All-optical modulation at mid-infrared wavelength with QCLs

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Abstract

We demonstrate an all-optical square modulation in a room-temperature quantum cascade laser with cross-polarization reinjection. The duty cycle of the pattern is controlled by varying the components of the polarization, paving the way for integrated photonic memories and direct modulation of light at mid-infrared wavelength.

Index Terms

Quantum cascade laser, mid-infrared, complex photonics, cross-polarization reinjection

I. 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 [2]. Essential building blocks, such as logic elements and modulators [3], are required for information processing on a chip scale. The advantage of these photonic memories is to be both high speed and energy efficient [4]. The data transmission can still be increased by wavelength multiplexing, thus pushing the all-optical modulators efforts towards higher wavelengths. QCLs are versatile mid-infrared optical sources used in many applications 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. Here, we experimentally apply a cross-polarization optical reinjection technique to a mid-infrared quantum cascade laser (QCL) and show for the fist time, to the best of our knowledge, that it is possible to generate a square wave with a controllable frequency, which offers more flexibility compared to other semiconductor lasers where the frequency of the square pattern is fixed by the roundtrip time. This work is also of paramount importance for the development of all-optical modulation techniques, in particular for the advent of free-space optical communications. A recent work reported on the demonstration of external optical modulation at mid-infrared wavelength from 5.5 to 11 microns, relying on a broadband Ge-rich graded SiGe platform [6]. Despite that, direct modulation of light remains a more simple way to generate optical RF signals. In this work, we also show for the first time that QCLs operating under reinjection can produce directly modulated optical signals.

II. Device description and experimental setup

The QCL under study is a distributed feedback laser emitting single mode at 5.7 μm when pumped with a continuous bias of 800 mA at 249 K. This configuration induces a high internal self-heating and this is the reason why the QCL is episide-down mounted on AlN substrate. The experimental setup, as presented in Fig. 1, is made of an analysis path with a Mercury-Cadmium-Telluride (MCT) detector with a bandwidth of 50 MHz (KMPV50-0.5-J2) for mid-infrared detection. The detector is linked to a real time spectrum analyzer (RSA) with a maximum real time bandwidth of 110 MHz (Tektronix RSA6114A) and a 40 GS/s oscilloscope (Tektronix TDS6154C) for real time analysis and acquirement. The external optical reinjection path is set with a gold plated mirror and a quarter-wave plate (P) designed for a wavelength of 4.5 μm. The latter is used to convert the TM polarization generated by the laser into a TE polarization and that corresponds to

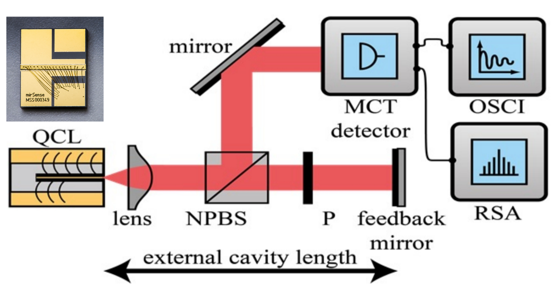

Fig. 1: Experimental setup which splits the beam between an analysis path above and an external optical reinjection path below. A close-up picture of the QCL is shown in inset.

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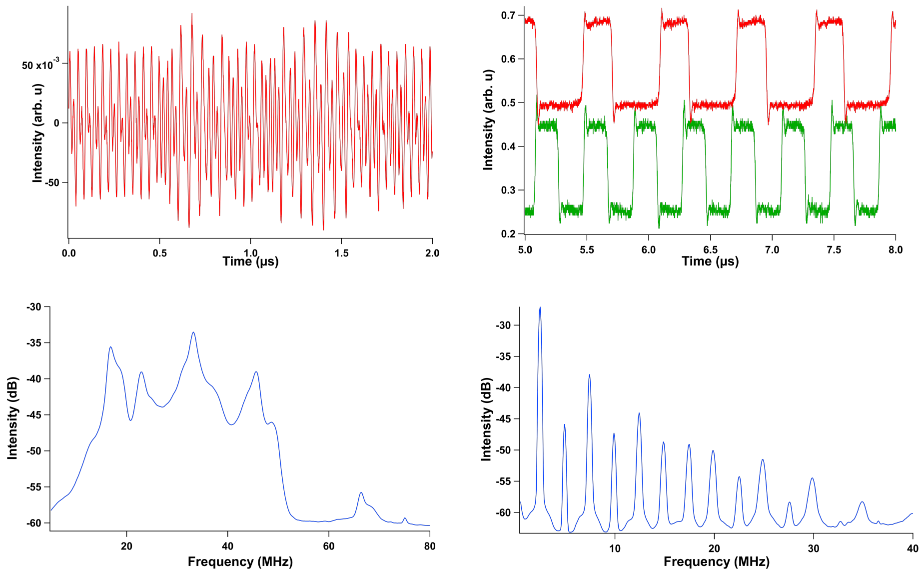

Fig. 2: Experimental time traces (top left) and RF spectrum (bottom left) of the wave emitted by the QCL under study when moderate reinjection without rotated polarization is applied. Experimental time traces (top right) of the wave emitted by the QCL under study when cross-polarization reinjection is applied and the quarter-wave plate is set to 35° (red) and 45° (green). RF spectrum (bottom right) of the wave emitted by the QCL corresponding to the top green waveform.

the cross-polarization reinjection technique. The external cavity has a total length of around 35 cm. The non-polarizing beam splitter (NPBS) has a measured absorption of 25% at the laser wavelength. The light that is not absorbed is mostly transmitted towards the reinjection mirror resulting in a maximum reinjection ratio of 35%.

III. Results and discussion

When moderate reinjection without rotated polarization is applied to a QCL, the laser emits non-linear dynamics such as low-frequency fluctuations (LFF) and deterministic chaos [7]. An example of such phenomenon is shown in Fig. 2 (left chart) and a typical feature of chaos is a broadband RF spectrum. Because the chaotic patterns cannot be predicted, they are of paramount interest for random number generation and chaos-based secure communications [1]. When rotating the reinjection polarization with the aforementioned setup, the reflected beam goes back into the laser cavity with mostly a TE polarization and the QCL emits a square wave pattern for high reinjection ratios (above 25%). Figure 2 (right chart) shows the characteristics of the generated square wave, with a discrete RF spectrum, when the quarter wave plate is oriented at 45° (green plot). In other semiconductor lasers under cross-polarization reinjection, 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 [8]. 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 (right chart) also shows a square pattern with a duty cycle of 35% when the quarter-wave plate is set at 35° (red plot).

We believe this work shows huge benefits from superior QCL features, not only for photonic memories but also for direct modulation of light and many other emerging applications in neuromorphic photonics and optical crowd synchrony.

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