Passive Mode-Locking and Tilted Waves in Broad-Area Vertical Cavity Surface-Emitting Lasers

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Abstract: We show experimentally that an electrically biased 200 μm multi-transverse mode VCSEL can be passively mode-locked using optical feedback from a distant Resonant Saturable Absorber Mirror. Optical feedback selects a tilted wave propagating along the transverse section of the VCSEL and leading to mode-locking of the external cavity modes. A large portion of the VCSEL transverse section contributes to mode-locked pulse emission with pulses of approximately 1 W peak power and 10 ps width.

Passive Mode-Locking (PML) is arguably one of the most elegant methods to obtain short and intense pulses in the output of a laser. It is achieved by combining two elements, a laser amplifier providing gain, and a saturable absorber (SA) acting as a pulse shortening element. The different dynamical properties of the SA and of the gain can create a window for amplification only around the pulse, thus leading to a pulsed emission [1,2]. While dye and solid-state lasers are generally used to generate the shortest and most intense pulses, semiconductor lasers are interesting for applications because of their compactness, low costs, high repetition rate and high plug-in efficiency. In semiconductor lasers, PML can be achieved by coupling Vertical External Cavity Surface-Emitting Lasers (VECSEL) with a Semiconductor Saturable Absorber Mirror (SESAM) [4]. The external cavity is designed to operate in the fundamental gaussian mode since the presence of higher order transverse modes is usually perceived as detrimental for PML stability. Nevertheless, the possibility of achieving a cooperative effect of transverse modes for which they would contribute to longitudinal mode-locking is very attractive for increasing pulse power.

In this work, we propose a scheme for achieving PML using an electrically biased 200 μm multi-transverse mode VCSEL. This device is mounted in an external cavity configuration closed by a Resonant Saturable Absorber Mirror (RSAM). Instead of using a self-imaging configuration in which the VCSEL transverse profile is mapped onto the RSAM, we form an image of the VCSEL onto the front focal plane of the collimating lens placed before the RSAM (Fig. 1). This has the effect to inject the Fourier Transform (i.e. the far-field) of the VCSEL near-field profile onto the RSAM. In addition the VCSEL profile is (inversely) imaged onto itself after one round-trip. Since VCSEL and RSAM lie on Fourier planes, any plane wave emitted by the VCSEL yields a spot on the RSAM and vice-versa. We therefore induce strong local saturation of the RSAM while gain section experiences low power density, which favors the onset of mode-locked pulses [3].

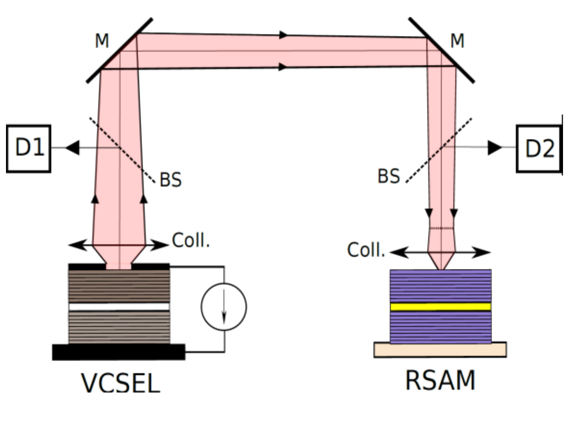

Fig.1: Experimental setup. Temperature stabilized VCSEL and RSAM. Coll : aspheric lens, BS: Beam Splitter, M : Mirror

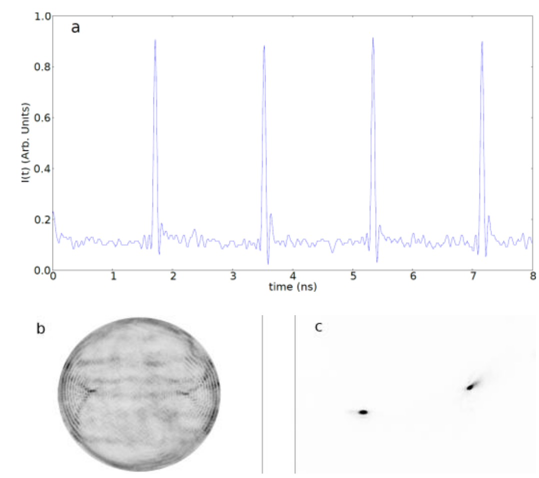

Fig. 2 : a)Total intensity output from the VCSEL in the mode-locking regime, b) near-field profile of the VCSEL, c) far-field profile of the VCSEL

Panel a) in Fig. 2 displays the time trace of the VCSEL in the mode-locking regime which consists of a regular train of pulses with a period equal to the roundtrip time in the external cavity (τ = 1.8 ns) and a pulse width equal to 10 ps FWHM. The time-averaged far-field of the VCSEL exhibits two bright off-axis spots that indicate the presence of two tilted waves travelling in the external cavity. The transverse wave-vector of each of these waves is related in direction and modulus to the position of the spots and their symmetry with respect to the optical axis indicates that the two transverse wave-vectors are one opposite to the other.

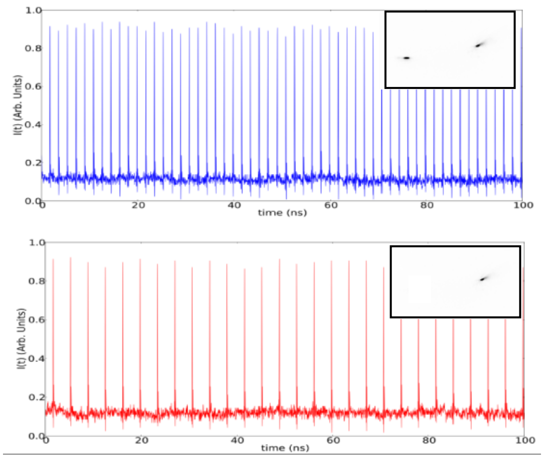

Fig.3 upper panel: Intensity output from the VCSEL obtained when detecting the two spots of the far-field emission (inset) of the VCSEL. Lower panel: Intensity output from the VCSEL obtained when detecting only one spot of the far-field emission (inset) of the VCSEL.

Remarkably, however, no interference pattern is visible in the VCSEL near-field emission. This implies that the transverse waves must not be simultaneously present. This is shown in Fig. 3 where we plot the intensity output from only one of the bright spots in the Far-Field. It consists also of a periodic train of pulses, but the period is now 2τ, thus showing that the two tilted waves are alternating each other after every round-trip.

This mode-locked dynamics doesn't critically depend on the transverse wave-vector selected by the system. Such value can be modified by adjusting the external cavity alignment, namely tilting one of the mirrors M in the setup or slightly displacing the collimator off the axis defined by the center of the VCSEL and the RSAM. On the other hand wave-vector selectivity may also arise from any imperfections on the RSAM/VCSEL mirrors that break the spatial invariance.

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