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Tilted waves and passive mode-locking in multi-transverse mode VCSELs

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We show experimentally that a electrically biased 200 μm multi-transverse mode VCSEL can be passively mode locked using optical feedback from a distant Resonant Saturable Absorber Mirror (RSAM). Optical feedback from RSAM selects a tilted wave propagating along the transverse section of the VCSEL and leading to mode-locking of the external cavity modes. A large portion of the VCSEL transverse section contribute to mode-locked pulse emission leading to pulses of approximately 1 W peak power and 10 ps width.

The laser mode-locking (ML) phenomena is still a subject of intense research. The complex nonlinear dynamics involving the self-organization of many laser modes remains an fascinating problem that was recently linked to out-of-equilibrium phase transitions [1]. From a practical point of view many applications require sources of short pulse like e.g. medicine, metrology and communications [2]. Passive ML (PML) is arguably one of the most elegant method to obtain such pulses. It is achieved by combining two elements, a laser amplifier providing gain and a saturable absorber (SA) acting as a pulse shortening element. The different dynamical properties of the SA and of the gain create a window for amplification only around the pulse [3, 4]. PML can also be achieved using artificial SA like e.g. nonlinear polarization rotation [5], Kerr lens mode locking [6], Crossed-Polarization [7] or Stark effect modulation [8]. The PML mechanism has led to the shortest and most intense optical pulses ever generated and pulses in the femtosecond range are produced by dye [9] and solid state lasers [10]. However, the large size of these devices and the need for optical pumping strongly limit their application domain. More compact solution can be envisaged using semiconductor devices [11, 12]. Large output power in the Watt range is commonly achieved by coupling vertical external-cavity surface-emitting lasers (VECSEL) with a semiconductor saturable absorber mirror (SESAM). The external cavity is designed to operate in the fundamental Gaussian mode while a large section of the VECSEL is optically pumped to achieve large power. External cavity size leads to repetition rates from few to tens GHz. PML is obtained also in monolithic edge-emitting semiconductor lasers which have the advantage of being electrically biased and to operate at high repetition rate $1 \sim 160$ GHz. In both schemes, the presence of higher order transverse modes of the resonator is usually perceived as detrimental for mode-locking stability and it is avoided by cavity designed. On the other hand, the possibility of achieving a cooperative effect of transverses modes for which they would contribute to longitudinal mode locking is very attractive for increasing the pulse power. Moreover, the optical power that can be extracted from a semiconductor laser is limited because of Catastrophic Optical

Damage (COD). One path used to circumvent this limit is to increase the volume of the lasing mode, which in the simplest case is achieved by increasing the lateral dimension. However, the emission profile of these lasers usually presents a low quality. This originates from the presence of many lateral modes that are nearly degenerated in gain. This leads to multi-peaked near-fields, but more important, the spatial profile usually depends on the current value due to carrier-induced self-focusing, which might even lead to chaotic filamentation of the beam [13]. The origin of this phenomenon is the so-called Spatial Hole Burning (SHB): in regions of high optical intensity, the local gain (and thus the local carrier density) is depressed by stimulated emission; this depression leads to a local increase of refractive index which tends to further confine the light and to increase the local field intensity.

In this work we propose a scheme for achieving mode locking using an electrically biased, 200 μm section VCSEL. This device is mounted in an external cavity configuration closed by a resonant saturable absorber mirror (RSAM). We show that a large section of the device contribute to mode-locking leading to pulses of 10 ps width and around 1 W of peak power.

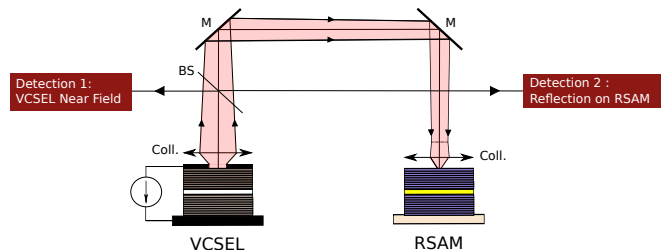


Figure 1: Experimental Set-up: Temperature-stabilized VCSEL and RSAM coupled together. Coll.: Aspheric Lens, BS : Beam Splitter, M: Mirror

The VCSEL is a 980 nm device manufactured by ULM photonics [14]. Its standalone threshold (J_{st}) is about 380mA , though emission is localized only at the external perimeter of the device up to $J=850$ mA, after which roll-off starts to occur. The RSAM is manufactured by BaTop and it has an absorption of 99% (1% reflection) at

cavity resonance peak which can be tuned by controlling the RSAM temperature. When saturated its reflection is increased to 60%. The FWHM of the RSAM cavity bandwidth is around 16 nm, its saturation fluence is at $15 \mu\text{J}/\text{cm}^2$ and relaxation time is around 1 ps. Both the VCSEL and RSAM are mounted on temperature controlled substrates which allow for tuning the cavities resonant frequencies and parameter are set for having a zero detuning at the VCSEL operated current. The set up is shown in Fig. 1, VCSEL light output is collected by a large numerical aperture (0.68) aspheric lens and the same kind of lens is placed in front of the RSAM. A 10% reflection beam splitter allows for light extraction from the external cavity. The light emitted by the VCSEL is monitored by a 33 GHz scope coupled with fast detectors (8 GHz or 42 GHz). Part of the light is sent to two CCD cameras, the first records the near-field profile, while the second records the far-field profile. The light reflected by the RSAM is also used for monitoring and a third CCD camera monitors the RSAM surface. The cavity length L is fixed at around 30 cm. One of the most important parameter for achieving mode locking in these conditions is the imaging condition of the VCSEL onto the RSAM. We obtain mode-locking when the RSAM is placed in the fourier plane of the VCSEL near-field. By consequence, in this condition, the VCSEL near-field profile is (inversely) imaged onto itself after a cavity roundtrip. This condition is obtained by finely tuning the position of the two aspheric lenses placed in front of the VCSEL and of the RSAM.

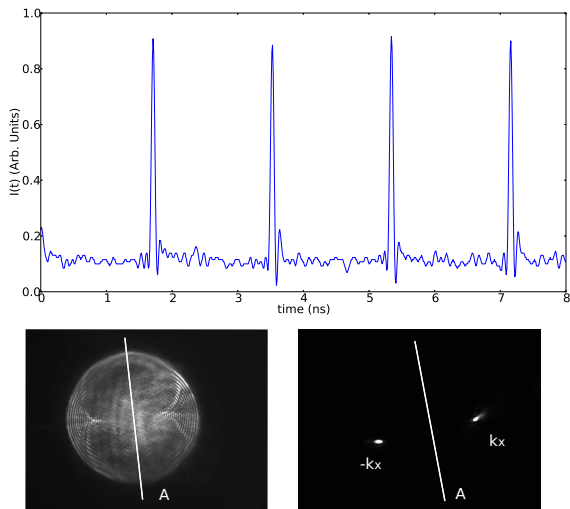


Figure 2: Panel a): Temporal trace of the VCSEL in the mode-locked regime. Panel b): Corresponding Near-Field emission of VCSEL. Panel c): Corresponding Far-field emission from the VCSEL. $J=600$ mA

In Fig. 2 we show the time output of the VCSEL in mode-locking regime. The repetition rate corresponds to $\frac{c}{2L}$, being L the external cavity length and the pulse width is limited by our real-time detection system (lim-

ited to 34 GHz). Acquisition of the same signal from an optical spectrum analyzer reveals a spectral pick 0.12 nm broad (FWHM). The panel b) and c) shows respectively the time-averaged near-field profile and far-field profile emitted by the VCSEL. In panel c), two off-axis bright spots indicate the presence of two counter-propagating tilted waves along the section of the VCSEL. Remarkably, no interference pattern is visible in the near-field emission. The concentric rings in the neighborhood of the device borders do not contribute significantly to the far-field bright spots, as it was verified by filtering out these rings. The image of the RSAM surface is very similar to Fig. 2c), thus revealing that the RSAM is effectively placed in the fourier plane of the VCSEL near-field. The two bright spots in the far-field emission of the VCSEL, indicate the the presence of two tilted waves which transverse wave vector is related in direction and modulus by the position of the spots. Their symmetry with respect to the optical axis indicates that the two transverse wavevector are one opposite the the other. There is a certain degree of control in the experiment on the separation between the two spots by playing with the external cavity alignment, namely tilting one of the mirrors M in the set-up. Within a given range, mode-locking dynamics (as shown in Fig. 2a) is not significantly affected when varying the distance between the two spots except for a slightly variation of the peak power. Outside this range, i.e. for spot separation exceedingly large, mode-locking is suddenly lost as a result of a too lossy external cavity because of misalignment. More important, mode-locking disappears suddenly as the two spots are brought to coincide, thus suggesting that plane-wave emission parallel to the optical axis of the VCSEL resonator does not allow for achieving mode-locking. The mode-locking regime stability versus pumping current has been established in the range $285\text{mA} < J < 703\text{mA}$. When the current is varied in this interval we did not observe any change in the separation between the two bright spots in the far-field profile corresponding to the two tilted waves. On the other hand the spectral peak corresponding to the mode-locking emission has shifted from 978 nm ($J = 703\text{mA}$) down to 976 nm ($J = 285\text{mA}$).

These observations disclose a possible explanation about the emergence of the mode-locking regime in our system. Let's consider a point A of the VCSEL section and we suppose that it emits a plane wave with a transverse component K_{\perp} . Because the RSAM is in the fourier plane of the VCSEL near-field, all the plane waves with a transverse component K_{\perp} emitted by any point of the VCSEL will be imaged on the same spot B on the RSAM, thus strongly saturating the absorber. Being saturated, the RSAM reflects back the light to the VCSEL. As in a conventional self-collimated optical system, when the object and the mirror are placed respectively on the object focal plane and the image focal plane, the light arrives onto the VCSEL with a transverse component $-K_{\perp}$. Besides, feedback is non-local since the VCSEL is imaged onto itself upside down. The image of point A after a

single round-trip is, say, A' and the feedback loop is not closed. A' amplifies and emits the plane wave with a transverse component $-K_{\perp}$ and this wave is imaged onto a spot B' of the RSAM which corresponds to the image in the K-space of all the plane waves emitted by the VCSEL with a transverse component $-K_{\perp}$. In B' , as in B the RSAM is saturated and it reflects light back into the VCSEL, in the form of a plane wave having a transverse component K_{\perp} and imaged at point A , thus closing the feedback loop. Two tilted waves are then propagating within the VCSEL resonator but they are alternate in time and the delay is given by the single round-trip of the external cavity. The two spots in the far-field are only an artefact of time-averaging operated by CCD camera; only a single tilted wave with K_{\perp} component or with $-K_{\perp}$ is traveling along the transverse section of the VCSEL. This explains why no interference pattern can be observed in the near-field profiles. In order to verify this explanation, we monitored a single far-field bright spot. The result is shown in Fig. 3 where we show the time signal obtained by detecting both spots in the far-field and a single one. The conclusion is that each spot is composed by pulses at a repetition period given by two times the round-trip of the external cavity and the pulses in each spot are delayed by the external cavity round-trip.

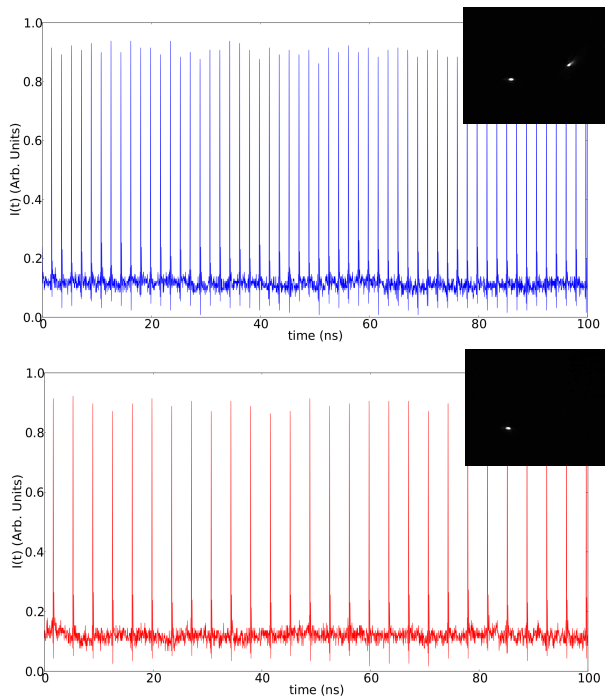


Figure 3: panel a) Time signal obtained when detecting the two spots of the far-field emission of the VCSEL. Panel b) Time signal obtained when detecting a single spot of the far-field emission of the VCSEL

The presence of a tilted wave travelling along the transverse direction of the VCSEL resonator avoids gain saturation inside the VCSEL, which, by consequence, is operated as an amplifier. At the same time, the optical geometry of our cavity makes that such a tilted wave strongly saturates the saturable absorber. The propagating transverse wavevector is selected by the VCSEL resonator which has a very high finesse with respect to the RSAM finesse. We are currently working on theoretical modeling of this experimental scheme for obtaining mode-locking.

In conclusion we have presented a novel experimental scheme for obtaining mode-locking in a electrically biased broad-area VCSEL coupled with a resonant saturable absorber as external cavity mirror.

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