Incoherent and coherent writing and erasure of cavity solitons in an optically pumped semiconductor amplifier

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Cavity Solitons in semiconductor amplifiers were, from the beginning of their study and observation, obtained either spontaneously or in a controlled manner by local coherent excitation. We describe in this letter two experiments demonstrating coherent and, for the first time, incoherent writing and erasure of cavity solitons in an optically pumped vertical-cavity semiconductor amplifier by short optical pulses.

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Cavity Solitons (CS) are self-localized spots forming in the transverse plane of a nonlinear cavity. They have been observed in various macroscopic systems [1,2], and predicted [3] and observed [4] in semiconductor systems too. They form in a spatially extended, bistable and modulationnally instable system and appear generally as bright spots sitting on a dark background. CS can be independently addressed with a control beam, and can be manipulated with the aid of phase or amplitude gradients of some control parameters. These peculiar properties make them good candidates for all-optical information processing applications. They can be thought of as logical bit units for parallel information processing, with reconfigurable capabilities. For that purpose, semiconductor materials reveal particularly challenging for the timescales (1 ns or less) and spatial scales ($\sim 10\mu$m) involved. The writing and erasure of CS represents a first key step in the manipulation of these bits of information and will be the subject of this paper.

Switching of spatial structures has already been discussed by several authors [4–6,9,10]. In Ref.6, a multiple quantum well microcavity is injected by a gaussian coherent field of 50 μm in diameter. Incoherent switching on and off of dark states (in reflection) is observed by application of nanosecond pulses with orthogonal polarization with respect to the injected field. In this regime however, the defocusing nonlinearity requires high intensity driving field for spatial structures to appear that limits the working diameter and induces a thermally driven dynamics with slow response times [8]. Moreover the tight Gaussian excitation creates high gradients of the parameters that hinders self-localization effects. In Ref.7 and in a similar system, the spontaneous switching of a unique spatial structure is shown with and without an optical pump below transparency in addition to the gaussian coherent injection. However, writing or erasure of the bistable spatial structure by an external beam is not studied and the same restrictions on the tight pump and excitation apply. In a different system, coherent CS switching on and off has been demonstrated in a 150 μm diameter pumped vertical-cavity semiconductor amplifier [4,9,10]. The cavity is electrically pumped below threshold but above transparency and coherently injected close to the cavity resonance frequency by a broad, external driving field (holding beam HB) of wavelength λ_i. In this regime, the driving field intensity needed for nonlinear spatial structures to appear is substantially decreased thanks to the focusing optical nonlinearity, hence thermal effects can be greatly reduced. In addition, the lateral extent and uniformity of the system allows for self-localized states to appear. Part of the driving beam is used to locally excite in phase, or out of phase, the transverse plane of the cavity and lead to the creation or annihilation of the CS. However the incoherent switching of CS in the amplifying regime has not been shown so far. The possibility to excite a CS with an incoherent beam can reveal very interesting since it eliminates the need for a controlled phase mismatch between the excitation and the driving field. In this paper we report on the incoherent and coherent writing and erasure of CS in a broad-area, optically-pumped, vertical cavity semiconductor amplifier.

This result has been obtained in an optically pumped microresonator thanks to an original cavity design [11]. Optical pumping is used here in order to improve the uniformity of the pumped region and to further reduce

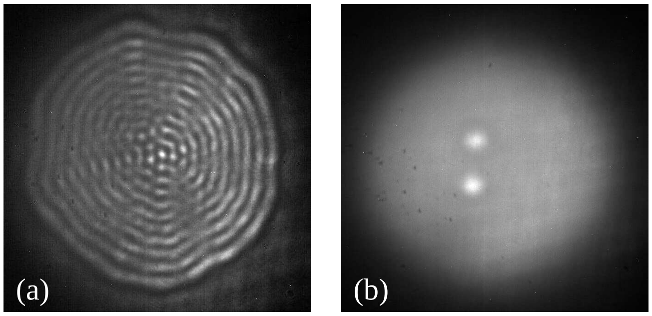

Figure 1. Near-field images of the reflected intensity for an optical pump diameter of $120\mu m$ and a $\sim$50mW HB power. (a): regular pattern ($\lambda_i = 888.38$nm, $I_p = 38$kW/cm^2). (b): two self-localized spots ($\lambda_i = 888.23$nm, $I_P = 14$kW/cm^2).

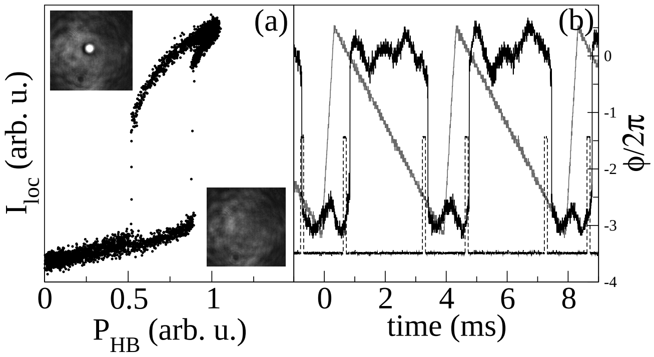

Figure 2. (a): local intensity at a CS (I_{loc}) vs HB power. Inset: corresponding near-field images in the upper and lower branches. (b): triggered coherent writing and erasure of a CS. Dark line: I_{loc}, dashed line: 100ns pulse trigger (rising edge) and grey line and right axis: phase mismatch ϕ (see text). Parameters are $\lambda_i = 883.09$nm, $I_P = 39$kW/cm^2 and $P_{HB} \sim 60$mW.

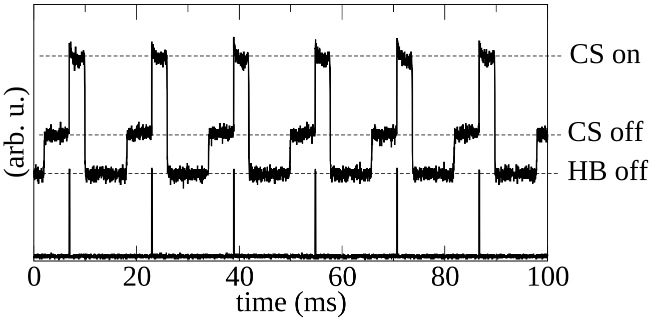

Figure 3. Triggered incoherent switching-on of a CS with a local 60ps writing pulse. Upper trace: local intensity at the CS. Lower trace: 60ps writing pulse trigger. Parameters are similar to those of Fig.4.

the heat produced by the pumping.

The cavity is composed of two aperiodic AlAs/AlGaAs mirrors designed for efficient optical pumping at 800nm. As a result, a pump window created on the high energy side of the multilayer mirror stop-band allows optical pumping over a 20nm spectral width with a maximum pump absorption. The active zone is composed of a bulk GaAs layer, surrounded by two AlGaAs absorbing spacers. The total cavity has a resonance around 880nm. The cavity is first grown upside-down by metal-organic chemical vapor deposition. The sample is then bonded onto a SiC substrate using a AuIn$_2$ layer. After etching away the GaAs substrate, we finally obtain a cavity with optimized pumping and heat dissipation, which are crucial requirements if one wishes to pump large diameter cavities [12]. The sample temperature is controlled by a Peltier element and a feedback loop at temperatures close to 275K with a stability of about 10^{-2}K. A 800nm high-power fiber-coupled laser diode array provides a uniform pump intensity of several Watts. The output facet of the optical fiber is then imaged onto the sample so as to form a $120\mu m$ or $70\mu m$ diameter pump region, with good uniformity. The laser threshold is crossed for a pump intensity $I_P \sim 38$kW/cm^2 in the case of a $70\mu m$ pump diameter, which is consistent with standard GaAs material parameters, and mirror reflectivities of 0.986 and 0.995 for the front and back mirrors respectively. However, due to a much stronger heating, laser action is not reached with that pumping intensity and a $120\mu m$ pump diameter. Small signal amplification measurements performed with a local probe indicate that amplification is present over the whole cavity resonance for a pump at least equal to 18kW/cm^2. The pump power at transparency is not known precisely but can be estimated around 10kW/cm^2. A broad coherent beam produced by a Ti:Sa laser is then injected onto the sample. The near-field of the sample is re-imaged on a CCD camera and a fast detector (90ps risetime) for local dynamical measurements. When the injection wavelength λ_i is blue-detuned with respect to the cavity resonance, the formation of broad patterns is observed (Fig.1a). These patterns are well known in this kind of system [13, 14] and show spontaneous symmetry breaking with hexagonal structures at the center and boundary-induced circular structures at the borders. In some parameter ranges, the pattern reduces to one or several self-localized spots (Fig.1b), with no apparent symmetry, and whose characteristic size is clearly independent of the boundaries of the system or of the specific set of parameters used. When the HB power P_{HB} (fig.2(a)) is varied, a hysteresis loop appears in the local response of the system between the ON-state, when the spot is present, and the OFF-state when it is absent, establishing the bistable character of the spots. The broad hysteresis is a consequence of the fact that the system is operated in the amplification regime. A very similar scenario happens when varying slightly the pump power around a constant bias (to avoid thermal effects as much as possible) instead of the HB intensity, however in that case the hysteresis is much smaller.

In a first experiment, we set the system close to the center of the local bistability cycle. The pumped diameter is $70\mu m$. Part of the HB is reconditioned to give a 10μm diameter spot in the sample plane. The phase mismatch between the HB and the local excitation beam (writing beam) is controlled thanks to a mirror mounted on a PZT. An electro-optic modulator is placed on the writing beam path to deliver 100ns width pulses. The writing beam power on the sample is of a few milliwatts. According to the phase difference ϕ between the two coherent beams, the local pulse adds up or subtracts to the HB intensity. By ramping the PZT and by triggering appropriately the writing pulse, the local disturbance switches the CS on and off repeatedly (see fig.2(b)). Indeed it has been shown theoretically and experimentally [10] that CS switch on can happen over a range of phase differences and writing beam intensities with an associated switch on delay. The smallest intensity is

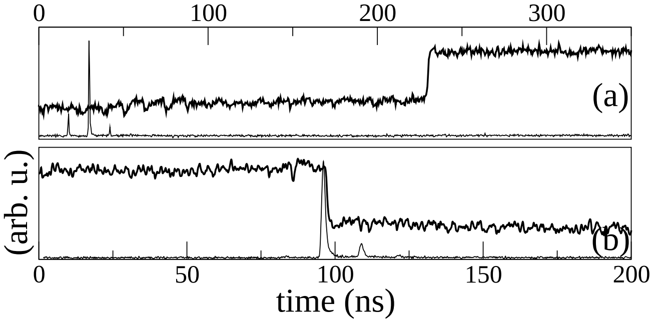

Figure 4. Fast incoherent writing (a) and erasure (b) of a CS by a triggered 60ps pulse. Thick line: local intensity at the CS. Thin line: writing/erasure pulse. The parameters are: $\lambda_i = 876.95\text{nm}$, $I_p = 26\text{kW/cm}^2$ and $P_{HB} \sim 65\text{mW}$.

associated with a zero phase difference and the shortest delay. The jitter in the CS switch on and off (fig.2) is however ascribable to a mechanical hysteresis in the PZT displacement, given the very different timescales at stake (ms versus ns for the switch on delay). The switch time is very fast, of the order of 1 ns.

In a second experiment, we replace the coherent writing beam by a picosecond Ti:Sa laser operating close to 795nm, a wavelength compatible with the sample's pumping window, and delivering triggerable 60ps pulses. The local excitation is obtained by mixing this beam to the pump beam with a beam splitter and imaging it on the sample surface to a diameter comparable to the one used in the latter experiment. We show (fig.3) that triggered CS switching-on is possible as in the coherent excitation case. A mechanical shutter erases the CS by shutting down the HB after each writing pulse. The minimum average power required is of the order of 1mW. In this type of excitation, the pulse creates carriers at high energy that cascade very rapidly to the bottom of the bands. By contrast to the coherent excitation, writing is initiated by the local excess of carriers. The 200ns delay in the CS switch-on (fig.4a) can be attributed to a local thermal effect or have a dynamical origin. In the first case, local excess of carriers locally heat the material, resulting in the displacement of the hysteresis cycle and in the switch-on delay. In the second case, noncritical slowing down that has already been observed in this kind of system [16] can also result in large delays. Surprisingly, we could also erase incoherently the CS as shown on fig.4b. However in that case switching-off is obtained by setting the pump bias away from the center of the hysteresis cycle, closer to the switch-off threshold, and we could not in the same experiment switch-on and off CS repeatedly. The exact mechanism by which switching-off occurs is currently under investigation. A carrier-induced index of refraction change could be responsible for an increase of the switch-off threshold for the HB intensity as observed in Ref.15 in a simple flip-flop semiconductor amplifier. Local heating could also have similar effects, limiting the device bandwidth, but the absence of delay in the erasure of a CS seems to indicate a fast mechanism, based on the carrier dynamics.

The localized spots generally appear in the central zone of the cavity, where a pump-induced transverse thermal gradient is present. The center of the pumped zone, where heating is more pronounced, has thus a red shifted cavity resonance which translates into a maximum of the field-cavity detuning, attracting the localized spot. Cavity resonance gradient combined to the relatively narrow parameter space region where bistable, self-localized spots can appear make that CS cannot be written and erased at any transverse position of the cavity. However, we could independently excite too nearby localized spots in sequence by a an incoherent excitation, thus demonstrating their CS character.

In conclusion we have shown the fast coherent and, for the first time, incoherent switching on and off of cavity solitons in a vertical cavity surface optical amplifier. Incoherent writing and erasure of CS opens new perspectives for optical information processing with CS as it greatly reduces the requirements on the writing beam.

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