Cavity-solitons switching in semiconductor microcavities

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Cavity solitons (CSs) are localized structures appearing as intensity peaks in the homogeneous background of the field emitted by a nonlinear microresonator. We experimentally and theoretically study the switch-on process of cavity solitons in semiconductor amplifiers. The switching time has two contributions: a lethargic lapse following the application of the switching pulse and a characteristic buildup time. While the latter is not significantly affected by the control parameters, the former crucially depends on them. Optimization of the parameters leads to a switch-on time of less than one nanosecond, assessing the CS competitiveness for all-optical applications.

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Recently there was a lively interest on localized structures in spatially extended systems [1–3]. Experiments on localized structures have been carried out in a wide variety of systems: granular media [4], gas discharges [5], magnetic materials [6], and, more recently, in optics [7–11].

The search for localized structures in optics is particularly interesting for the possibility of developing practical devices like optical memories, shift registers, and all-optical processors [12–14]. Cavity solitons (CSs) [11] are single-peaked localized structures that arise in the transverse plane of optical cavities with nonlinear media. As for every localized structure, the CS width, shape, and position are not determined by the boundary conditions of the cavity. Moreover, CSs exhibit the remarkable property of being individually addressable which makes them very attractive for applications. Today, the formation of CSs in semiconductor materials [15–17] is a current research focus for the possibility of minimizing the size of the optoelectronic devices. We recently showed the existence of CSs in a vertical cavity semiconductor amplifier [18,19] driven by a coherent field (holding beam, HB) and full optical control of CSs by applying a local optical perturbation (writing beam, WB).

In this work we experimentally and numerically study the CSs switch-on process, which is a highly relevant feature to applications since its duration determines the maximum speed at which the device can be addressed. On the fundamental viewpoint, speed rates are linked to the local and global dynamics of the nonlinear system [20]. An experimental confirmation of the character of such phenomena was, to the best of our knowledge, still missing.

We show that the CS switching process is characterized by the sum of a lethargic time, during which the intensity does not grow significantly, and by the buildup time of the CS intensity. While the second one is not significantly affected by the control parameters, the first one is strongly influenced by the relative phase ϕ of the WB with respect to the HB, showing the crucial role that the field phase plays in the properties of CSs. We also show that the delay time decreases upon an increase of the amplifier pumping current J as well as of the WB and HB powers.

Our experimental setup is similar to the one described in Refs. [18,19]. It consists in a large area vertical cavity surface emitting laser (VCSEL, 150-μm diameter [21]) operated as an amplifier. We inject along its vertical axis a coherent, 200-μm-wide CW field (HB), generated by a tunable laser; the HB power is controlled by an acousto-optic modulator (AOM) together with a polarizer. In Ref. [18] we demonstrated that, under properly chosen parameters, CSs may be switched on and off by injecting a local perturbation in the form of a narrow coherent (10-μm-wide) beam (WB), superimposed to the HB. For a control pulse in phase with the HB (ϕ=0 rad), the CS switches on, and it can be switched off by injecting again the WB pulse with $\phi=\pi$ rad.

In order to analyze the switch-on time of the CS after the application of the WB, we insert a Pockel's cell (electro-optic modulator, EOM) on its path to the VCSEL cavity. We drive the EOM in order to generate WB pulses of 100 ns width, rise time (10–90 %) $\tau=575\pm50$ ps with a repetition rate of 1 KHz. However, the bistable character of the CS ensures that once it is switched on, it persists even when the WB is gated off by the EOM. In order to switch off the CS before the arrival of the next pulse of the WB we could change the phase of the WB with respect the HB but, in our setup, this is done by a piezoelectrical actuator whose modulation response is not fast enough for our needs. Instead, we

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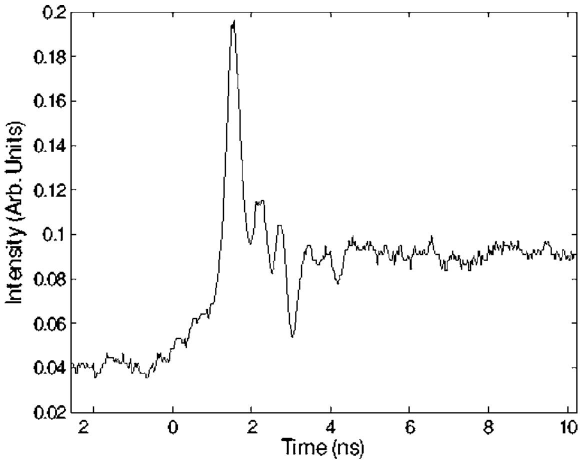

FIG. 1. Switch-on process of a CS for P_{hb}=7.8 mW, P^{s}_{wb}=160 μW, J=270 mA, ϕ=0 rad. The WB pulse duration is 100 ns. The WB is applied at the time t=0.

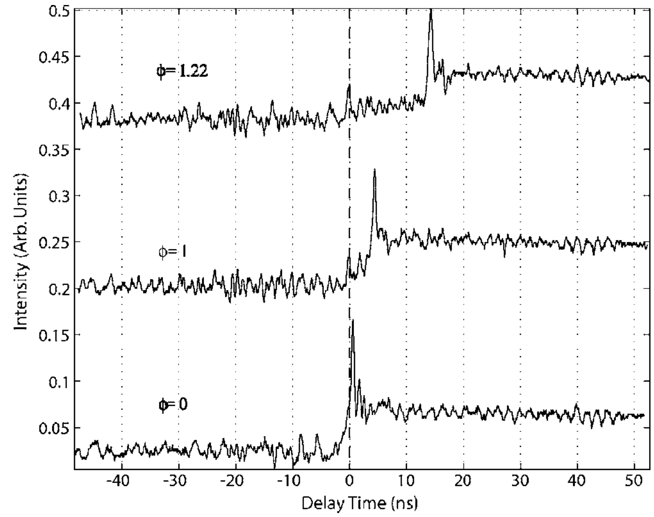

FIG. 2. Rising fronts of CS for different values of ϕ. The other parameters are J=271 mA, P_{hb}=7.8 mW, P^{s}_{wb}=145 μW. The curves for ϕ=1 rad and ϕ=1.22 rad have been displaced vertically of 0.18 units and of 0.36 units, respectively.

reset the CS by gating off the HB, using the AOM that sets the HB power. The periodic sequence of events is structured in this way: we first gate on the HB, then we gate on the WB switching the CS on, then we gate off the WB, and finally we gate off the HB switching the CS off. The two gates are delayed by 50 ms, long enough for the system with injection to reach the stationary state before applying the addressing beam.

An avalanche photodiode (180-ps rise time) detects the power output over a spot 20 μm wide, at the same transverse location ("target") where the WB addresses the CS. The detector output is analyzed by a 6-GHz analog bandwidth scope (Le Croy WaveMaster).

In order to switch a CS on, the WB energy (E_{wb}) must reach a critical value E^{C}_{wb} that induces the system to locally jump from the homogeneous solution to the CS solution. The WB power P_{wb} as a function of time can be described in this way: for $0<t<\tau$, $P_{wb}(t)$ can be approximated with a linear growing function of time with a slope given by the stationary value of $P_{wb}(P^{s}_{wb})$ divided by the rise time τ of the EOM. For $t>\tau$, $P_{wb}(t)=P^{s}_{wb}$. Then, the total energy injected into the system in a time Δt after the application of the WB is given by $E_{wb}=\int_0^{\Delta t}P_{wb}(t)dt$.

After a critical time Δt_c (delay time), the critical energy is reached ($E_{wb}=E^{C}_{wb}$) and the buildup of the CS starts. The value of E^{C}_{wb} depends on the system parameters, namely the HB power, the VCSEL current J, and the detuning θ between VCSEL cavity resonance and the HB frequency.

The range of variation of these parameters, in the region where CSs exist, is limited by the following criterion: the corresponding E^{C}_{wb} must be large enough to avoid that the CS switches on spontaneously (noise-induced switching) and low enough to be attainable by our experimental setup (the largest value for P^{s}_{wb} is about 160 μW). In Fig. 1 we show the output intensity at the target region vs time, during the injection of the WB pulse of P^{s}_{wb}=160 μW into the VCSEL. The switch-on process is characterized by a high intensity peak followed by damped oscillations and stabilization of the CS intensity around a stationary value. The period of the oscillations is 0.9±0.1 ns. The switch-on process (from 10% to 90% of the switching peak intensity) takes 800±50 ps since the application of the WB, and can be divided in two stages: a first stage where the intensity growth is slow, followed by a steep front rise of 520±50 ps. The former is significantly affected by the system parameters and WB power, as opposed to the latter which is not. This lethargic stage is related to the experimental time Δt_c necessary for injecting into the system the critical energy and therefore it depends critically on P^{s}_{wb} and on E^{C}_{wb}. The lethargic stage can also be a feature of the finite response of the system itself, in this case it cannot be arbitrarily reduced decreasing Δt_c. Figure 1 has been taken in the optimal experimental conditions in order to minimize Δt_c: P^{s}_{wb} is set to the maximum value available in our experimental setup, while the system parameters have been set in order to minimize E^{C}_{wb}, compatibly with the requirement of avoiding noise-induced CS switchings. The rise time obtained in Fig. 1 can be considered an overestimation of the fastest rise time of CS because we are at the limits of our experimental possibilities. On the other hand, the duration of the steep CS front (520±50 ps) cannot be changed and therefore it is the lower limit of the CS rise time. If the phase difference ϕ between HB and WB is varied, the efficiency of the energy injection through the WB is diminished, since the interference with the intracavity field, whose phase is fixed by the HB phase, is not fully constructive. In Fig. 2 we plot the switching process for different values of ϕ. We observe that the lethargic stage increases up to 15 ns, shifting the rising front which, as explained, remains unchanged to about 0.5 ns. The lethargic delay as function of the phase ϕ is plotted in Fig. 3(a). For $|\phi|>1.22$ rad, the CS does not switch on anymore. The measured uncertainty for the points in Fig. 3(a), due to the noise present in the system, is less than 2 ns.

Fixing the phase ϕ=0 rad, the lethargic delay increases when decreasing the WB power P^{s}_{wb}, since the critical duration of injection Δt_c necessary to reach the energy E_{wb}

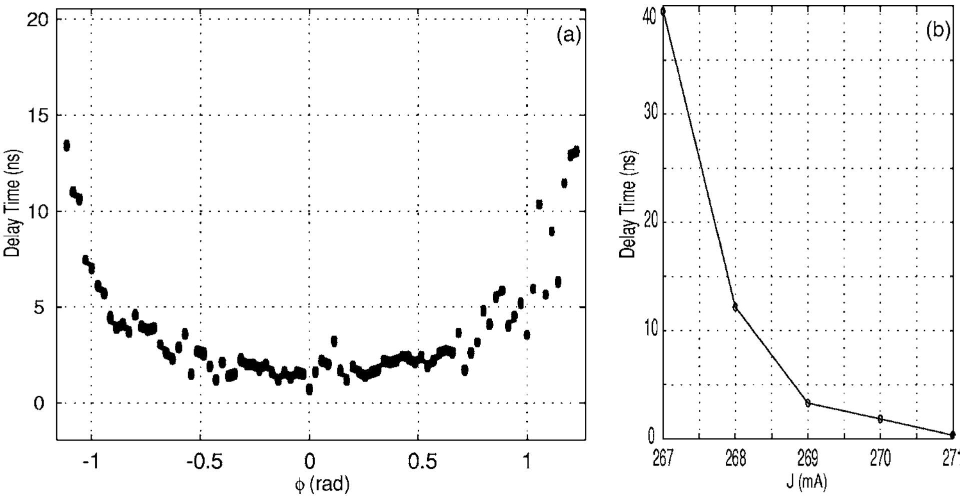

FIG. 3. (a) Lethargic time as a function of ϕ; the other parameters are as in Fig. 2. (b) Lethargic time as a function of J, for $\phi=0$ rad. The other parameters are as in Fig. 2.

$=E^{C}_{\mathrm{wb}}$ increases, so does the lethargic time. For $J=270$ mA and $P_{\mathrm{HB}}=7.8$ mW, it spans from around 1 ns when $P^{s}_{\mathrm{wb}}=160$ μW to 30 ns when $P^{s}_{\mathrm{wb}}=10$ μW. Fixing $\phi=0$ and $P^{s}_{\mathrm{wb}}=160$ μW, the lethargic time is affected by the pumping current of the VCSEL and it increases as J decreases as a consequence of a variation of E^{C}_{wb} [Fig. 3(b)]. Again, the rising front of the CS remains unchanged versus variations of J. The same applies for increasing HB power: for $J=271$ mA and $P^{s}_{\mathrm{wb}}=10$ μW, the delay time spans from a negligible value when $P_{\mathrm{HB}}=27$ mW to 25 ns when $P_{\mathrm{HB}}=15$ mW.

Simulations of the switch-on dynamics of the CS were performed, adopting the model of Refs. [16,19]. The inset of Fig. 4 shows the plane-wave (PW) stationary curve with the coexisting stable CS branch as predicted by the stability analysis. By injecting a narrow WB pulse we can access the CS branch and create a soliton. We model a Gaussian HB with waist $\sigma_{\mathrm{HB}}=200$ μm, as in the experiment, and a maximum amplitude $E_I=0.75$ in our scaled units. Then we add a narrow Gaussian WB at an arbitrary position with a waist $\sigma_{\mathrm{WB}}=10$ μm. The duration and temporal shape of the WB pulse is the same as in the experiment: the stationary value (P^{s}_{wb}) is reached with a linear growth and a rise time of 560 ps (10–90 %), and then the WB remains stationary for 100 ns. All simulations are performed after adding white-noise terms to the field and carrier density equations to simulate noise in the injected field and current, respectively, as in Sec.

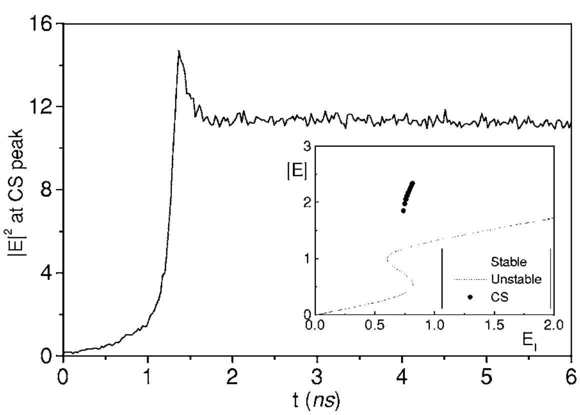

FIG. 4. CS switch-on process, numerical simulation. Parameters (in scaled units) are cavity detuning $\theta=-2$, normalized injected current $J=2$ (laser threshold is $J=2.11$), normalized WB amplitude $E_{\mathrm{WB}}=0.75$, WB phase relative to the HB $\phi=0$ rad. Small inset: homogeneous steady state (solid stable, dashed unstable) and CS as a function of the HB amplitude, for the parametric case in study. From now on, the HB amplitude is taken $E_I=0.75$.

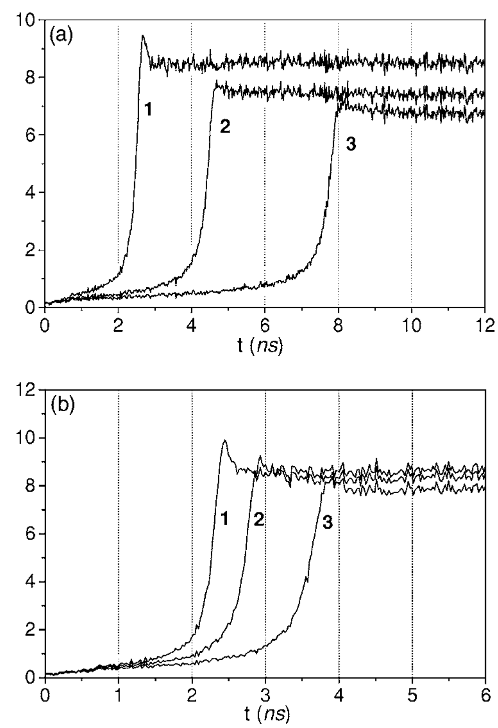

FIG. 5. CS switch-on process, numerical simulation. (a) The intensity at the CS peak is displayed as a function of time, for different values of ϕ: $\phi=0$ rad (curve 1), $\phi=1$ rad (curve 2), and $\phi=1.22$ rad (curve 3). Other parameters are $\theta=-2$, $J=2$, $E_{\mathrm{WB}}=0.4$. (b) The intensity at the CS peak is displayed as a function of time, for different values of J: $J=2.01$ and $\theta=-2.05$ (curve 1); $J=1.99$ and $\theta=-1.95$ (curve 2); $J=1.96$ and $\theta=-1.8$ (curve 3). The cavity detuning parameter θ has been slightly decreased as J is increased, to simulate the thermal redshift of the cavity resonance. Other parameters are $\phi=0$ rad, $E_{\mathrm{WB}}=0.4$.

E of Ref. [16]. It is worth noting that, as in the experiment, the amount of noise included in the equations is not enough to cause a spontaneous switch on of the CSs.

In Fig. 4 we report the intensity of the intracavity field at CS center during the injection. A delay time of about 1 ns followed by a steep front of about 400 ps characterize the switch-on process, in excellent agreement with the experiment. At difference from the experimental result, the overshoot peak is much less pronounced, and the following relaxation oscillations are absent.

The second step is to evaluate the effect of parametric changes on the buildup and on the delay times. The steep front duration mainly depends on intrinsic parameters of the system, like carrier recombination rate, and cavity loss rate which cannot be varied in the experiment. The delay time instead is strongly affected by the control parameters. First of all, we vary the relative WB-HB phase ϕ. As in the experiment, the optimal phase is zero, and the delay time increases with ϕ. In Fig. 5(a) we show the switch-on process for increasing values of ϕ. When $\phi=1.5$ rad, more injected power is necessary to create a CS and the delay time reaches 36 ns.

As for the variation of the current J, it must be said that simulations in our simple model yield an *increasing* delay time upon increasing J, as opposed to the experimental evidence. The reason is that this model does not include the experimentally observed redshift of the cavity resonance with injection current, which in our device is about -0.7 GHz/mA. In our scaled variables, this is equivalent to a variation of θ of -0.05 for a current increase of 0.01. When we include this phenomenological dependence of θ on J [22], our model correctly predicts a delay time decrease versus increasing current, as shown in Fig. 5(b).

Finally, we could confirm that decreasing WB and HB intensities cause the delay time to increase, while leaving practically unchanged the buildup time, as in the experiment. In particular we could confirm that the delay time varies considerably, from a negligible value to more than 20 ns (for $E_{\mathrm{WB}}=0.75$ and $E_{\mathrm{WB}}=0.15$, respectively).

In conclusion, we have reported an interesting analysis of the switch on of CSs in semiconductor microcavities as a function of parameters. The results presented show that the CS switch-on time depends on current injection level, on the phase difference between the control beam and the HB, and on the WB and HB powers. Therefore CS control can be realized on time scales of less than one nanosecond, which makes these objects attractive for competitive applications.

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