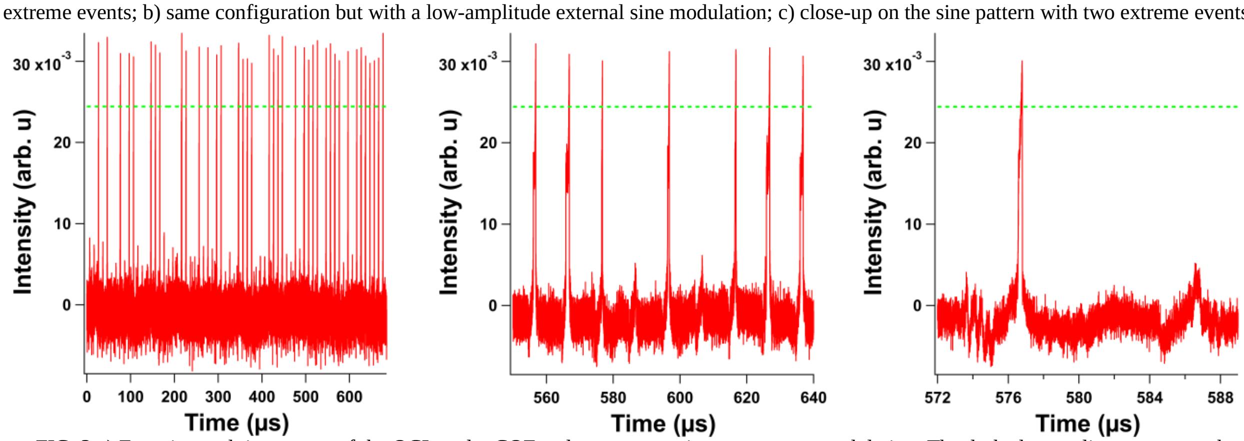

FIG. 3 a) Experimental time traces of the QCL under COF and an asymmetric square wave modulation. The dashed green line represents the threshold criterion for extreme events; b) and c) close up on extreme events and the asymmetric low-amplitude square modulation

4. References

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