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Abstract: We experimentally generate controllable extreme pulses in a mid-infrared quantum cascade laser with external optical injection and square wave perturbation.

OCIS codes: (140.5965) Semiconductor lasers, quantum cascade; (140.3070) Infrared and far-infrared lasers

1. Introduction

The term rogue waves describes random isolated events with amplitudes well above that of neighboring ones, and which occur more often than expected from the distribution of lower amplitude events [1]. Optical rogue waves were first demonstrated experimentally 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]. In order to detect rogue waves from experimental data, the probability density function (PDF) of an appropriate attribute of the data needs to be analyzed, and crest or wave heights are commonly used. Once extracted from the data, heights are compared to a threshold value above which events can be considered as extreme. This criterion is often defined in terms of the standard deviation of the whole time series frame : any event whose height is higher than the mean value (μ) plus height times the standard deviation (σ) is considered as an extreme event ($\mu \pm 8\sigma$) [3]. We apply this criterion to a mid-infrared quantum cascade laser (QCL) under conventional optical feedback (COF) and asymmetric square low modulation to experimentally report the first extreme pulses in such lasers. We further unveil a method to produce controllable extreme pulses which is highly relevant for sensing applications [4]. Mid-infrared QCLs are intersubband semiconductor lasers and their versatility make them candidates of choice for a wide range of free-space applications such as high-speed communications [5] or light detection and ranging (LIDAR) [6].

2. Device description and experimental apparatus

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

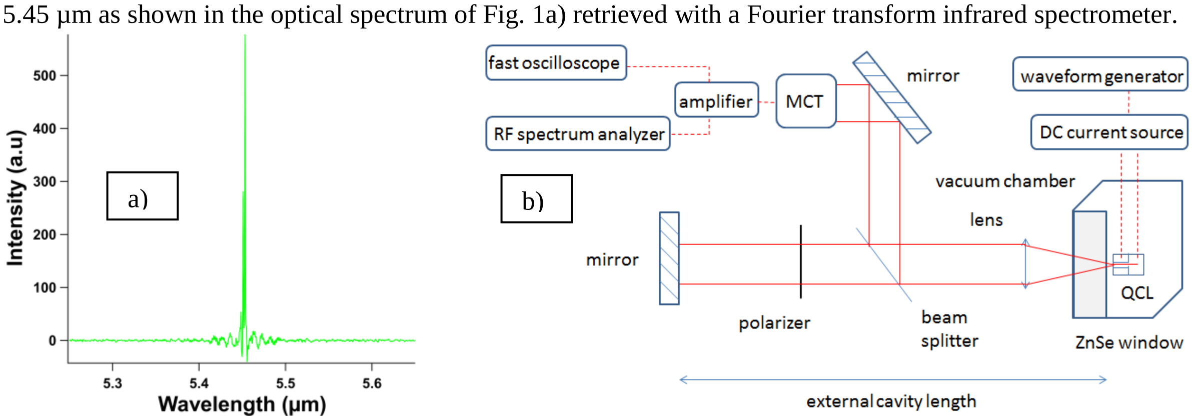

FIG. 1 a) optical spectrum characteristics of the free-running DFB QCL operating at 77 K under a continuous bias of 340 mA; b) experimental apparatus split between the analysis path above and the external optical feedback path below.

COF 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 high-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 sample per second (Atten ADS112CAL) and a

RF spectrum analyzer (Agilent Technologies CXA N9000A), the latter being used to optimize the alignment of the COF. The QCL is powered with a low-noise 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 pumped with a continuous bias at 600 mA and a square wave modulation with a period of 10 µs and a low amplitude of 4 mA is added. This square wave is asymmetric and the upper part of the square lasts for only 2 µs. Spikes with a large amplitude occur in the time trace every 10 µs, as shown in Fig. 2, except for some few cases where the amplitude of spikes is low and actually corresponds to the low amplitude of the square modulation. The dashed blue line in Fig. 2 corresponds to the aforementioned criterion ($\mu + 8\sigma$) and shows that the spikes with large amplitude are extreme pulses because the maximum of these spikes are above the dashed blue line. It is relevant to notice that, if either the duty cycle of the square signal or the amplitude of the square signal is modified, extreme pulses are still visible in the time traces but it becomes tougher to precisely control their likelihood. Further analysis is required to thoroughly determine the optimal parameters to control extreme pulses. Replacing the square modulation by a sine one gives the same conclusion. If the amplitude of the modulation is too large, the spikes can be controlled but the criterion for extreme events is no longer met as shown in Fig. 3. We thus reported the first extreme pulses in a QCL as well as a method to control the likelihood of such events through a periodic perturbation.

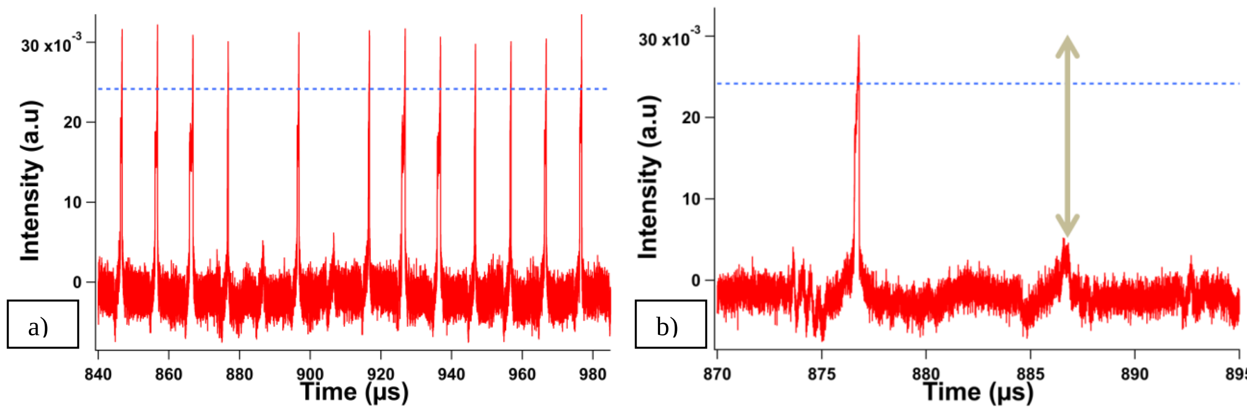

FIG. 2 a) Experimental time traces of the QCL under COF and a square wave modulation with a period of 10 µs and an amplitude of 4 mA. The dashed blue line represents the threshold criterion for extreme events; b) close up on an extreme event and the low-amplitude square modulation, the grey arrow represents the amplitude discrepancy between the extreme pulse and the square wave modulation.

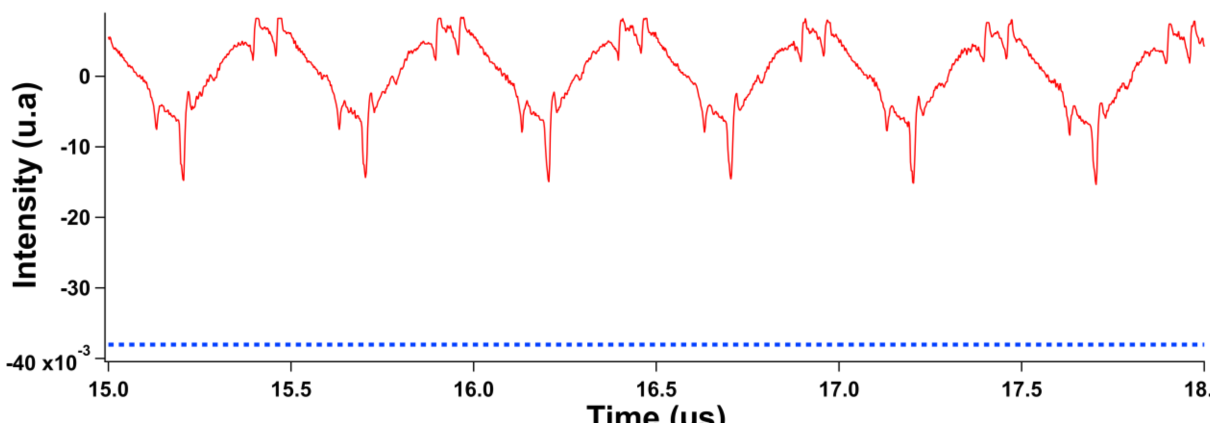

FIG. 3 a) Experimental time traces of the QCL under COF and a sine modulation of 120 mA at 2 MHz. Spikes with a relative large amplitude are controlled but they do not meet the extreme events criterion, symbolized by the dashed blue line ($\mu - 8\sigma$)

4. References

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