Excitability in a semiconductor laser with saturable absorber

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We show that a monolithic and compact vertical cavity laser with intracavity saturable absorber can emit short excitable pulses. These calibrated optical pulses can be excited as a response to an input perturbation whose amplitude is above a certain threshold. Sub-ns excitable response is promising for applications to novel all-optical devices for information processing or logical gates.

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Excitability is a non-linear dynamical mechanism underlying all-or-none responses to small perturbations in many biological (neurons, cardiac tissue), chemical (Belousov-Zhabotinsky reaction) and physical (driven mechanical pendulum, lasers, photonic crystals and amplifiers) systems. An excitable system has only one stable state and reacts to an external perturbation with a well-calibrated, nonlinear, "macroscopic" output pulse provided the amplitude of perturbation exceeds a given threshold. Otherwise, it returns to its stable state with a small linear response [1]. Well-known in neuronal dynamics [2], excitability was first demonstrated in optics in a CO_2 laser with saturable absorber (SA) [3]. In optical systems, the excitable response takes the form of a light pulse: a small optical perturbation above a certain threshold can trigger a large fixed amplitude output pulse. Over the past decade, research on excitability in optics has mainly focused on semiconductors, essentially due to the fast time scales and miniaturization capabilities of such materials. In this context, excitable dynamics was first reported in a semiconductor laser with optical feedback [4]. Excitability is believed to have an enormous potential for applications in photonics such as clock recovery, pulse reshaping and optical delay lines. Interestingly, excitable solitons have been recently proposed as protocols for the realization of all-optical logic gates [5]. From the fundamental point of view, it has attracted much attention due to the richness of both spatio-temporal and noise-induced excitable phenomena [6, 7]. Here we demonstrate ultrafast excitable dynamics in a semiconductor microcavity, namely a monolithic and compact VCSEL with intracavity SA.

Close to the excitable regime, an excitable system undergoes a transition to self pulsing behavior. This allows to distinguish between three types of excitable dynamics: in class I excitability, the frequency of self-oscillations is zero at the transition (or bifurcation) point whereas in class II excitability oscillations are born with non-zero frequency; class III excitability is related to a specific transition to Q-switch-like pulsing through a homoclinic bifurcation in lasers with SA [8, 9]. In semiconductor photonics, class I excitable regimes usually take place in microcavity lasers with injected signal [10, 11], or optical feedback [4, 12]. Integrated optical injection and feedback [13, 14] devices have received a particular attention in this context. On the other hand, class II excitability emerges from a competition between the fast electronic timescale and the slow thermal response in active semiconductor resonators. Typical semiconductor class II excitable systems are broad area optical amplifiers [15, 16]; more recently, class II excitability has been demonstrated in an active 2D photonic crystal band-edge resonator [17].

Among the different classes of optical excitable systems, class III excitability in semiconductor devices has two main advantages for applications: i) the pulse duration and the pulse rate are governed by the carrier recombination time in active nanostructures (such as quantum wells or quantum dots), which can potentially reach sub-ns timescales; and ii) no coherent light injection or holding beam are necessary to achieve excitability, which arises as a competition between gain and saturable absorption in an incoherently pumped device. The latter is also advantageous in the context of cavity solitons for which lasers with SA have already shown to be robust devices supporting localized structures [18,19]. In this work we show evidence of excitable dynamics in a monolithic, planar vertical cavity with integrated SA. To our knowledge, this is the first experimental realization of class III excitability -i.e. without coherent injection and/or feedback- in a semiconductor device. In the experiment, we use a specially designed, optically-pumped VCSEL with intracavity SA as described in [19] and whose structure is sketched in Fig.1. It is composed of two InGaAs/AlGaAs quantum wells for the gain medium, and one InGaAs/AlGaAs for the SA. The cavity resonance is targeted around 980nm and the whole non-periodic multilayer structure composing the back and front mirrors is optimized for efficient optical pumping in a 20nm window around 800nm. The sample is pumped thanks to a high-power, fibre-coupled laser-diode array emitting at 800nm. A mode-locked, Ti:Sapphire laser is used to provide external perturbations in the form of 60ps duration pulses with 12.5ns repetition period at a wave-

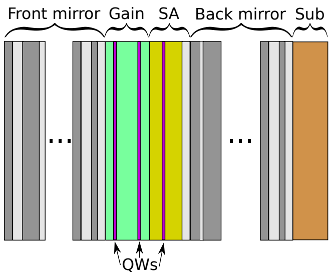

Figure 1. Design of the vertical cavity laser with SA used in the experiment. Sub: substrate; QW : Quantum-wells (see text).

length around 800nm. The pump spot size on the sample is 80μm with a top-hat shape whereas the local perturbation spot has a diameter of the order of 10μm . A high-speed avalanche photodiode with 90ps rise-time is used for optical detection combined with a 1GHz or 6GHz bandwidth digital oscilloscope. The sample temperature is controlled using a Peltier cooler and a feedback loop. The laser with SA is biased at a power below the onset of self-pulsing, at 90% of the homoclinic bifurcation [20] pump threshold. As shown in Fig. 2b, for low intensity perturbation pulses, the system remains in its stable state which is the non-lasing state. When the perturbation exceeds a critical threshold, a pulse is emitted whose FWHM width is in the sub-ns range (0.73ns in Fig. 2b-vi) and whose amplitude does not depend critically on the excitation one. The critical behaviour is checked by performing statistics on the output pulse amplitude following triggering events by the incoming pulses. We plot in Fig. 2a the mean amplitude of the response pulse $\langle R\rangle$ versus the mean power of the perturbation pulses $\langle P_0\rangle$, as well as their standard deviation σ. $\langle R\rangle$ and σ are scaled to the extrapolated value $\langle R\rangle_{ex}$ of $\langle R\rangle$ at the excitable threshold $\langle P_0\rangle_{ex}$. The excitable threshold is assumed to correspond to the perturbation power at the maximum of σ. The energy per pulse at the excitable threshold is 28nJ. A critical behaviour is evidenced by the abrupt change in the response amplitude when the intensity reaches the threshold. Moreover, σ increases dramatically at the threshold crossing because of finite dissipation in the system response resulting in a high sensitivity to noise. As the perturbation amplitude increases further, σ stabilizes and the response is more regular, which marks the calibrated nature of the output pulse. To assess our interpretation in terms of excitable response, we have performed numerical simulations of the system. The model is taken from [21] and is consistent with the well-known Yamada model of a semiconductor laser with SA [22]. A stochastic term is included to mimic spontaneous emission noise as in [8]. The adimensional equations are the following :

$$\begin{aligned} \dot{N}_1 &= -b_1(-\Lambda + N_1(1+I)) \\ \dot{N}_2 &= -b_2(\gamma + N_2(1+sI)) \qquad (1) \\ \dot{I} &= (N_1+N_2-1)I + R_{sp}(N_1+\eta_1)^2 + F_I(t) \end{aligned}$$

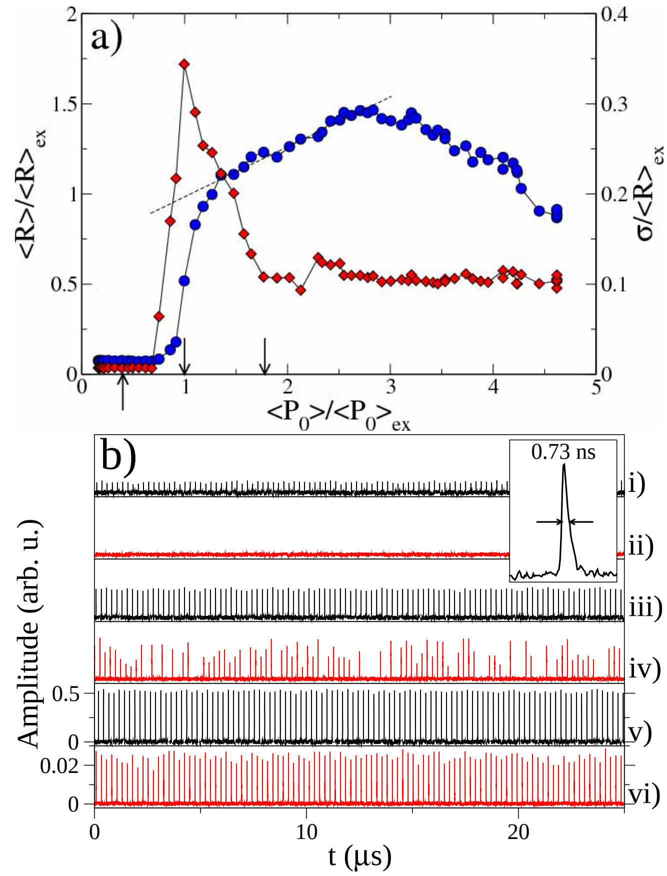

Figure 2. a) : Mean ($\langle R\rangle$, blue circles) and standard deviation (σ, red diamonds) of the peak amplitude of the laser response at 980nm versus mean power $\langle P_0\rangle$ of the input perturbation pulses at 800nm, scaled to their values at the excitable threshold $\langle P_0\rangle_{ex}$. b) : Time traces of the input perturbations (black) and system response (red) below (i,ii), close to (iii,iv) and well above excitable threshold (v,vi) ($\langle P_0\rangle/\langle P_0\rangle_{ex} = 0.40$, 1.00 and 1.78 resp.). Inset : output pulse zoom from vi) trace.

N_1, N_2 are proportional to the gain and SA carrier densities respectively, and I to the intracavity intensity. b_1, b_2 are the non-radiative recombination rates, Λ is the pump, γ is the linear absorption in the SA and η_1 is gain to mirror loss ratio at transparency. Time has been rescaled to the cavity photon lifetime, which is estimated to be 5.6ps. The parameter s is a ratio involving the differential gain/absorption coefficients $a_{1,2}$ and recombination rates $s = b_1a_2/b_2a_1$. If s is large enough ($s > 1 + 1/\gamma$ for $R_{sp} = 0$) the laser intensity versus pump curve has a "C" shape meaning the bifurcation at threshold is subcritical. Morevoer, it is observed that a larger differential absorption than differential gain, or a carrier recombination time faster in the SA [23] than in the gain medium generally favors the self-pulsing against the bistable regime. The former is true in semiconductor materials while the latter can somehow be tuned by temperature [19]. The spontaneous emission noise source term is proportional to R_{sp} and is of the bimolec-

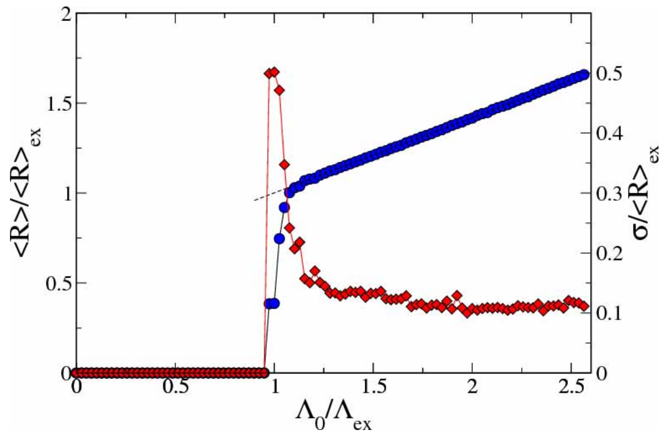

Figure 3. Scaled mean (blue circles) and standard deviation (red diamonds) of the response peak amplitude for the system of Eqs.1.

ular type. The associated Langevin force F_I is given by $F_I(t) = (N_1 + \eta_1)\sqrt{2R_{sp}I}\xi(t)$ where it is assumed that spontaneous emission noise principally comes from the pumped region since carrier density is much higher there. $\xi(t)$ is a white Gaussian noise with zero mean such that : $\langle\xi(t)\rangle = 0$ and $\langle\xi(t)\xi(t')\rangle = \delta(t - t')$. Note that for simplicity we did not include specifically bimolecular recombination terms in the carrier density equations since it does not affect the qualitative dynamical behaviour.

The equations are simulated with the Xmds package [24] and a fourth-order Runge-Kutta method. The parameters are chosen like in [21] such that $b_1 = 0.01$, $b_2 = 0.005$, $\gamma = 2$, $s = 10$, $\eta_1 = 1$, $R_{sp} = 10^{-5}$ [25]. They are consistent with the semiconductor system considered here. The introduction of the noise and spontaneous emission source terms slightly decreases the laser threshold from 3.0 without these terms to approximately 2.9. Above threshold, the system is self-pulsing. The system is fed with time-periodic perturbations of amplitude Λ_0, width 20 and period 100, and is integrated up to 100000 time units in order to have a sufficient statistics. The bias pump is fixed below threshold at $\Lambda_b = 2.7$. We have analyzed the temporal trace using the same procedure that has been used to analyze the experimental results. The mean response $\langle R\rangle$ and its standard deviation σ are displayed in Fig. 3. There is a good agreement between the numerical simulation and the experimental results. The noise present in the system is indeed responsible for the relatively smooth transition below and above the excitable threshold as observed in the experimental data.

In conclusion we have shown excitable response in an original and compact design of a vertical cavity laser with intracavity SA. This kind of response may be interesting in view of innovative optical signal processing applications, e.g. for optical reservoir computing [26]. Moreover, the vertical cavity design presented here constitute a compact platform for realization of excitable and nonlinear wave propagation studies in semiconductor micro and nanophotonic devices.

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