Chaotic polarization dynamics and chaos synchronization in VCSELs

*Invited Paper*

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Abstract—We review our recent results related to nonlinear polarization dynamics and chaos in VCSELs. The possibility to generate multimode chaos motivates the study of chaos synchronization in coupled VCSELs and its application for secure communications.

I. INTRODUCTION

Vertical-cavity surface-emitting lasers (VCSELs) exhibit interesting polarization properties: they typically emit a linearly polarized along one of two preferential and orthogonal directions (x and y) but light polarization can easily switch between the x and y linearly polarized (LP) modes when modifying the injection current and/or device temperature [1]. The interplay between VCSEL peculiar polarization properties and the nonlinear dynamics resulting from optical feedback, optical injection or large current modulation induces new, possibly chaotic polarization dynamics and polarization switching mechanisms that we review here.

II. OPTICAL FEEDBACK: SWITCHING AND RESONANCE

When VCSEL is subject to a relatively strong optical feedback, its dynamics may exhibit severe instabilities resulting in chaos in its two orthogonal polarization modes. A typical example is the low-frequency fluctuation (LFF) regime where the chaotic fluctuations of the LP mode dynamics may either be in phase and then lead to similar dynamics in the VCSEL total power, or rather be anticorrelated and lead to a laser output power almost constant in time [2], [3]. Recently, we have shown that another dynamics resulting from optical feedback consists of slow hopping between the two LP modes complemented by fast anticorrelated pulses at the external cavity frequency [4]; see Fig. 1. Interestingly, the VCSEL can exhibit a resonant behavior at the time-scale of the time-delayed optical feedback when adding an optimal amount of noise in the laser injection current, a situation typically referred as coherence resonance for nonlinear systems [5].

III. OPTICAL INJECTION: ROUTE TO CHAOS

We have investigated another configuration where a VCSEL is subject to optical injection with an orthogonal polarization. For a large enough injection, the VCSEL polarization switches to the one of the injected light and its frequency locks to that of the so-called master laser [6]. However this injection locking steady state dynamics may easily destabilize and lead to complex polarization dynamics [7]; see Fig. 2. The VCSEL initially is locked to the master laser (a) but when increasing the injection strength it exhibits a Hopf bifurcation to a self-pulsating dynamics (b)-(c), which in turn may exhibit a period doubling bifurcation (d) to chaos (e). We have analyzed in detail the bifurcation scenarios as a function of the frequency detuning between VCSEL and master laser and as a function of the injection strength [8], [9].

IV. LARGE CURRENT MODULATION: CHAOTIC PULSING

When VCSEL is subject to current modulation with large modulation amplitude and frequency above the relaxation oscillation frequency, theoretical works have predicted the existence of chaotic dynamics in the VCSEL higher order transverse modes [10] or in its two LP modes [11]. We have recently shown theoretically that the transverse mode and
polarization mode competitions in VCSELs may interplay and lead to new dynamical scenarios: transverse mode competition may suppress chaos or, by contrast, lead to chaos in parameter regions where otherwise the VCSEL polarization competition leads to regular pulsing [12]. We have moreover confirmed experimentally two theoretical predictions. First, nonlinear dynamics can be observed in VCSELs with large current modulation as a result of polarization mode competition [13]; see Fig. 3 where the polarization modes exhibit an irregular pulsing at half the modulation frequency (period doubling) while the total power exhibits a regular period-two dynamics. Second, we have shown that transverse mode competition only can lead to nonlinear dynamics [14].

![Fig. 3. Experimental time traces of the intensities of the total, x-polarized and y-polarized powers, showing nonlinear dynamics in VCSEL with large current modulation. Results plotted in (d)-(f) correspond to zooms of (a)-(c), respectively, where the latter result from three independent experimental runs.](image1)

![Fig. 4. Experimental observation of synchronization of chaos in the two polarization modes of mutually coupled VCSELs. Temporal waveforms and correlation plots for (a),(b) y-mode of VCSEL 1 and y-mode of VCSEL 2, and (c),(d) y-mode of VCSEL 1 and x-mode of VCSEL 2.](image2)

**V. VCSEL CHAOS SYNCHRONIZATION**

Apart from optical feedback, injection or large current modulation, coupling between VCSELs may also significantly modify their polarization properties and dynamics. We have shown for example that mutual coupling between VCSELs may induce successive polarization switchings with increasing coupling strength in otherwise polarization stable VCSELs [15]. Mutually coupled VCSELs may also exhibit chaotic dynamics in almost perfect synchronism; see Fig. 4. The anti-correlated dynamics between orthogonal polarization modes of each VCSEL yields moreover to anti-synchronization between coupled orthogonal polarization modes.

We have shown several configurations leading to bistable polarization switching and rich nonlinear dynamics in VCSELs. The possibility to synchronize VCSEL chaos opens the way towards high speed, multiplexed secure communication schemes that are currently in progress.

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**REFERENCES**