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Fast manipulation of laser localized structures in a monolithic vertical cavity with saturable absorber

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Abstract We show the spontaneous and controlled formation of bistable and localized laser spots in the transverse section of a monolithic vertical cavity laser with a saturable absorber. Successive incoherent writing and erasure is obtained up to 80MHz repetition rate with a 60ps localized excitation. We also show the formation of clusters of laser localized states. All these observations are in good qualitative agreement with existing models.

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1 Introduction

After the first demonstrations of cavity solitons in semiconductor optical amplifiers [1,2], much efforts have been devoted towards finding simpler schemes and implementations to observe cavity solitons. Of such schemes, cavity soliton lasers occupy a primordial place. Recently, demonstrations have been reported in a vertical cavity laser with external feedback grating [3], and mutually coupled, vertical cavity lasers [4]. Both these schemes make use of external cavities. We propose a more integrated implementation making use of a monolithic vertical cavity laser with intracavity saturable absorber (SA). This allows a system more compact, more immune to mechanical vibrations or alignments problems, and readily comparable to existing theories that deal with single longitudinal mode systems.

Cavity soliton lasers are broad area devices able to sustain self-localized micro-lasers. These micro-lasers must share, in principle, the same properties as their counterparts in amplifying systems, that is to say cavity solitons in these systems are stationary, individually controllable optical structures. Their size and shape are fixed by the system parameters and one can excite or shut them down at any transverse location of the system. Although not yet demonstrated, laser cavity solitons can also be put into motion in appropriate intensity gradients. A first result in that direction is presented in [5]. All these properties may be exploited for achieving new functionalities in the field of all-optical processing of information.

From a theoretical point of view, cavity solitons are dissipative optical solitons appearing in the transverse plane of a broad area, nonlinear cavity. Their existence is often linked to the presence of bistability, or multistability [6], between a stable, uniform, background and a pattern forming instability . This regime can be obtained through coherent injection with a holding beam in the amplifying (or slightly above threshold [7]) regime, with a wavelength selective feedback or in the laser regime with a SA.

The latter system has been extensively studied theoretically and numerically in the seminal work on laser autosolitons (see e.g. [8] and references therein) and later on in semiconductor systems in [9,10]. It is shown that stable laser localized states can appear in the laser regime but close to threshold, along with a great variety of higher-order structures. With respect to systems making use of optical injection, cavity soliton lasers have, in addition to being individually manipulable sources of micro-lasers, the obvious advantage of being much simpler to operate since they only need one source of (incoherent) pumping. This pumping can be provided either through electrical injection, or as we shall use, optical pumping. The advent of cheap, high-power fiber coupled sources makes these ones more and more interesting for applications. Moreover, they allow to easily shape optical injection and to obtain a good uniformity of the pump with simple means. Since no special processing is required, we expect also less defects to be created in the structure, and this reveals particularly useful in this context : localized states are known to be very sensitive to defects and tend to get trapped at their location [11,12]. At last, optical pumping allows us to design a monolithically integrated VCSEL with intracavity saturable absorber. A careful engineering of the cavity is performed in order to optimize the pump efficiency and to minimize the generation of heat into the sample [13]. In the following we first describe our sample and the ex-

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perimental setup we used. We then present experimental results showing the formation of bistable, localized laser spots and show their basic, fast, optical manipulation with an external beam.

2 Experimental setup and results

Our sample consists in a vertical-cavity surface emitting laser (VCSEL) that was grown by metal-organic chemical vapor phase deposition. The details on the design of the structure can be found in [13]. Basically, the device is composed of optimized back and front multilayer mirrors sandwiching an active zone with two $In_{0.2}Ga_{0.8}As$/-$Al_{0.05}Ga_{0.95}As$ quantum wells acting as a gain material and one $In_{0.2}Ga_{0.8}As/Al_{0.22}Ga_{0.78}As$ quantum well acting as a saturable absorber. Both quantum wells are grown for a nominal 980nm peak photoluminescence in the lasing conditions. The quantum wells' nonradiative recombination rates have been measured by time-resolved photoluminescence and are found to be respectively 1.2 and 1.6ns for the gain and saturable absorber. The multilayer mirrors are composed of alternating $Al_{0.22}Ga_{0.78}As$/-GaAs layers giving a nominal 0.999 and 0.996 back and front mirror reflectivities and a 5ps photon lifetime.

The experimental setup is shown in Fig.1. The VCSEL temperature is tuned and regulated by a Peltier cooler and a feedback loop. The pump beam is delivered by a high-power, fiber-coupled, laser diode array emitting around 800nm. The output facet of the multimode 800-µm-diameter fiber is imaged onto the sample surface to a 70-µm-diameter disk thanks to a microscope objective (MO). The pump excitation is then mostly uniform on this area and has a top-hat shape. The intensity reflected by the sample is then analyzed by a CCD camera (CCD), a 5GHz avalanche photodiode (APD) and an optical spectrum analyser (OSA, Yokogawa). Another photodetector (bandwidth 15MHz) monitors the pump beam intensity that can be set by an arbitrary waveform generator (SG). The generator output consists in a small amplitude ramp with a period of 1ms on top of a larger constant bias. A 1GHz bandwidth digital oscilloscope acquires the signals from the different detectors.

Different experimental conditions can be obtained by changing three parameters (that are not fully independent) :first of all, due to the fact that a small wedge is introduced into the cavity because of the growth process, a variation of the operating location on the sample implies a small change of the cavity resonance. However this wedge does not affect in the same way the quantum wells (their bandgaps vary little on the whole sample's surface), thus a change in the operating location on the sample's surface corresponds to a detuning between the cavity resonance and the gain and absorption bandgaps. Then, temperature also influences the cavity resonance by thermal expansion of the sample and thereby modification of the length of the cavity. It also

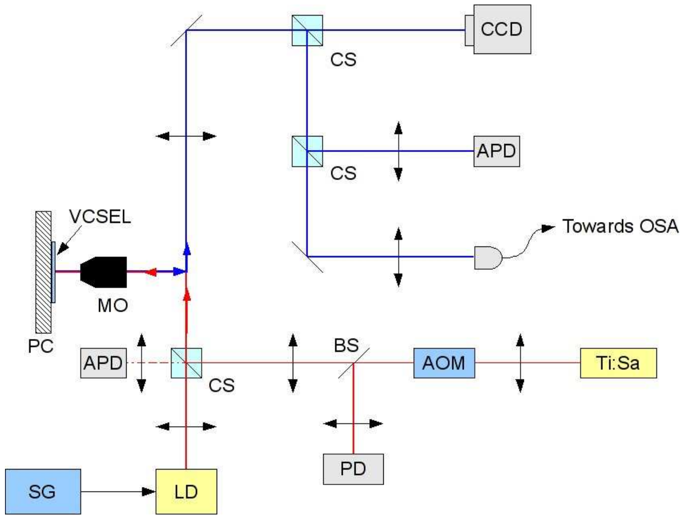

Figure 1: (color online) Experimental setup. LD : laser diode, SG : signal generator, Ti:Sa : Titanium Sapphire laser, AOM : acousto-optic modulator, PD : photodiode, APD : avalanche photodiode, CS : cube splitter, BS : beam splitter, MO : microscope objective, PC : Peltier cooler, CCD : CCD camera, OSA : optical spectrum analyzer.

modifies the position of the gain and saturable absorber material bandgaps and thus changes the index of refraction of each layer composing the sample. Increasing the temperature redshifts both cavity resonance and gap position. Finally, the aforementioned parameters influence the pump power intensity, hence the carrier density, close to laser threshold : by increasing it, the gain peak is blue-shifted because of Coulomb effects and its height increased. The experimentally available range of variation of the heat-sink temperature lies between -20°C and 25°C, giving a cavity resonance tuning range of about 45nm ; the estimated bandgap tuning range is 13nm . The cavity resonance on the sample varies little in the center of the sample but can vary appreciably close to its edges. The cavity resonance can then be tuned between ∼972nm and 997nm .

Fig.2 (a) shows a near field image of what can be seen far above threshold (with a pump power twice that of the threshold). Laser emission fills the disposable surface and extends up to the size of the pump spot. Nevertheless, when getting close to threshold, spot-like localized structures can form. These spots are either packed in clusters (or complexes) of two to five spots (Fig.2 (b)-(e))or appear as single localized spots depending on the operating conditions : substrate temperature, location on the sample (see figure caption). Each spot is stationary in time and has a full width at half-maximum of $\sim 10\mu m$. The multispot and single spot structures do not appear in general at the centre of the pump beam. These clusters are very similar to the ones presented in models of laser localized states [14,15,16,17] in which

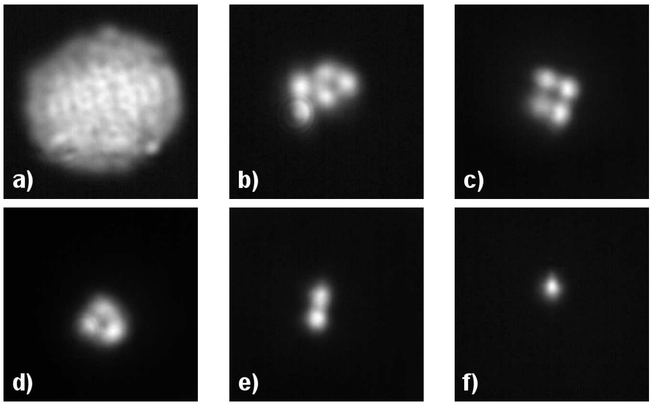

Figure 2: Near field average images of the laser output. All images' width are equal and the pump diameter is 70µm. (a) Above threshold (T=9.70°C, λ=982.7nm, P_p=130mW cw), (b)-(f) At threshold, for different locations on the VCSEL and for different pump powers. (b) $T\sim 2$°C, λ=973.9nm, P_p=57mW ; (c) $T\sim 2.6$°C, λ=979.6nm, P_p=21mW ; (d) $T\sim 2.6$°C, λ=981.2nm, P_p=23mW ; (e) $T\sim 2.6$°C, λ=980nm, P_p=20mW ; (f) $T\sim 1$°C, λ=977.3nm, P_p=61mW .

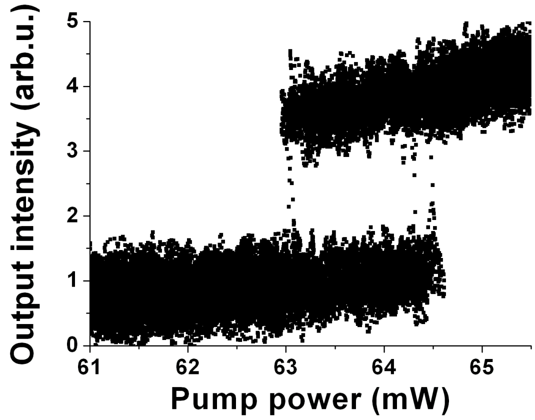

Figure 3: Bistability cycle of the single spot. Same experimental conditions as in Fig.2 (f).

the interaction and motion of laser solitons were investigated theoretically.

Fig.2 (f) shows a single spot. This spot is bistable as shown on Fig.3 : when the pump intensity is varied close to the laser threshold, the systems switches between the off-state (the system is uniformly non-lasing) and the on-state (a single laser spot appears) with a wide hysteresis cycle very stable in time and against noise. Switching between the ON and OFF states by locally exciting the sample was also achieved. Local excitation is provided by a "writing" beam, emitted by a Ti:Sa laser and superimposed to the pump beam. Its full width at half maximum is about 50µm, its wavelength (795nm) is slightly different from that of the pump wavelength, and the repetition rate of its 60-ps-duration pulses can be modified from 80MHz to a subharmonic by an acousto-optic modulator-based pulse picker (AOM in Fig.1). It provides a localized kink in the carrier distribution and does not interfere with the pump nor the laser fields. A photodiode (PD) monitors the writing beam signal.

Successive writing-erasure of the localized structure was possible for repetition rates of the local excitation ranging from 4kHz (Fig.4 (a)) to the maximum rate available in the experiment of 80MHz (Fig.4 (b)). It is important to stress that, with respect to previous demonstrations in laser systems [4,3], writing and erasure are achieved here with very short pulses (60ps), up to high repetition rates, and with the same beam characteristics : power, pulse duration and location of the writing beam.More specifically in a system with external feedback grating [3,18] and in a mutually-coupled laser system [4], writing and erasure of a cavity soliton are accompanied by long transients (some hundreds of nanoseconds for the erasure process in both cases) due to the presence of the external cavity. Moreover in these experiments a switching pulse duration of several tens of nanoseconds is used.

The possibility to switch the localized structure on and off at high repetition rates and with the same beam characteristics reveals crucial for the targeted applications of localized structures to information processing. It was also noticed that successive and successful writing-erasure is only achieved for defined ranges of the available parameters (pump power and writing beam power); otherwise, the commutation is not consistently effective and an incoming pulse does not switch on or switch off a localized spot. Therefore, parameters have to be adjusted carefully so as to insure that each pulse sent will write or erase at will, according to the sought functionnality.

When looking closer at the processes of writing (Fig.4 (c)) and erasure (Fig.4 (d)), one can see different behaviors appearing. Indeed, writing turns the system into the on-state by going through a stage of damped oscillations, while erasure sharply turns the system off. These oscillations consist in a train of decreasing amplitude, short pulses, with a period of several ns. They can be attributed to the damping of a stable Hopf mode that is excited by the writing pulse. Thus, the writing process takes roughly 10ns to complete (to bring the localized structure up to a steady state) while the erasure process takes a shorter time, less than a ns. This is in sharp contrast to what was reported in [19] in an external-cavity system where switching a structure on and off with an incoherent external perturbation occurs after a long transient of the order of 600ns. This is also different from the incoherent switching dynamics observed in amplifying systems [20] where the incoherent switch on was due to the local heating of the sample through the localized pumping, giving rise to a delay very sensitive to noise in the switching on of a localized state.

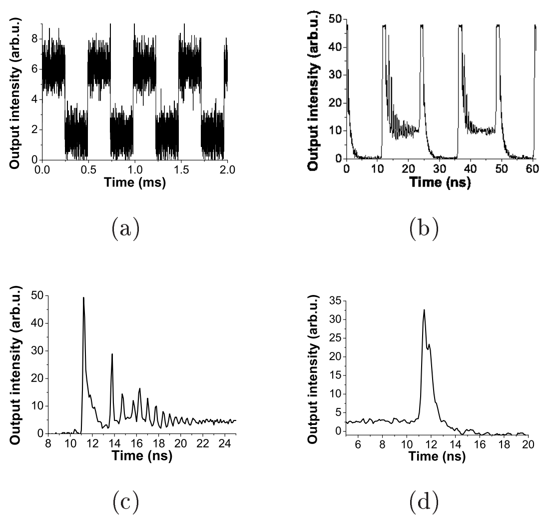

Figure 4: Successive writing-erasure for a panel of repetition rates : from f_{WB}=4kHz (a) to f_{WB}=80MHz (b). Magnifications of the writing (c) and erasure (d) processes at f_{WB}=80kHz (the writing beam is sent at 11.3ns). ($T \sim 1$°C, P_p=60mW cw)

A theoretical analysis of the switching dynamics of cavity solitons in a VCSEL with intracavity saturable absorber has been performed in [21]. In this paper, incoherent injection is investigated numerically and the same behavior as the one observed in our experiment is reported : on the one hand, the writing process consists in a large pulse followed by damped oscillations leading the system to the upper state. On the other hand, in the erasure process, the intensity shows only a small bump that appears with the writing beam and then rapidly falls down to the laser off state. Local excitation or erasure of the localized structure is obtained by changing the spot size. A large spot allows to switch-on the localized state, whereas a small spot allows to switch-off the structure. The latter case is easily understood when recalling that a hole in the gain carrier density is present at the same time as a localized peak of the intensity exists. Hence it is sufficient to "fill" the carrier density hole with carriers to bring the system back to its homogeneous state and then switch off the localized state. On the contrary, the switch on of a localized state is less obvious since locally adding some carriers, starting from a uniform state, one must end up with a hole in the gain carrier density. This is only possible thanks to a mechanism involving spatial coupling : a large excitation beam, as shown in [21], can produce an excitation that collapses in its center so as to form a hole in the carrier density and allows the appearance of a localized state. In our experiment, both the switch-on and switch-off processes occur with the same spot size.The numerical analysis performed in [21] shows that the spot sizes that allow the CS writing and erasure are parameter dependant.

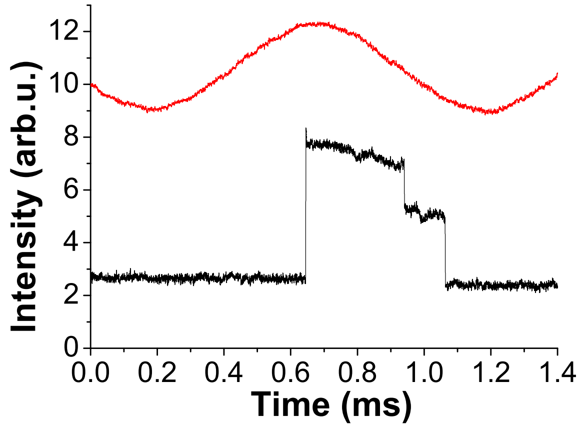

Figure 5: Output signal (black) and sinusoidal pump (red) corresponding to the two-spot structure 2 (e). Same experimental conditions as in Fig.2 (e).

Although the writing process seems to generally require a larger spot size than needed for the erasure process, an overlapping of the spot size ranges for which CS can be written or erased is not overruled. This could occur in our specific case and would explain the observations.

Moreover, the system in Figure 2 (e) composed of two spots was found to be multistable. When varying sinusoidally the pump beam, one spot sometimes turns off before the other one (Fig.5). This implies that the two spots have the same upper threshold (when the pump power increases) but a different lower one (when the pump power decreases). As a consequence, it is not possible to write them separately : the two spots form a coupled state (a complex as in [22,23,15,16]) and therefore are not spatially decorrelated.

This idea is validated by the theory in [10] that gives the distance over which two localized structures can be individually manipulated. Any structure written in the vicinity of another one (less than 60µm) will form a cluster and not two independent localized structures. Indeed, even though the intensity in each structure falls off exponentially fast, the phase associated with each microlaser extends over much greater distances and may provide the coupling mechanism. In our experiment, we could not individually manipulate two CS because the pump diameter was limited to 70μm. A larger pump diameter with the same external parameters leads to a change in the spatio-temporal dynamics of the VCSEL possibly because of a larger amount of heat produced by the sample or because the system developed a spatially-dependant temporal instability [10], inhibited at smaller pump diameters.

3 Conclusion

In conclusion we have shown the fast switch-on and off (writing and erasure) of a single localized laser spot with an incoherent, local and pulsed excitation at a repetition rate up to 80MHz . This result has been obtained in a compact, optically-pumped, monolithic VCSEL with intracavity saturable absorber. The switching dynamics is shown to be consistent with what is expected from numerical works, and even if not yet in the GHz range, shows major improvement over what was reported in other systems. This is encouraging in view of applications in the information processing field, since the switching time itself is quite small and the transient due to the presence of relaxation oscillations could certainly be attenuated by a proper choice of the working parameters, as e.g. the photon lifetime in the cavity, even though its effect on the localized states stability is difficult to predict.

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