Time-localized Structures in Vertical-Cavity Surface-Emitting Lasers (VCSELs)

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***Abstract*— In this presentation we will review the results recently obtained on Time-Localized Structures (TLS) in VCSELs coupled to an external cavity. We show that, when the cavity roundtrip is much larger than the medium timescales, this system exhibits a temporal aspect-ratio large enough to host TLS. Two configurations will be considered. In the first one the system is submitted to cross-polarization reinjection which leads to the formation of vectorial TLS. In the second one the external cavity is closed by a Resonant Saturable Absorber Mirror, a scheme conventionally used to obtain mode-locked pulses. Here we will show how TLS can be obtained from mode-locking.**

I. INTRODUCTION

Localized structures (LS) are nonlinear inhomogeneous states of dissipative extended systems characterized by a correlation range much shorter than the size of the system, thus allowing for individual addressing. LS appear ubiquitously in nature and in optical systems they are very appealing for applications to information processing. This interest is further increased when the LS substrate are fast, scalable and cheap devices as semiconductor lasers [1]. Single-peaks LS in optical cavities injected by a coherent electromagnetic field, also called Cavity Solitons (CS), have been observed in the transverse section of broad-area semiconductor microcavities [2], while temporal CS have been reported recently in a fiber resonator [3]. In these systems, self-organization leads to LS by modifying the injected field (passive morphogenesis). More recently spatial LS have been observed also in *lasing* cavities where self-organization takes place from spontaneous emission noise (active morphogenesis) [4,5]. These *laser* LS appear in phase invariant system and thus they have different properties with respect to LS in injected systems.

In this contribution we address the possibility of generating temporal LS (TLS) in a laser system based onto a Vertical-Cavity Surface-Emitting Laser (VCSEL) mounted in an external cavity configuration. As LS appear in large aspect-ratio system, the first requirement for observing TLS is to size the external cavity such that the round-trip (τ) is much larger than the medium timescales. Since the slowest timescale in semiconductor systems is the gain recovery time ($\gamma \sim 0.2$ - 1 ns), we set $\tau >> \gamma$. We give evidence of TLS existence in two different systems: the first is based on the polarization degree of freedom of VCSELs and it generates *vectorial* TLS, the second is based on a traditional mode-locking configuration where the VCSEL is coupled to a Saturable Absorber Mirror.

II. VECTORIAL TIME-LOCALISED STRUCTURES

VCSELs lack of anisotropies strong enough to pin the polarization direction and competition between orthogonal linearly polarized states is easily induced by (anisotropic) optical perturbations. We place a single-transverse mode VCSEL in a double external-cavity which induces such a competition. The cavity selects one of the linearly polarized (LP) states and feeds it back twice into the VCSEL: along the first path, the selected LP state is reinjected after a time delay τ (polarization selective feedback, PSF), but along the second path it is fed back with a time delay τ_r after rotation of the polarization direction into the orthogonal one (crossed polarization reinjection, XPR).

We show that such a configuration leads to generate vectorial TLS. i.e. localized pulses appearing in each LP component with a high degree of anti-correlation, thus leaving the total output intensity constant (Fig. 1a).

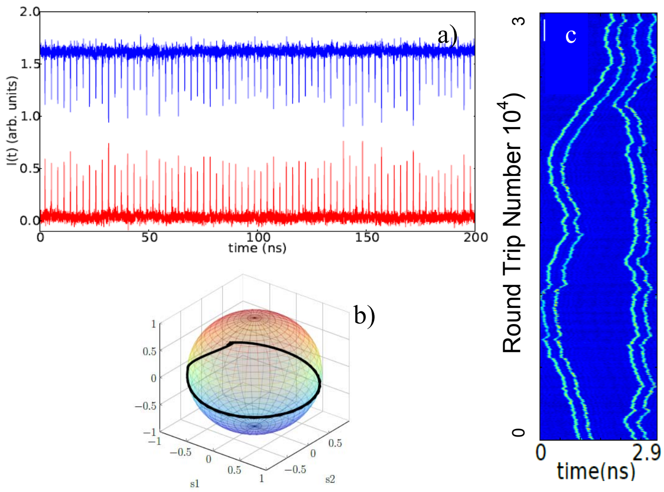

Fig.1 a): Time signal of the Y (blue) and X (red) polarization outputs when the VCSEL is submitted to XPR (rate 1.4%) and PSF (rate 0.6%). J=3.0mA, τ=2.9ns, τ_r =3.3 ns. b) Numerically calculated trajectory on the Poincare map in correspondence of a pulse. c) Space-time like diagram showing two independent molecules composed by two pulses each.

Theoretical analysis reveals that each pulse is associated to a polarization slip on the Poincaré sphere (Fig.1b). The repetition rate of these pulses is fixed by τ and, when the external cavity is long enough, several of them can be generated within one roundtrip, either as independent TLS or in bound entities (molecules). These two forms of TLS can be discriminated by recording their noise-induced motion within the external cavity as a function of the number of round trips (space-time like diagram), as shown in Fig. 1c). Different emission states coexist in parameter space, and the system may evolve from one to another in response to perturbations or parameter sweeps, in the latter case displaying a high degree of hysteresis. Observed states are: no pulses, a variable number of single-pulse TLS, two double-peak TLS (Fig. 1c), and a unique localized structure composed by three, four and up to seven –peaks.

III. TLS IN VCSEL COUPLED TO A SATURABLE ABSORBER

A laser amplifier is usually coupled to saturable absorber in order to obtain passive mode-locking (PML). The different dynamical properties of the SA and of the gain create a window for regeneration only around the pulse. We show that TLS can be generated in this system when: i) the trivial off solution is stable and it coexists with the mode-locked solution and ii) $\tau >> \gamma$. Haus background stability criterion for PML pulsation [6] indicates that condition ii) would necessarily lead to N-order harmonic mode-locking. Instead, we show that, upon proper parameters, condition i) may be verified and a large quantity of stable solutions becomes available, each one characterized by a variable number of pulses (ranging from zero to N) with variable arrangements. In these conditions mode-locked pulses becomes TLS and they can be individually addressed as bits for information processing.

The common settings for achieving PML in semiconductor lasers consider usually a cavity round-trip shorter than the gain recovery time $\tau < \gamma$; PML solution appears above the solitary laser threshold and exhibits a single pulse per round-trip (fundamental mode-locking). As the pump or the cavity length is increased, the so-called regime of harmonic mode-locking develops at the expense of the fundamental PML solution. Such transition can be understood via the background stability criterion, which is not verified anymore for the fundamental mode-locking. Further increases of the pumping current or of the cavity length lead to an increasing number of pulses N in a single round-trip, such that the newfound value of N becomes again compatible with the background stability criterion.

The scenario described above radically changes in the limit $\tau >> \gamma$, provided that the saturable absorber parameters are properly chosen. Our theoretical analysis reveals that the bifurcation to the PML solution becomes subcritical leading to coexistence of this solution with the zero emission one (off state). This change in the bifurcation scenario has a profound consequence on the mode-locked solutions: the fundamental PML solution becomes stable even in the limit $\tau >> \gamma$ and a large number of pulsing solutions with different number of pulses per round-trip become stable for the same parameter values. This multi-stability suggests that the harmonic mode-locked solution of maximal order becomes *fully decomposable*, since essentially any pulse of this solution can be set on or off. Accordingly, we show that information can be stored in the cavity as an all-optical buffer with a bit rate limited by the size of LS, i.e. approximately 1 Gb/s for typical parameters.

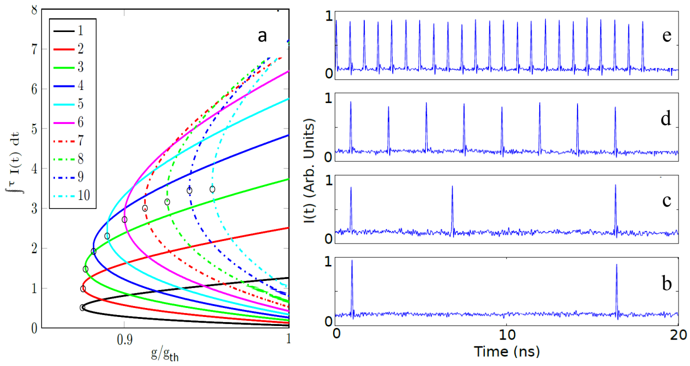

Fig. 2 a): Numerically calculated folding of several PML solutions having a different number of equally separated pulses per round-trip, for $\tau = 16\,\gamma$.
b-e): Coexisting time output traces (J=290 mA)

The results of our theoretical analysis are confirmed by an experiment considering a VCSEL coupled to a distant Resonant Saturable Absorber Mirror (RSAM). The VCSEL is lasing at 980 nm and its standalone threshold J_{st} is about 380 mA. The RSAM has 1% reflectance at cavity resonance which increases to 60% when saturated and its relaxation time is 1 ps. The VCSEL and RSAM temperatures are set for having the emission of the VCSEL resonant with the RSAM. In order to match the conditions for observing LS we set the cavity round trip τ=15.4 ns, corresponding to a free-spectral-range of 65 MHz. Moreover the VCSEL is biased at $J < J_{st}$. Laser mode-locked pulses are emitted at the fundamental repetition rate of 65 MHz, as shown in Fig. 2b. Several emission states with different number of pulses (from zero up to nineteen) per round-trip coexist for the same value of bias current (Fig. 2 b-e). Each state can be visited by sweeping properly the VCSEL current.

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