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Optical injection of mid-infrared extreme events in unilaterally coupled quantum cascade lasers

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Abstract: This experimental work reports on the unilateral injection of extreme events, those being non-linear phenomena which can be observed in mid-infrared quantum cascade lasers with tilted feedback. Contrary to chaos dynamics leading to synchronization when a master quantum cascade laser is unilaterally injected in a slave quantum cascade laser, the optical injection of these extreme events triggers a peculiar spiking dynamics in the injected slave quantum cascade laser. The slave's dynamics share similarities with the time derivative of the extreme events waveform generated by the master quantum cascade laser.

1. Introduction

Quantum cascade lasers (QCLs) are semiconductor lasers relying on intra-band transitions to achieve emission in the mid-infrared and the terahertz domain. Mid-infrared wavelengths around 10 μm are characterized by low atmosphere attenuation [1] and this, in combination with recent progress in room-temperature modulators [2] and detectors [3], has opened the way towards high-speed free-space communication. Another recent experimental efforts showed free-space private transmission based on chaos synchronization in QCLs [4]. This method relies on a master QCL driven chaotic by optical feedback and unilaterally injected into a slave QCL. The peculiarity of chaos synchronization is that the slave QCL reproduces the chaos output of the master QCL if the two lasers are similar. If the output of the master QCL is forced, the synchronization does not occur. For instance, if one biases the master QCL with an electrical sine wave, the master QCL emits a sine wave but the optical output of the slave QCL is not a sine wave. Apart from chaos, QCLs under external optical feedback can generate various types of non-linear dynamics [5, 6] and one can legitimately wonder if these dynamics are also compatible with synchronization. In this work, we experimentally study the injection process of mid-infrared extreme events [5]. Intriguingly, the optical response of the slave QCL can be compared with the time derivative of the master's signal. Thus, the observed phenomenon is not synchronization but accounts for a new non-linear process at mid-infrared wavelength.

2. Experimental setup

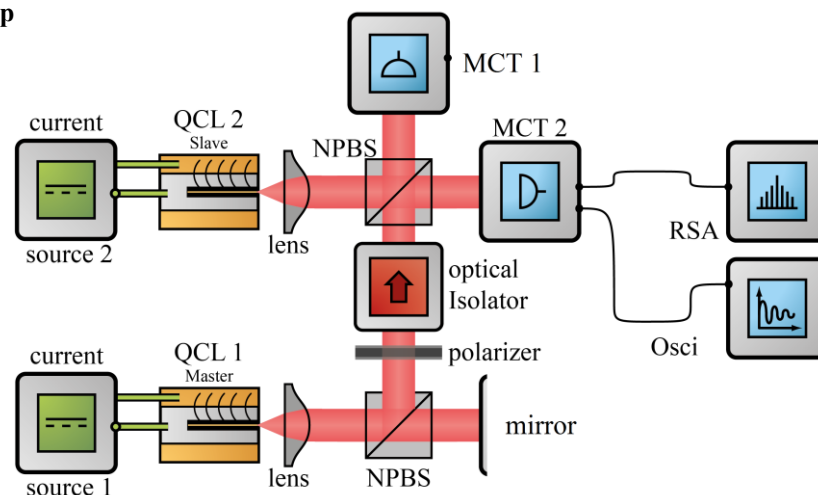


Figure 1: Experimental setup for optical injection in unilaterally coupled QCLs. The master laser is in an external-cavity configuration and drives the slave laser that emits the same single wavelength (zero detuning). The analysis of the optical signals is performed with mid-infrared detectors (MCT 1 and MCT 2), a real-time oscilloscope (Osci) and an electrical spectrum analyzer (RSA); NPBS: non-polarizing beam splitter.

The room-temperature master QCL emits single wavelength at 5.7 μm and is placed in an external-cavity configuration. A gold-plated mirror is used to reinject the light back into the master laser's cavity and, in our case, this leads to extreme events in the output of the master QCL because the mirror is tilted [5]. The master light beam is sent towards the room-temperature slave QCL. In order to avoid cross-interaction between the slave QCL and the master QCL, an optical isolator is placed between the two lasers. This corresponds to

unilateral optical injection. The light intensity that is injected into the slave QCL is controlled with polarizer before the optical isolator. The slave QCL is not in an external-cavity configuration, which means that only the injection process can trigger non-linear dynamics in the slave output. Signal from master QCL is retrieved with Mercury-Cadmium-Telluride detector 1 (MCT 1) and the timetrace is recorded with a fast oscilloscope. MCT 2 plays the same role for the slave signal and the oscilloscope allows real-time comparison of the two waveforms.

3. Results and discussion

Figure 2 shows the spiking master signal, the slave response signal and the numerical time derivative of the master's signal. For the master's signal (in dark blue), light blue arrows indicate low-amplitude electrical forcing which does not disturb the main spiking dynamics. The electrical amplitude of this forcing is 4 mV and one can compare the magnitude of the non-linear spiking with that of the low-amplitude forcing. The global picture is that the slave laser displays a response every time the master laser triggers a spike. A closer look at the slave's signal shows that the response (in red) is similar to the calculated time derivative (in black) and more specifically when the master's signal has a positive slope. In that specific case, the response of the slave displays a main pulse followed by weaker oscillations which are also found in the numerical calculation. When the master signal shows a decreasing slope, the slave laser outputs a magnified response compared to the numerical calculation but the shape of the response is still consistent. We thus experimentally demonstrated an all-optical differentiator with a unilaterally injected QCL. These findings complement the recent experimental efforts about basic optical neurons in QCLs [5]. The explanation for the slave's behavior is the object of ongoing work but to the best of our knowledge, this differentiator feature has not yet been explored theoretically and experimentally in other semiconductor lasers such as laser diodes and VCSELs. This is worth noting because usually, the dynamics observed in QCLs have previously been thoroughly reported in near-infrared semiconductor lasers.

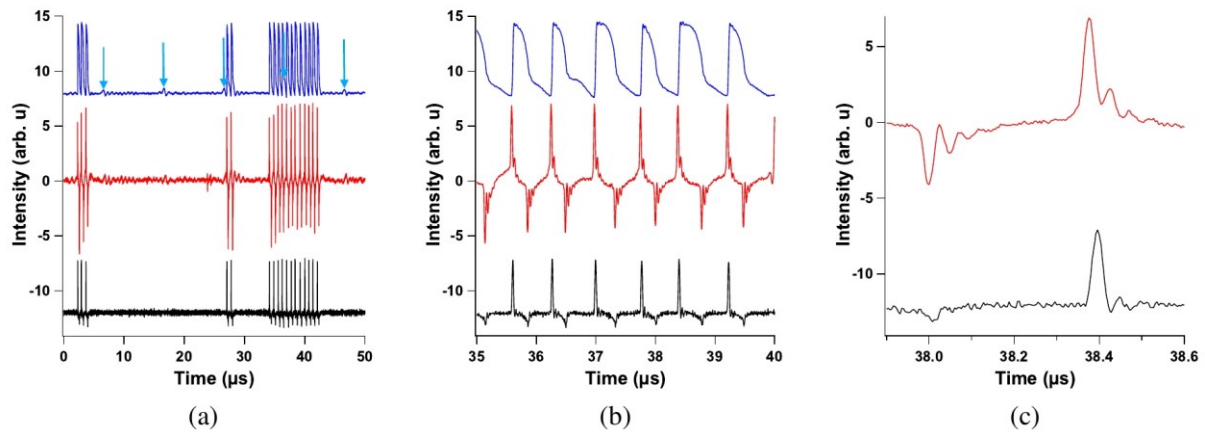


Figure 2: Experimental time traces of the output of the master QCL (blue), the injected slave QCL (red) and the calculated derivative of the master signal (black) when the master laser exhibits spiking dynamics; (a) global picture showing trains of pulses; (b) zoom on the behavior of the slave QCL when the master QCL fires a spike; (c) focus on the similarities between the slave's signal and the calculated derivative of the master's signal, the pulse-down occurs simultaneously in both cases but their amplitude is different while the pulse-up occurs also simultaneously but with a comparable intensity.

5. References

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