Tunable All-Optical Modulation and Building Blocks for Optical Neurons at Mid-Infrared Wavelength

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Abstract: Quantum cascade lasers (QCLs) under optical feedback can output several non-linear dynamics whose properties depend on the reinjected light polarization. We demonstrate all-optical modulation, thresholding and excitability in QCLs, to experimentally build basic optical neurons.

1. Introduction

Recent progress in the study of non-linear dynamics using delay-coupled semiconductor lasers has paved the way for integrated complex photonics [1], which is becoming a field versatile enough to mimic bioinspired concepts such as neural networks and large-scale synchronization. Essential building blocks, such as logic elements and modulators, are required for information processing on a chip scale. The advantage of these photonic memories is to be both high speed and energy efficient [2]. The data transmission can still be increased by wavelength multiplexing, thus pushing the all-optical modulators efforts towards higher wavelengths. In parallel, efforts have pushed towards the realization of neuromorphic grids using optics to overpass the speed limitation of electrical neurons [3]. The various non-linear dynamics we are able to exhibit with QCLs under external optical feedback prove that they can be mid-infrared emitters of paramount interest. QCLs are versatile mid-infrared optical sources used in many applications [4] and recent studies about QCLs on silicon [5] emphasize they are promising semiconductor lasers for low-cost integrated photonics. Contrary to bipolar semiconductor lasers, QCLs generate purely TM polarized light due to the intersubband selection rules [4]. Here, we experimentally apply a cross-polarization optical feedback technique [6] to a mid-infrared QCL and show that it is possible to generate a square wave with a controllable frequency. We further unveil tonic and phasic spiking [3] when a QCL under external optical feedback is subject to a threshold activation coming from a square signal. These two findings allow envisioning all-optical neural networks able to display the full spectrum of patterns usually found in biological synaptic transmissions at lower frequencies.

2. Device description and experimental setup

The QCL under study is a distributed feedback laser emitting single mode at 5.7 µm when pumped high above threshold, at room temperature. The external optical feedback setup is very similar to the one described in Ref. [7], except that the external cavity is tuned to create the desired optical phenomenon (all-optical modulation or excitability). In the case of all-optical modulation, a quarter-wave plate (QWP) is inserted as illustrated in Fig. 1 and in the case of excitability, the cavity is made asymmetric by tilting the feedback mirror. In all experiments, the external cavity has a total length of around 35 cm. The non-polarizing beam splitter (NPBS) divides the beam between the external cavity and the detection arm, composed of an optical density (P) to avoid saturation in the mid-infrared detector. The signal is analyzed with a fast oscilloscoppe (OSCI) and an electrical spectrum analyzer (RSA).

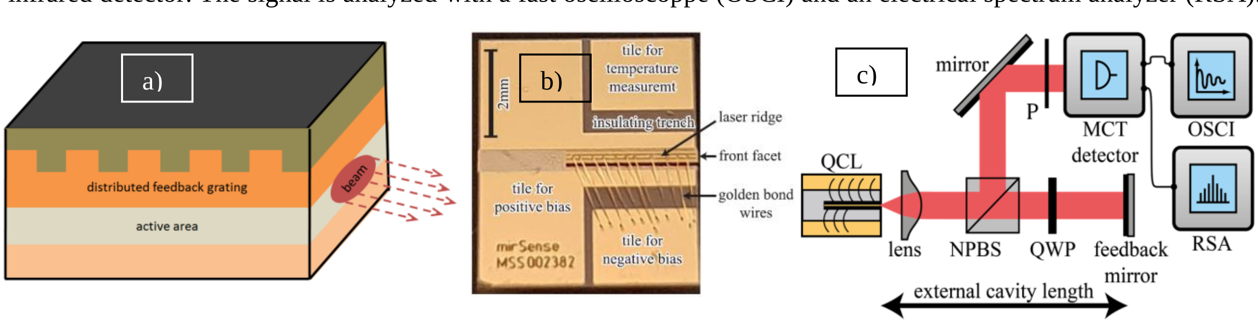

Fig. 1 a) sketch of the laser ridge with the distributed feedback grating allowing single mode emission; b) photograph of the QCL chip with bonding and connectors; c) experimental setup for external optical feedback operation, the quarter wave plate (QWP) is used to generate the all-optical modulation and is removed in the case of neuromorphic spiking. MCT : Mercury-Cadmium-Telluride detector, NPBS : non-polarizing beam splitter, OSCI : fast oscilloscope, P : optical density, RSA : real time spectrum analyzer.

3. Results and Discussion

When moderate feedback without rotated polarization and without asymmetric external cavity is applied to a QCL, the laser generates non-linear dynamics such as low-frequency fluctuations (LFF) and deterministic chaos [7]. Because the chaotic patterns cannot be predicted, they are of paramount interest for random number generation and chaos-based secure communications [8]. When rotating the feedback polarization with the aforementioned setup, the QCL emits a square wave pattern for high feedback ratios (above 25%). Figure 2 a) (red curve) shows the characteristics of the generated square wave, when the quarter wave plate is oriented at 45°. In other semiconductor lasers under cross-polarization feedback, such as laser diodes and VCSELs, the frequency of the square wave is determined by the frequency of the external cavity and the duty cycle can be tuned by varying the pump current and the coupling strength [6]. In our experiments with QCLs, we show that both the frequency and the duty cycle of the square pattern can be tuned by varying the angle of the quarter-wave plate. Figure 2 a) (orange curve) shows square patterns with a duty cycle of 35% when the quarter-wave plate is set at 35°. This square pattern can be used as the excitation signal in the case of optical neurons [3] based on QCLs. Indeed, we experimentally discovered that QCLs under external optical feedback can behave like bursting neurons as illustrated in Fig. 2 b) when implementing an asymmetric external cavity. When the excitation is not applied, the QCL randomly fires pulses (green curve), and this cannot compare with biological neurons. The square excitation allows triggering a regular and consistent train of pulses with a high success rate (blue curve). The advantage of our all-optical feedback configuration is that it reduces the number of optical sources in comparison with injection schemes commonly used with VCSELs [3]. This paves the way for neuromorphic grids faster than biological neurons and artificial electrical neurons, with a wavelength of operation that is compatible with tissue samples due to high absorbtion in the mid-infrared domain [9].

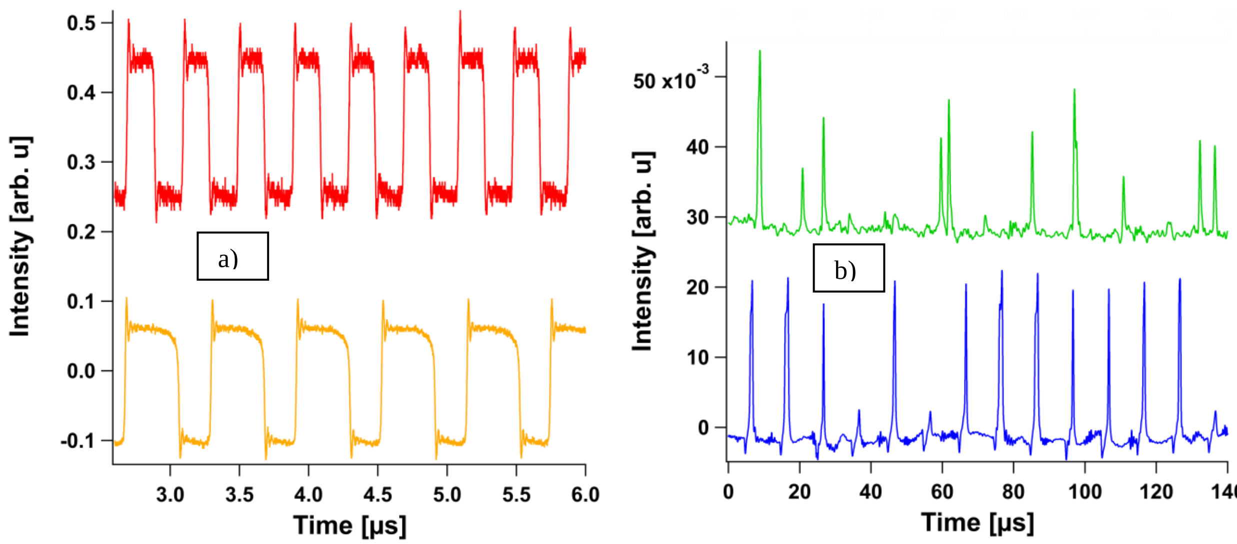

Fig. 2 : Experimental time traces of the laser intensity when the QWP is inserted in the cavity (a). A square pattern is triggered and the angle of the QWP allows tuning the period and duty cycle of the pattern (e.g. duty cycle of 50% in the case of the red curve and duty cycle of 65% in the case of the orange curve). Experimental time traces of the laser intensity in a configuration with an asymmetric cavity (b). Without activation, the QCL is bursting erratically (green curve) but when a square pattern excitation is applied, the QCL generates consistent pulses with a periodic time interval and a high success rate (blue curve). This corresponds to tonic and phasic spiking and relates to the behavior of biological neurons.

4. References

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