Excitability in Mid-Infrared Quantum Cascade Lasers: from Communication Jamming to Neuromorphic Photonics

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Abstract: We experimentally build a basic optical neuron by taking advantage of excitability in a semiconductor laser under optical feedback, rather than conventional injection schemes. This optical neuron operates faster than its biological and electronical counterparts.

1. Introduction

Quantum cascade lasers, first envisioned for applications nearly 20 years ago [1], have known a renewed interest in free-space-optics systems for communications, as an alternative to the widespread optical fiber systems. With these mid-infrared devices, transmissions at several Gbits/s have been demonstrated [2] and simulations emphasize that their beam quality is less affected by scattering and scintillation during long-haul transmission, compared to near-infrared lasers [3]. These studies complimented findings showing the high transmission potential of mid-infrared devices in the two transparency windows of the atmosphere, namely 3-5 µm and 8-12 µm. When subjected to external optical feedback, QCLs are known to be more resistant than other semiconductor lasers [4] but still exhibit several non-linear dynamics [5]. Amid these phenomena, excitability can be detrimental for communications because it blurs the encoded signal. However, it is also possible to take advantage of excitability in neuromorphic photonics schemes [6]. The purpose of neuromorphic computing systems is to process information tasks inspired by the brain's powerful computational abilities. We experimentally show how to fire spikes that replicate biological neurons' response with an amplitude that does not depend on the excitation strength, provided that this excitation reaches a threshold. This is the first experimental demonstration of excitability in a semiconductor laser under external optical feedback and this paves the way for optical neuron clusters based on QCLs.

2. Device description and experimental apparatus

The QCL under study (Fig. 1 a) and b)) is a distributed feedback (DFB) laser operated with a continuous bias at the temperature of boiling nitrogen. The current threshold of the laser is 590 mA and the maximum output power is 10 mW, as can be seen in Fig. 1 c). When pumped above threshold, the laser emits single mode at 5.45 µm as shown in the optical spectrum of Fig. 1 d) retrieved with a Fourier transform infrared spectrometer (FTIR).

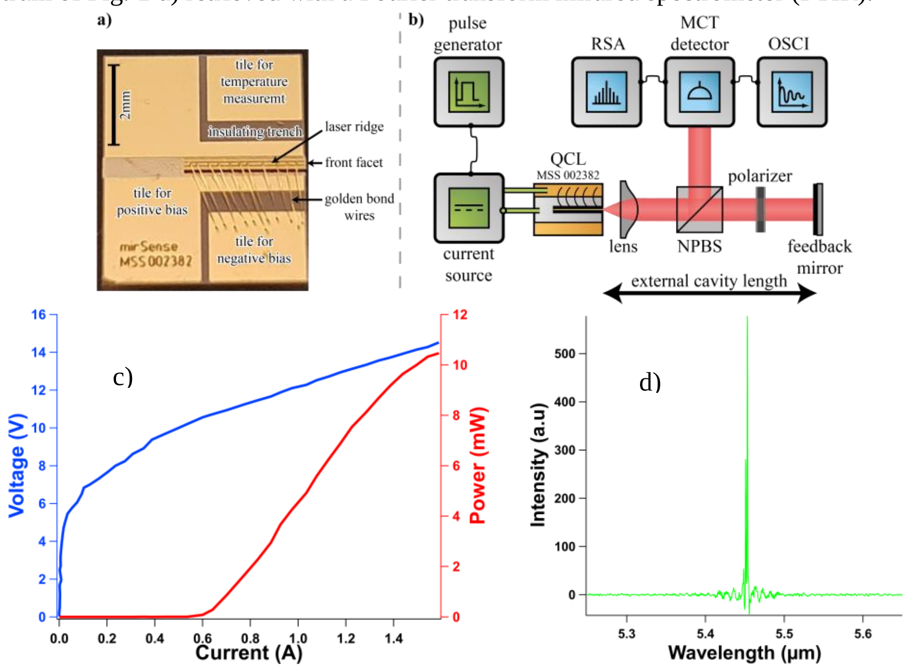

FIG. 1 a) & b) experimental setup split between the analysis path above and the back-reflection path below with a close-up on the QCL chip; c) and d) LIV curves and optical spectrum characteristics of the free-running DFB QCL operating at 77 K under a continuous bias, respectively.

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). Back-reflection is assessed by a gold plated mirror, which defines the external cavity, and a mid-infrared polarizer. This cavity is 27 cm long and a non-polarizing beam-splitter (NPBS) is placed between the QCL and the mirror. The wave reflected by the beam-splitter is retrieved by 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 (OSCI; Atten ADS112CAL) and an electric spectrum analyzer (RSA; Agilent Technologies CXA N9000A), the latter being used to optimize the alignment of the back-reflected light.

3. Results and Discussion

The QCL is continuously biased far from the current threshold and, in a first step, an electrical sine modulation is added to study a transmission configuration. Strong optical back-reflections detrimentally disturb the sine signal by exciting large spikes and consequently, the communication is jammed as depicted in Fig. 2 (a). When, in a second step, the sine modulation is replaced by a pulse-up signal, the aforementioned spikes synchronize with the pulse-up and are triggered on a regular base, with a high success rate as visualized in Fig. 2 (b). Another peculiarity of these spikes is that they all have the same amplitude, which is compatible with the key requirement of a super-threshold stimulus strength for the system to fire a spiking response. For each occurrence, the spike has a characteristic time of the order of the µs and that is of paramount importance in neuromorphic photonics. This indeed means that our basic optical neuron system operates 1 million times faster than biological neurons and 1000 time faster than the electronic artificial neurons [7]. Compared with existing optical neuromorphic systems which use semiconductor lasers under the injection of a remote laser [6], our configuration takes advantage of external optical feedback and consequently, only one laser component is required to build one basic spiking neuron. Improvements will focus on clusters of QCLs under optical feedback and the implementation of more complex architectures.

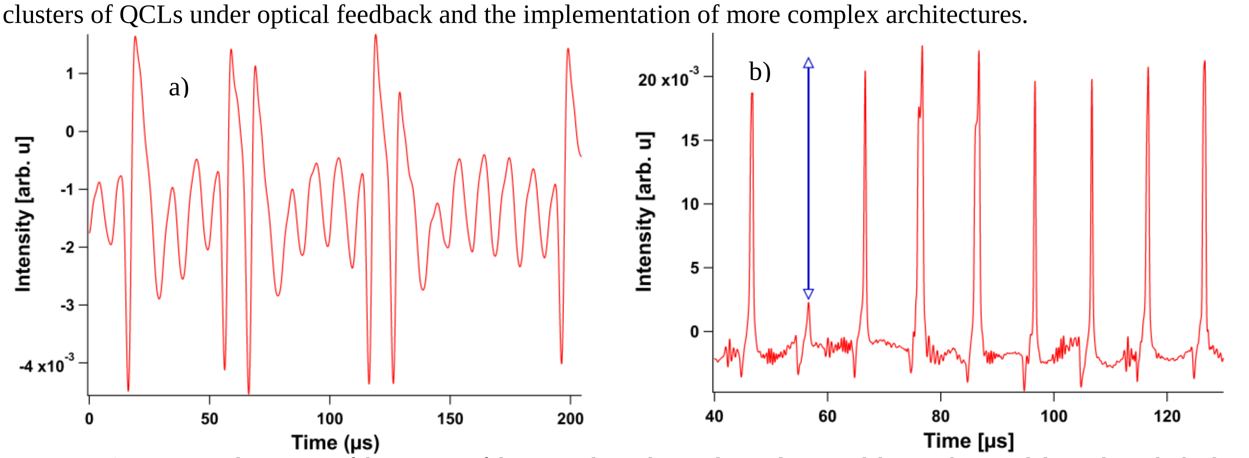

FIG. 2 a) Experimental time trace of the intensity of the QCL subjected to an electrical sine modulation. The excitability is driven by back-reflections and blurs the periodic signal. b) Experimental time trace of the optical neuron based on a QCL under external optical feedback. One of the pulse-up remains untriggered (below the blue arrow) in order to emphasize the difference between the stimulus and the laser's response.

4. References

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