Exploiting bistability, time delay and noise for obtaining all-optically square-wave switching

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International Conference on Delayed Complex Systems, Palma de Mallorca, June 2012

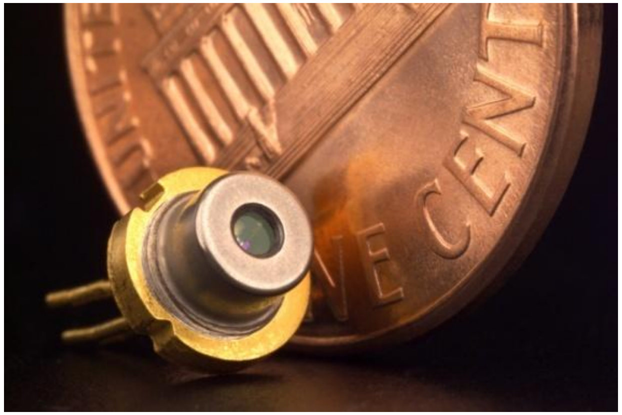
Outline

- Introduction
  - Semiconductor lasers (SLs) with time-delayed feedback or coupling
  - Edge-emitting lasers (EELs) & vertical-cavity lasers (VCSELs)

- All-optical square wave switching
  - Polarization rotated feedback
  - Polarization rotated coupling

- Conclusions and perspectives

Semiconductor lasers (SLs)



- Semiconductor lasers have many advantages:
  - are compact, fast, reliable and inexpensive
  - emit at a wide range of wavelengths
- Nowaday used in
  - Telecommunications
  - Optical data storage (CDs, DVDs)
  - Optical mouse
  - Barcode scanners, laser printers
  - Sensing & material processing
  - Life sciences applications
  - etc
- Under time-delayed feedback or coupling SLs display wide range of complex nonlinear dynamics

  that can be exploited for applications

Our Motivation: to produce all optically regular square-wave switching with GHz repetition rates without the need of high-speed electronics

High-frequency polarization self-modulation and chaotic phenomena in external cavity semiconductor lasers

W. H. Loh, Y. Ozeki,[a] and C. L. Tang
School of Electrical Engineering, Cornell University, Ithaca, New York 14853

(Received 7 February 1990; accepted for publication 27 April 1990)

Optical pulses with repetition rates up to several hundred MHz have been generated through a polarization self-modulation effect in an external cavity semiconductor laser modified by the insertion of a quarter-wave retardation plate. These pulses are generated without the need for any high-speed electronics. At higher bias, period-doubling and chaotic phenomena are also observed.

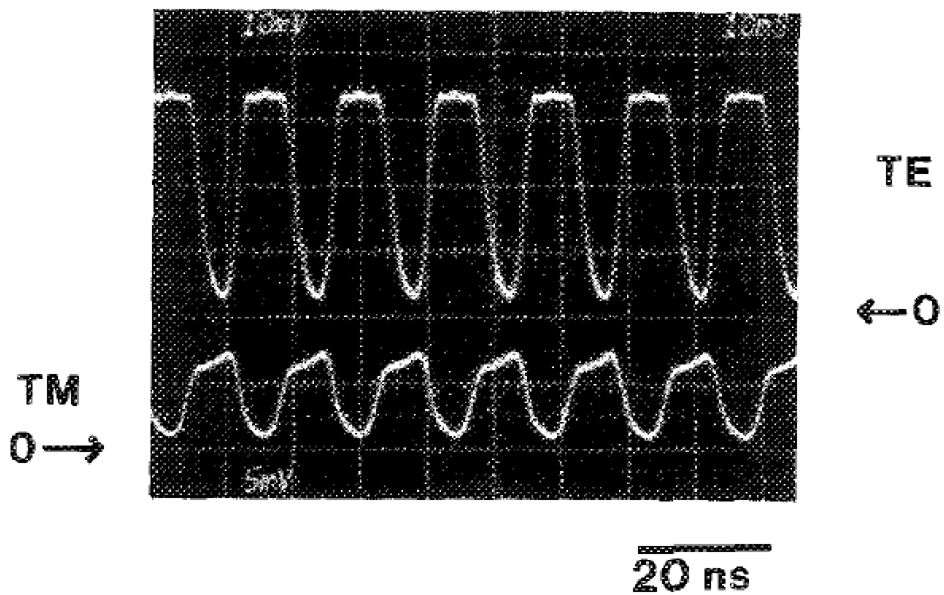
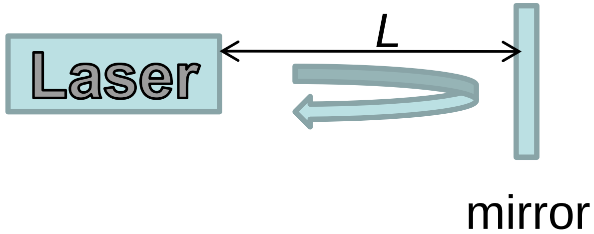


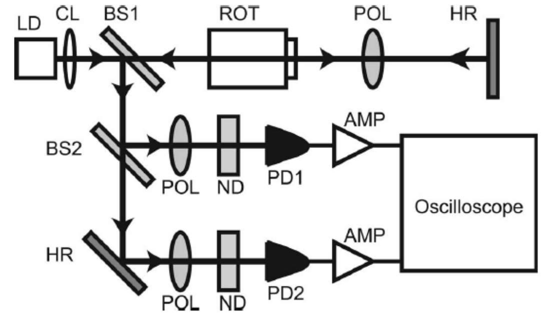
FIG. 3. Oscilloscope trace of optical pulses: upper trace: TE component, lower trace: TM component. The external cavity length is 100 cm and the current bias is 27 mA.

Types of time-delayed optical feedback

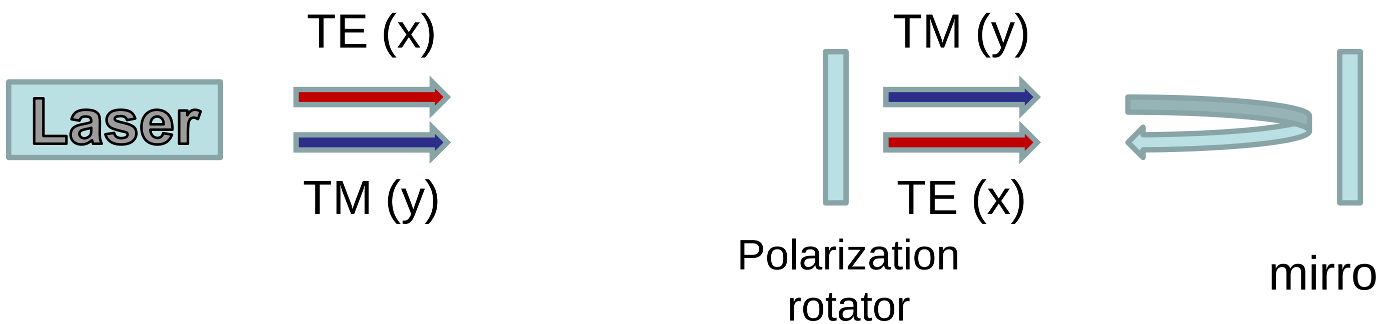
<u>Isotropic</u>:

$$\tau = \frac{2L}{c}$$



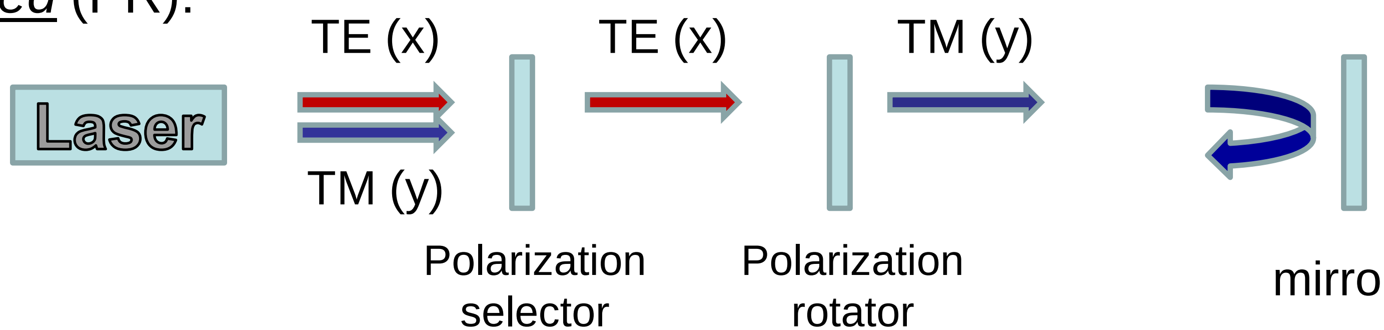


<u>Orthogonal</u>:



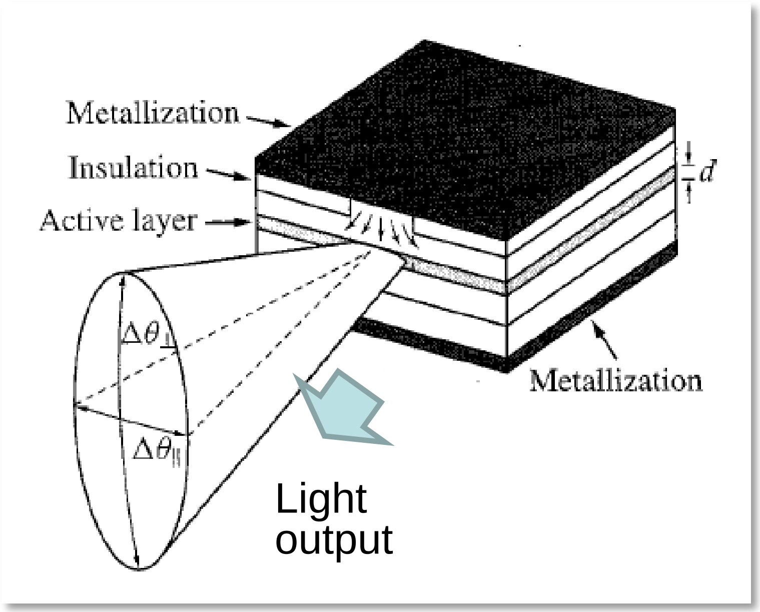
<u>Polarization-rotated</u> (PR):

<u>TE (x) is the natural lasing</u> polarization of the solitary laser.

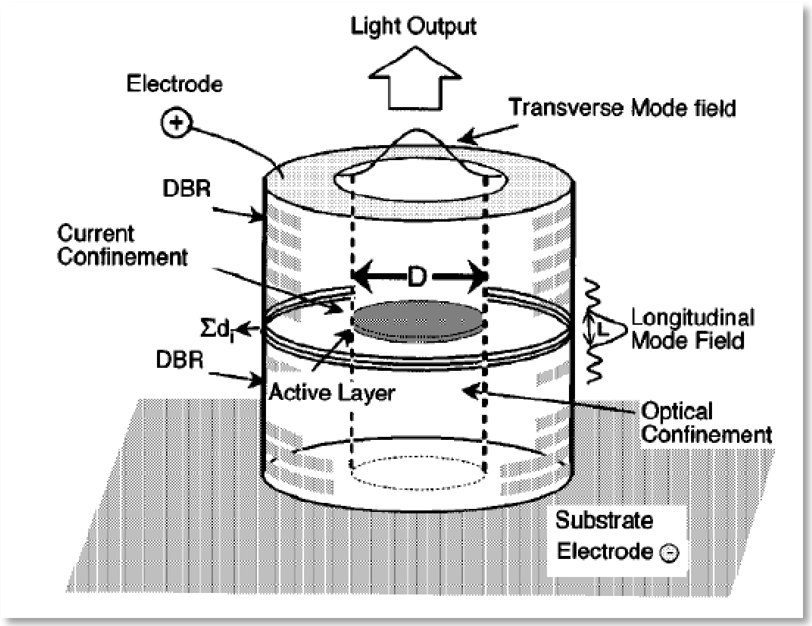


Two types of Semiconductor lasers

Edge-Emitting lasers (EELs)

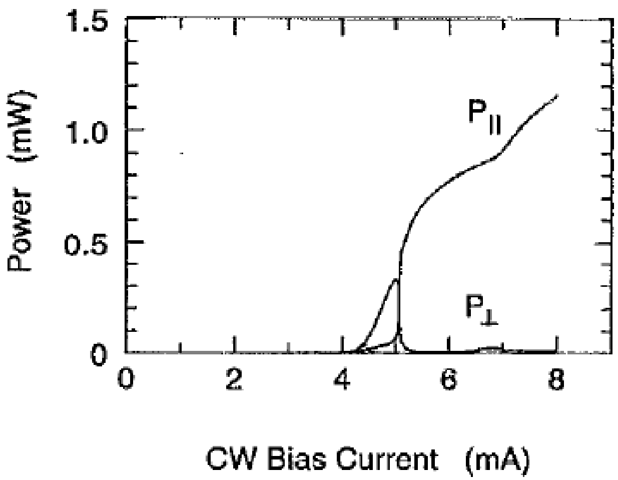


Vertical-Cavity Surface-Emitting Lasers (VCSELs):

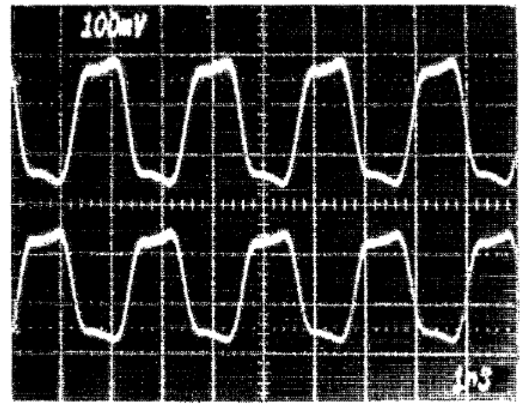


because of different cavity geometries: EELs & VCSELs have different polarization properties

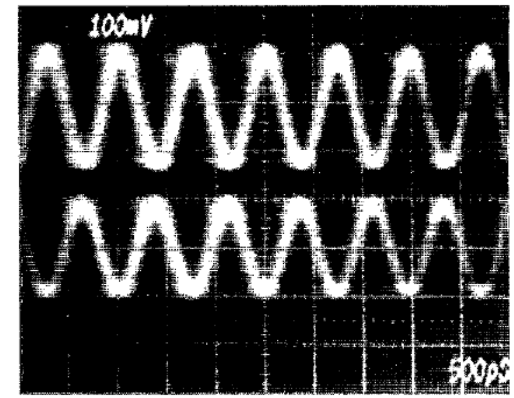
Square-wave switching in VCSELs with feedback

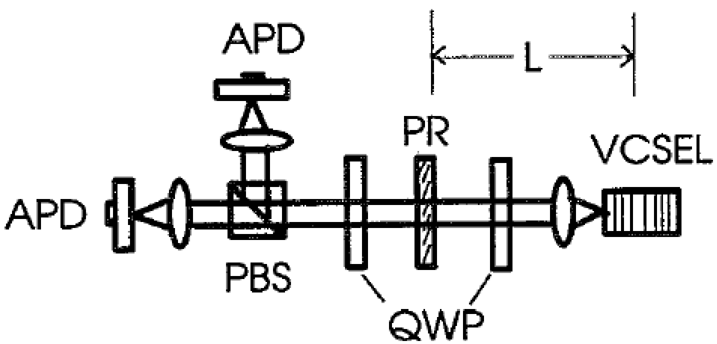


L=16.5 cm



L=5.5 cm



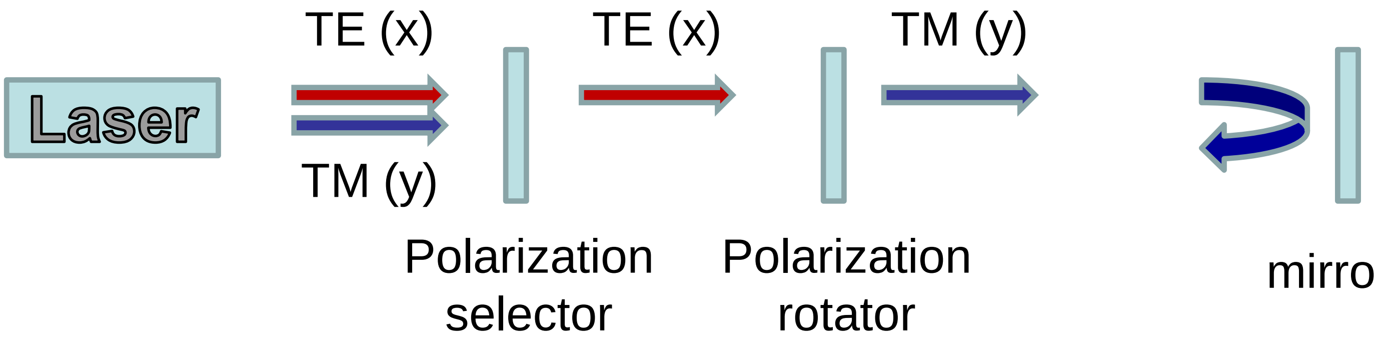


Physical interpretation: polarization self-modulation is a time-dependent solution that connects two fixed points ("external cavity modes") that are orthogonally polarized

M. Sciamanna *et al.*, Opt. Lett. 27, 261 (2002) + Phys. Rev. A 65, 041801(R) (2002)

S. Jiang *et al.*, Appl. Phys. Lett. 63, 3545 (1993)

Model for polarization-rotated (PR) time-delayed feedback



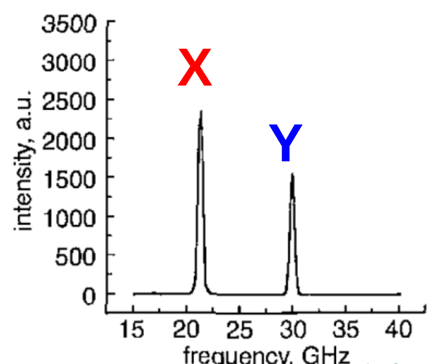
$$\frac{dE_x}{dt} = \frac{1}{2\tau_p}(1+i\alpha)(N-1)E_x + \sqrt{2\beta_{sp}}\xi_x(t)$$

$$\frac{dE_y}{dt} = \frac{1}{2\tau_p}(1+i\alpha)(N-1-\gamma_a)E_y + i\gamma_p E_y + \sqrt{2\beta_{sp}}\xi_y(t) + \underbrace{\eta E_x(t-\tau)e^{-i\omega_0\tau}}_{\text{Polarization-rotated feedback}}$$

$$\frac{dN}{dt} = \frac{1}{\tau_N}\left[\mu - N - N\left(|E_x|^2 + |E_y|^2\right)\right]$$

Polarization-rotated feedback

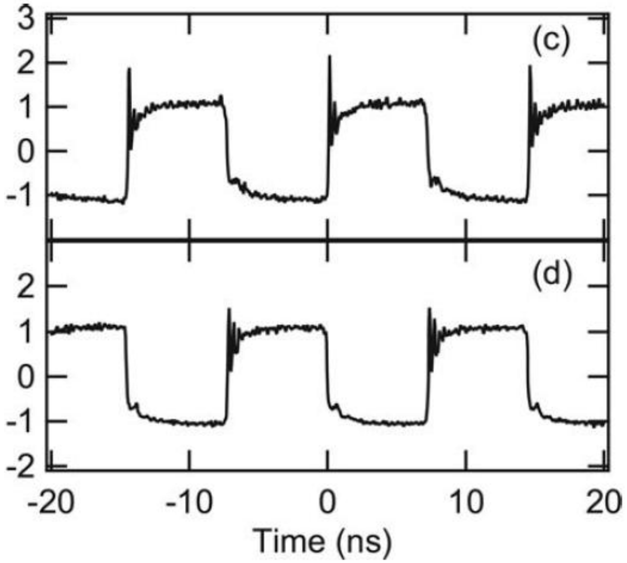
Two parameters represent the anisotropies between the two polarizations: γ_a and γ_p



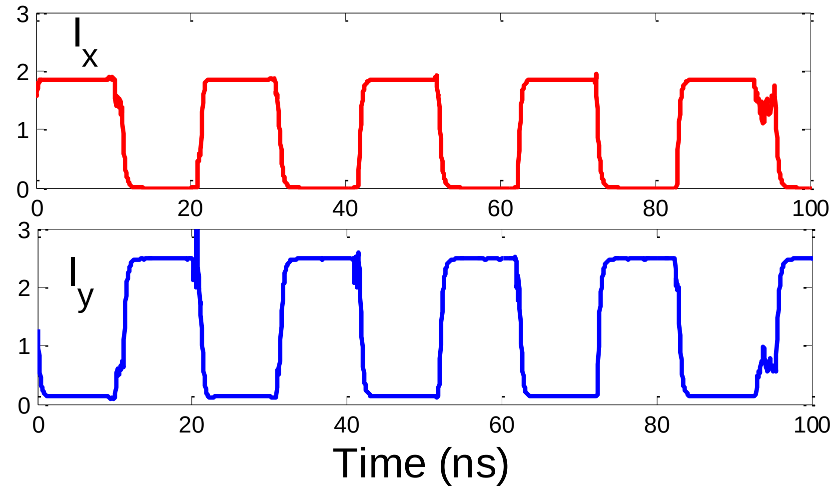
Adapted from Hong et al, Elec. Lett. 36, 2019 (2000)

Square-wave switching in EELs with PR feedback

Experimental observations
Gavrielides et al, Opt. Lett. 31, 2006 (2006)



Simulations
τ=10 ns

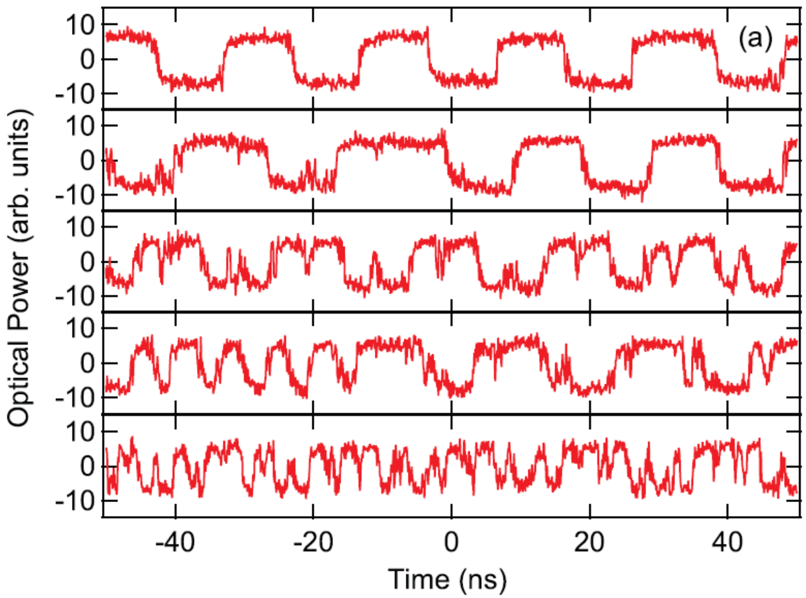


Periodicity: 2τ

- sharp rising and falling edges

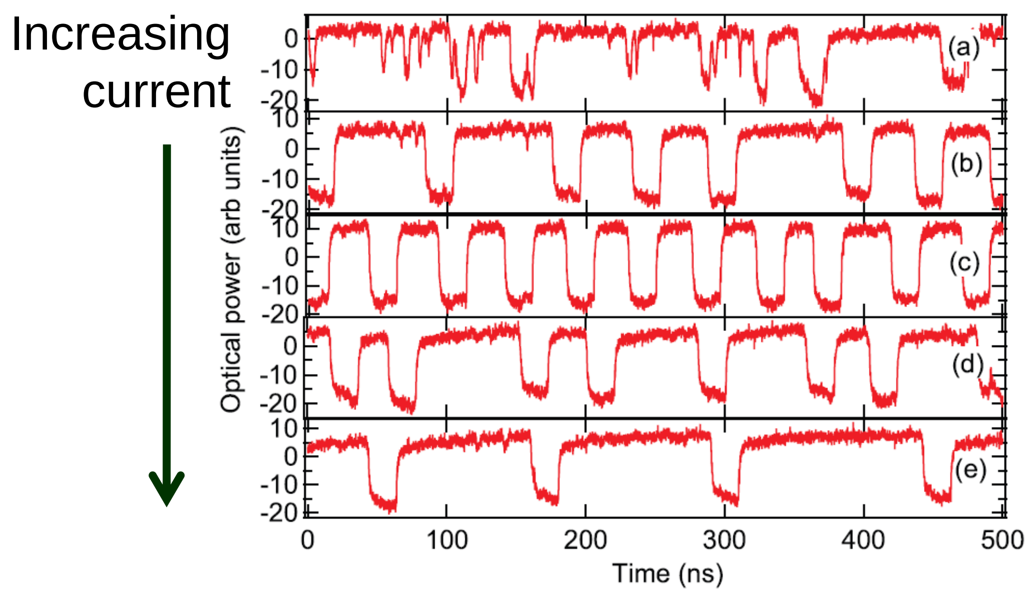
Experimental observations with VCSELs

Noisy and unstable SWs:



Time traces taken under identical conditions

Influence of the laser current:



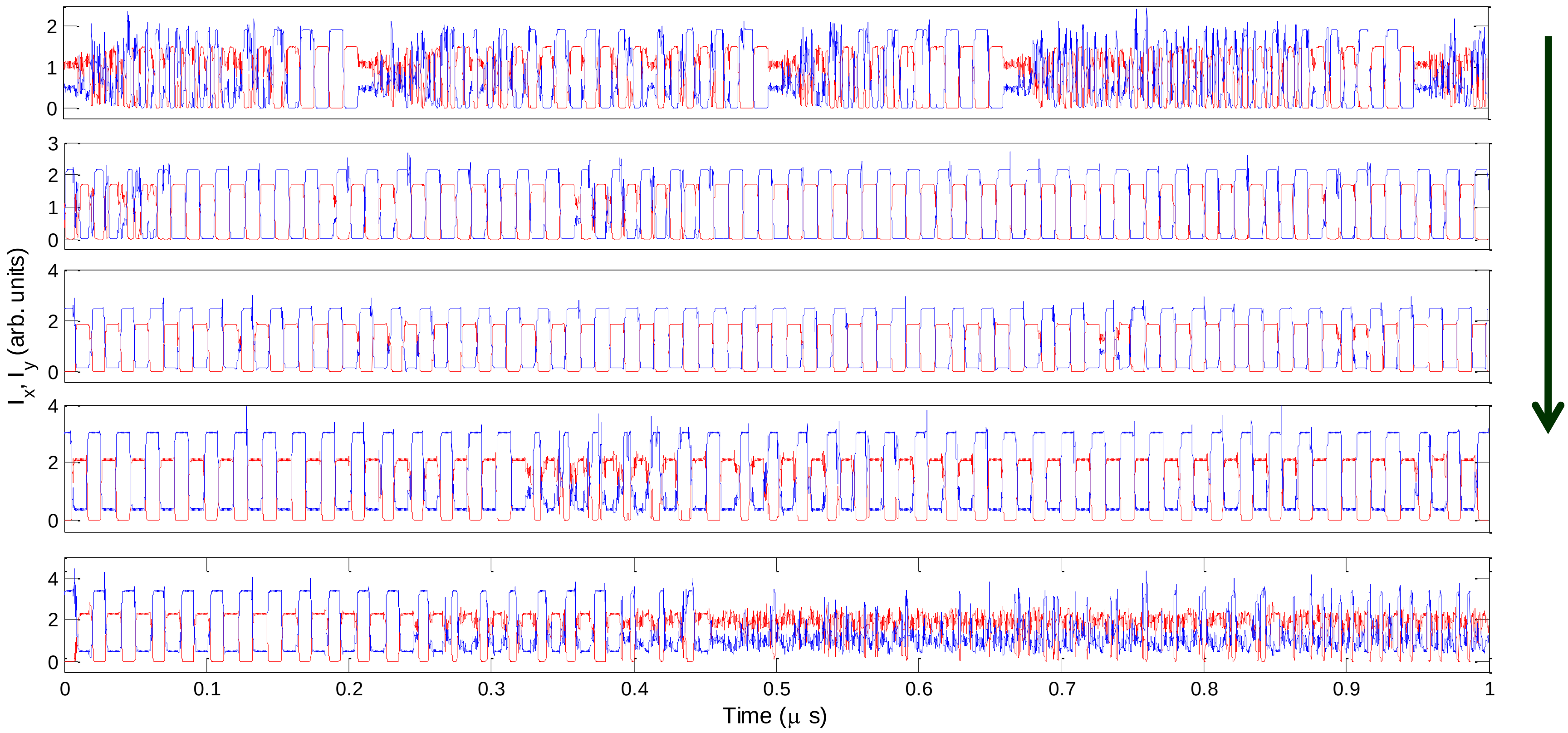
Optimal regularity at a certain current value

D. Sukov et al (submitted)
Mulet, Giudici, Javaloyes, and Balle, PRA 2007

Simulations based on the spin-flip VCSEL model
(Martín-Regalado et al, JQE 1997)

Influence of the injection current:

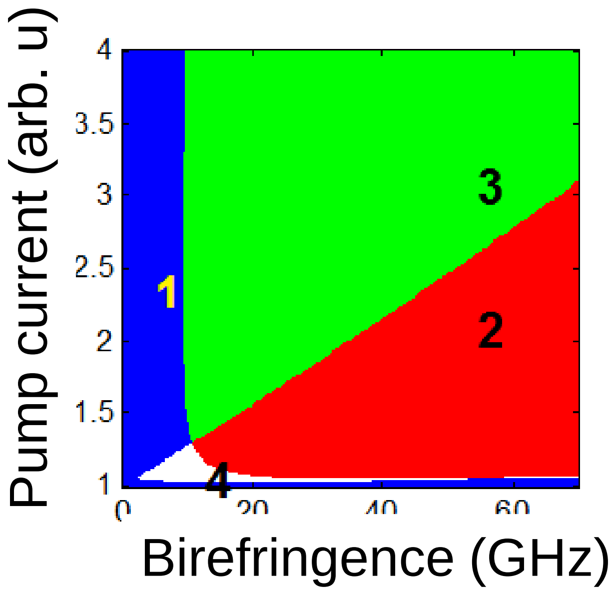
Increasing μ



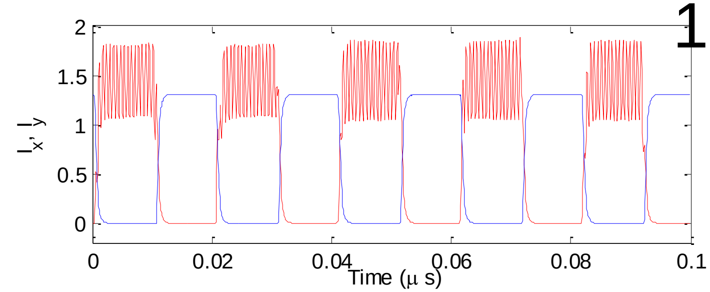
SWs in relation with the parameter region where the solitary VCSEL is mono-stable

Stability of the solitary modes:

Red: X, **Blue: Y**, White: X & Y, Green: none



1



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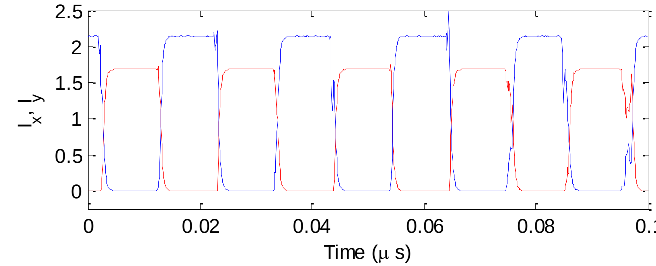

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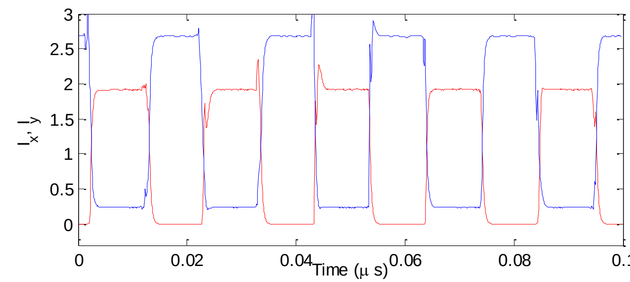

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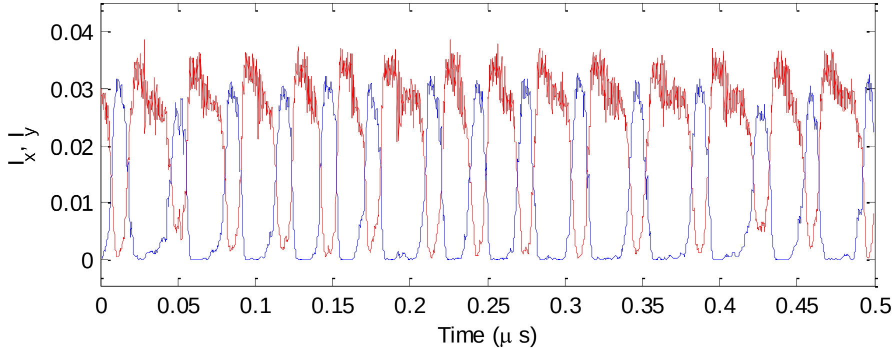
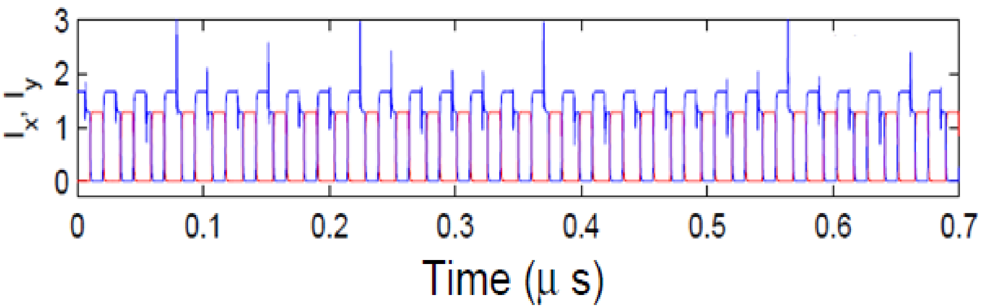
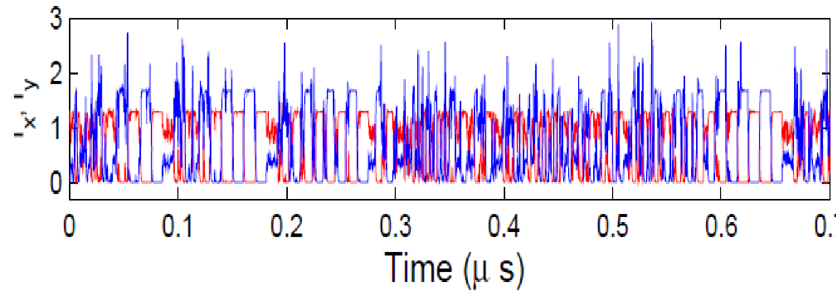


Influence of noise





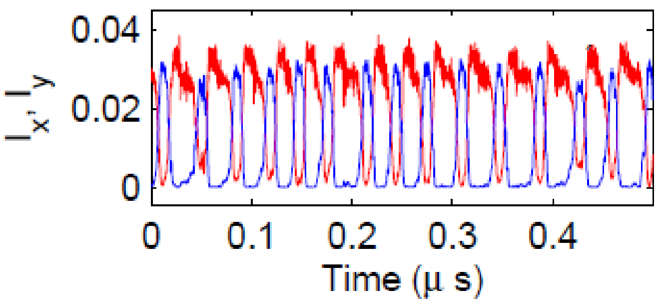
Pump current $\mu = 2.3$

Noise strength $\beta_{sp} = 0$

$\mu = 2.3$

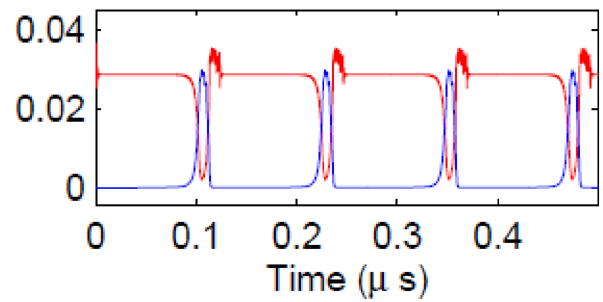
$\beta_{sp} = 10^{-4}\,\mathrm{ns}^{-1}$

- *Irregular switching can be noise-induced.*
- *Near the bistability region the switching periodicity can be controlled by the noise strength*



$\mu = 1.03$

$\beta_{sp} = 10^{-4}\,\mathrm{ns}^{-1}$

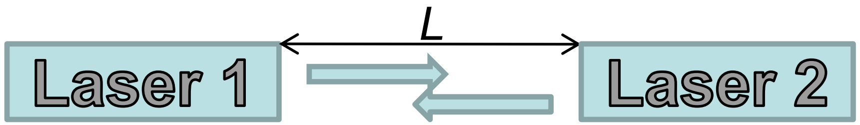


$\mu = 1.03$

$\beta_{sp} = 0$

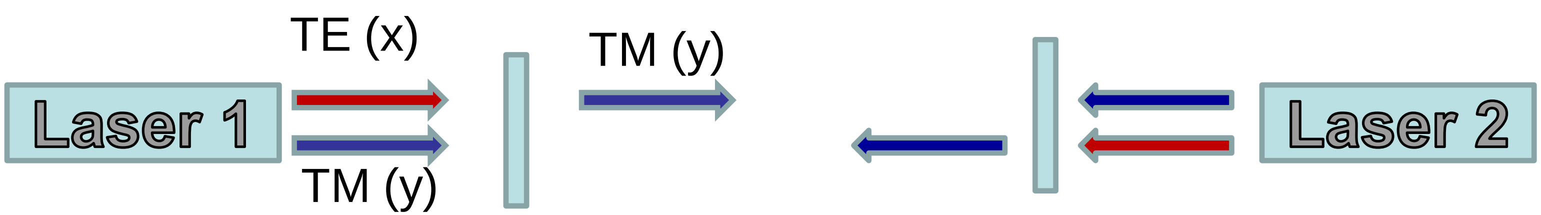
Time delayed mutual coupling

Isotropic



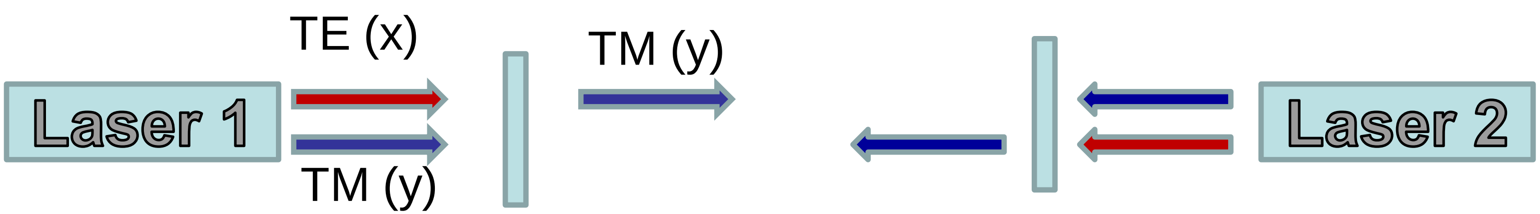
$$\tau = \frac{L}{c}$$

Polarization-rotated coupling



TE (x) is the natural lasing polarization of the solitary lasers.

Model for polarization-rotated coupling



<u>Laser 1</u>

$$\frac{dE_{1,x}}{dt} = \frac{1}{2\tau_p}(1+i\alpha)(N_1-1)E_{1,x} + \sqrt{2\beta_{sp}}\xi_{1,x}(t)$$

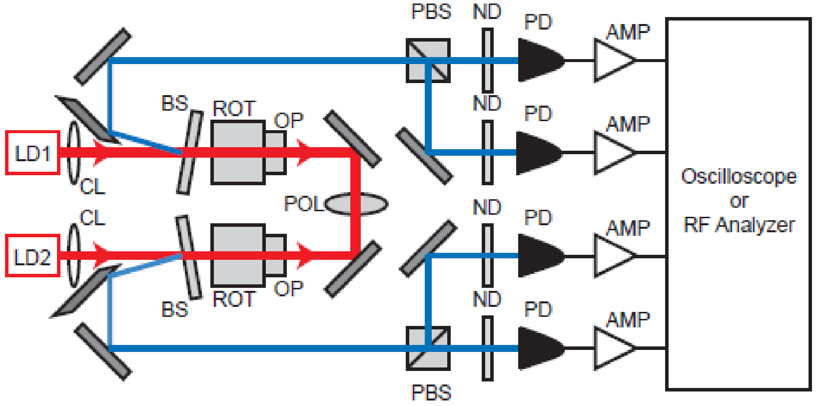
$$\frac{dE_{1,y}}{dt} = \frac{1}{2\tau_p}(1+i\alpha)(N_1-1-\underline{\gamma_a})E_{1,y} + i\underline{\gamma_p}E_{1,y} + \sqrt{2\beta_{sp}}\xi_{1,y}(t) + \underbrace{\eta E_{2,x}(t-\tau)e^{-i\omega_0\tau}}_{\text{Polarization-rotated coupling}}$$

$$\frac{dN_1}{dt} = \frac{1}{\tau_N}\left[\mu - N_1 - N_1\left(\left|E_{1,x}\right|^2 + \left|E_{1,y}\right|^2\right)\right]$$

Polarization-rotated coupling

And vice-versa for <u>laser 2</u>

Experimental observations (EELs)



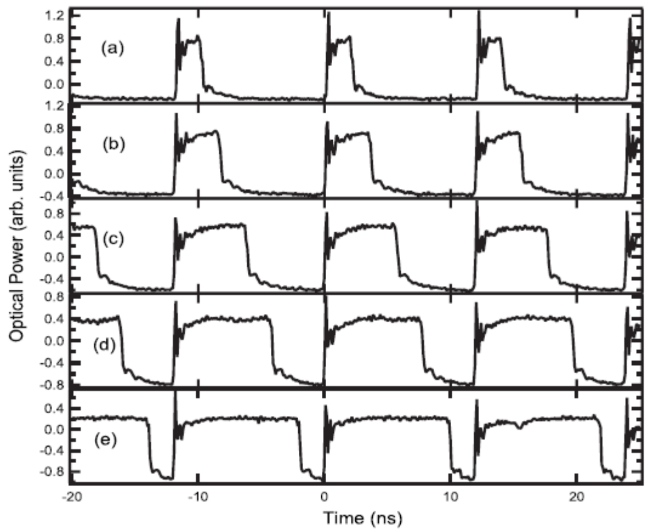
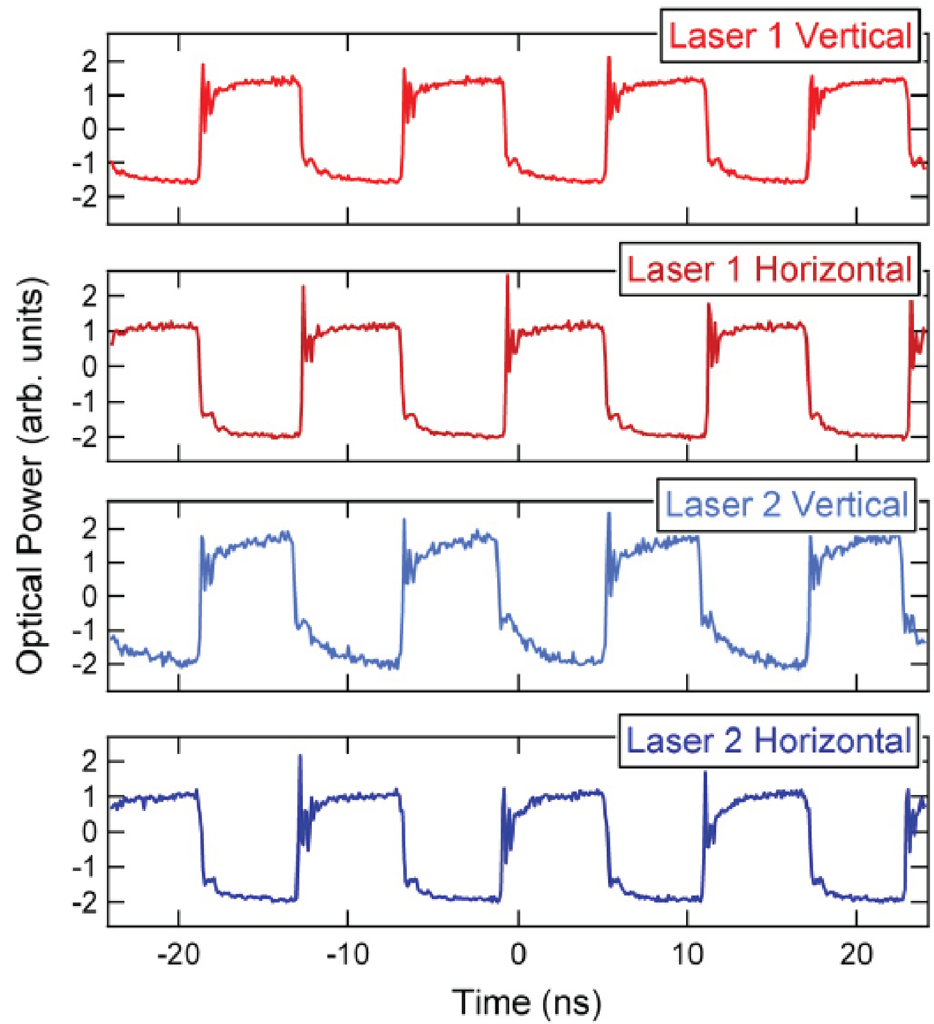


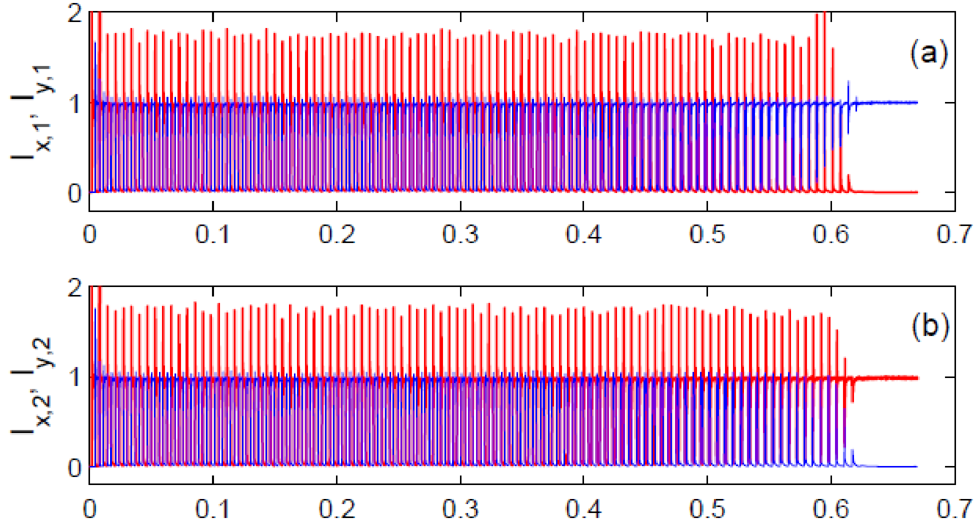
FIG. 4. Experimental square waves with variable duty cycle as a function of pump current. Only the TE mode of LD2 is illustrated for clarity.



D. Sukow et al, PRE 81, 025206R (2010)

Numerical simulations (EELs)

square-wave switching is a *transient* dynamics:



'Injected laser'

'Solitary laser'

And the inclusion of noise does not modify the average duration of the transient time

'Injected laser'

'Solitary laser'

Polarization selector & rotator

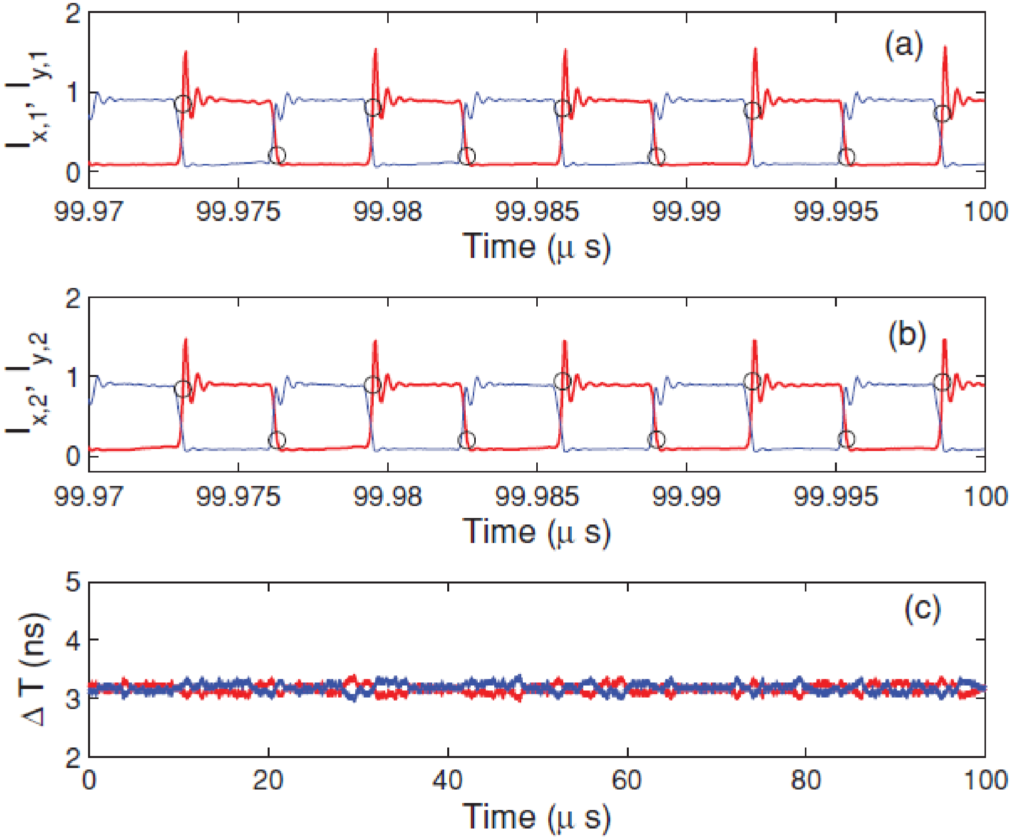
Polarization selector & rotator

<u>Stationary state</u>: master-slave unidirectional coupling, Laser 2 → Laser 1

C. Masoller, D. Sukow, A. Gavrielides & M. Sciamanna, PRA 84, 023838 (2011)

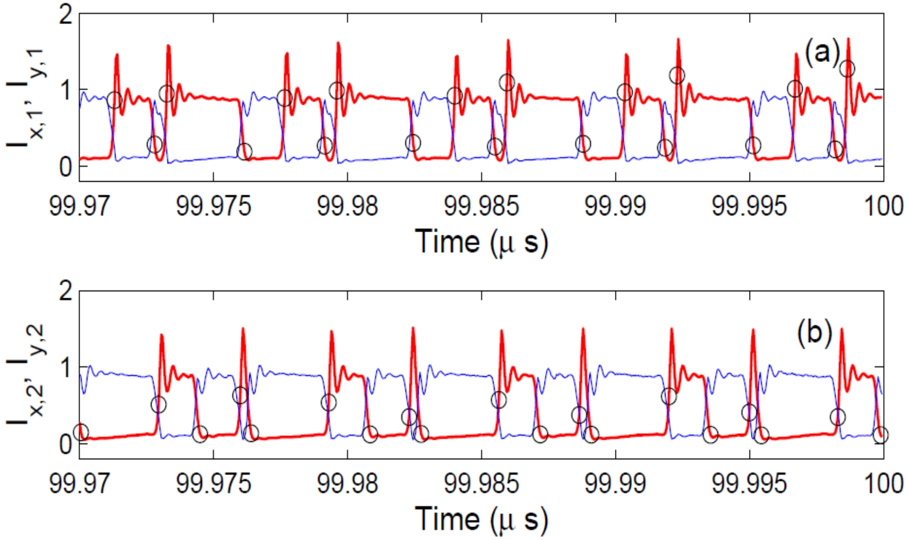
Transient vs stationary SW switching

However, by including in the model nonlinear gain saturation (self and cross saturation coefficients), in certain parameter regions, regular square-wave switching is a stable dynamics even in the absence of noise.

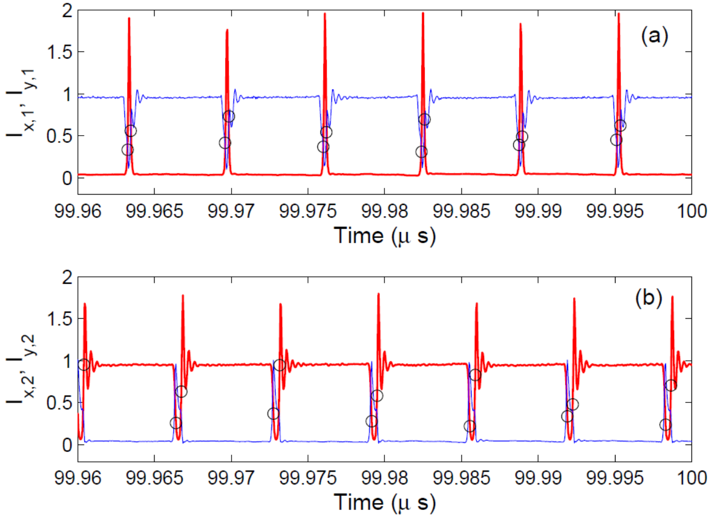


Multi-stability: coexisting waveforms

Nonsymmetrical switching

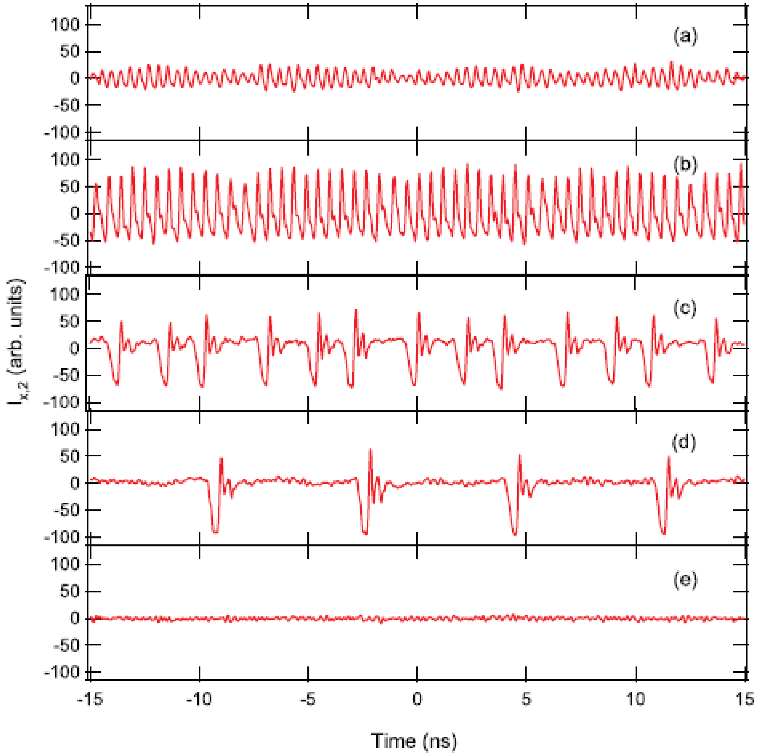


Nonsymmetrical pulses

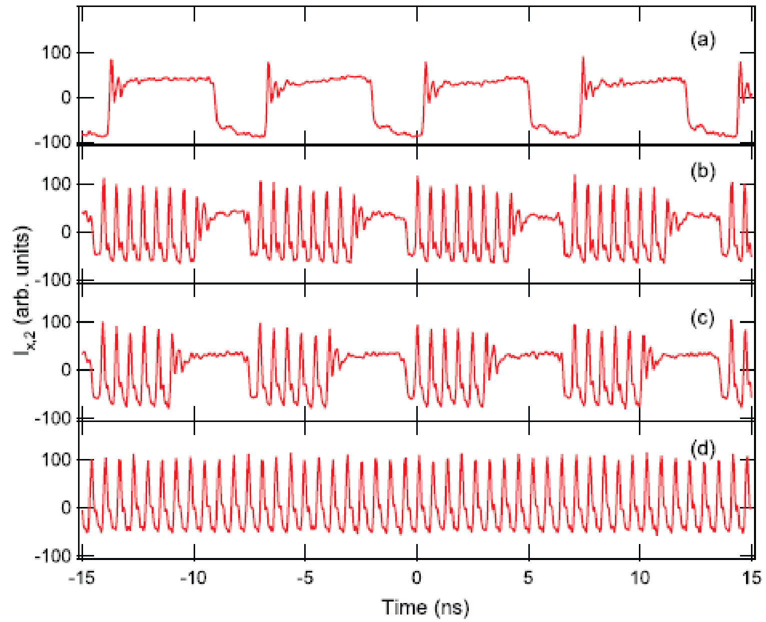


Experimental observations

For increasing coupling strength



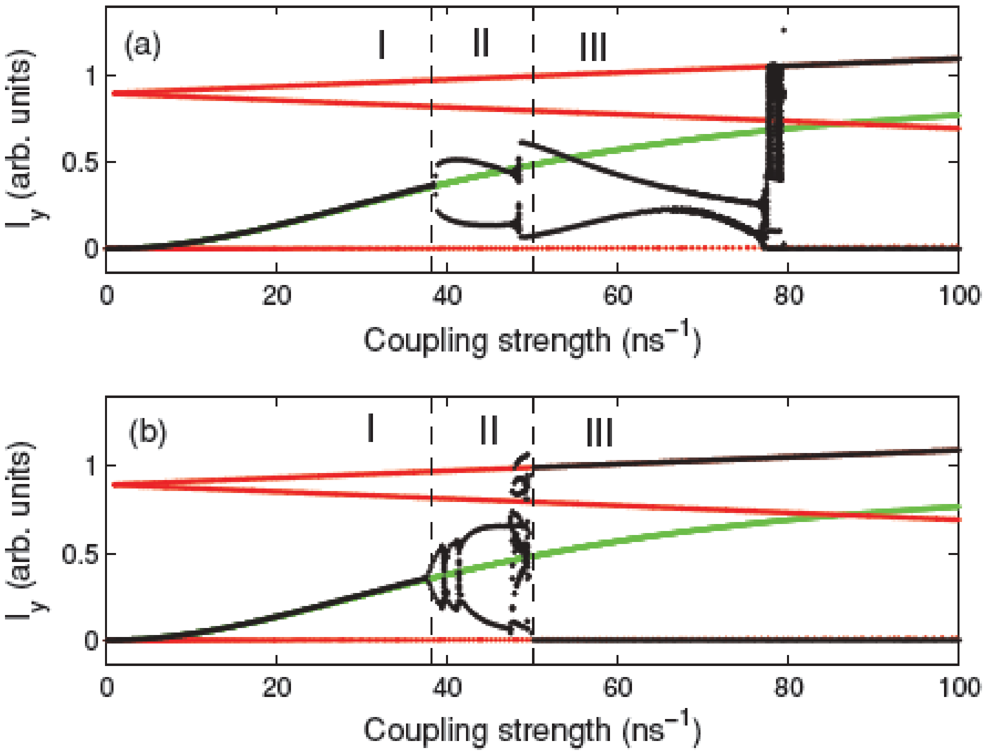
Multi-stability of coexisting solutions

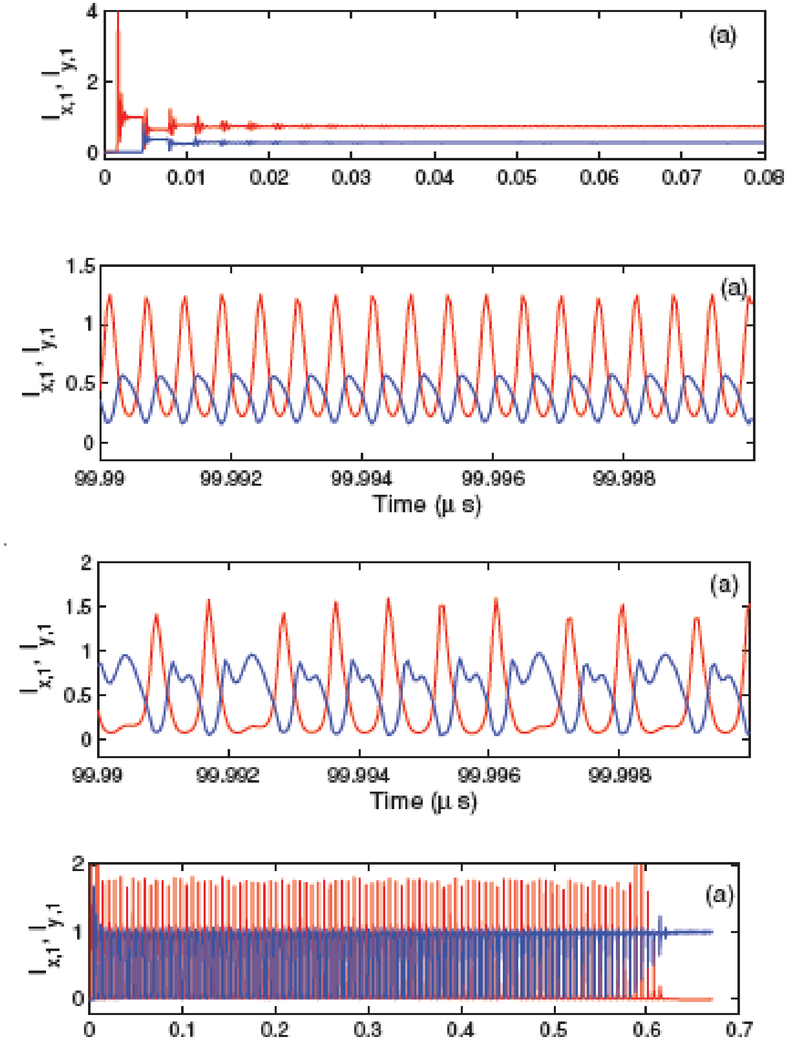


Time traces of the intensity of one mode of one laser

C. Masoller, D. Sukow, A. Gavrielides & M. Sciamanna, PRA 84, 023838 (2011)

Bifurcation analysis

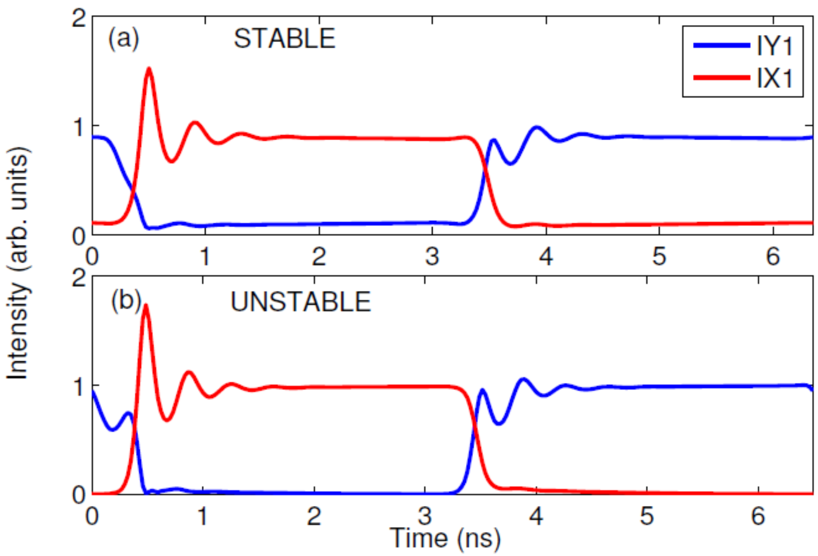




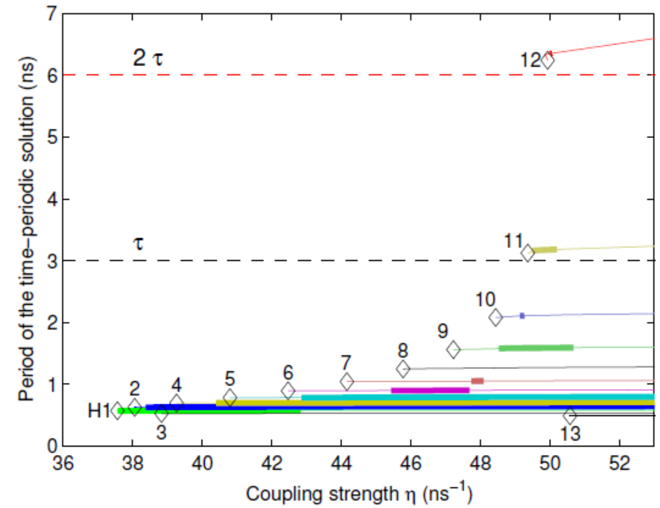
- Region I: : steady-state (mixed mode)
- Region II: multistability + square-waves
- Region III: steady-state (pure mode)

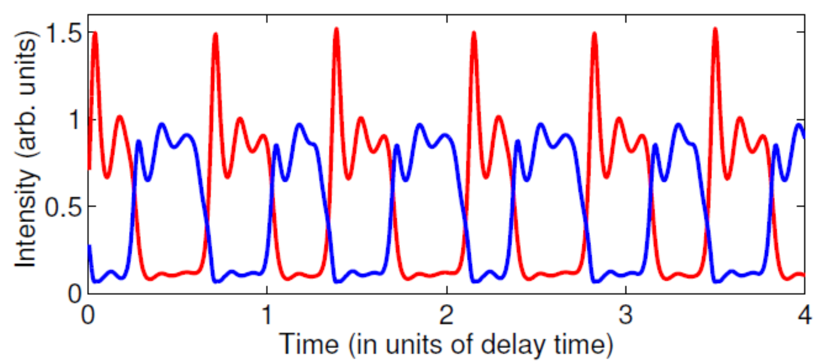
Bifurcation analysis reveals stable and unstable SWs with different periods

- ❑ Stable square-wave switching (intensity above zero)



- ❑ Unstable square-wave switching (intensity gets to about zero)





Period ≈2τ/3

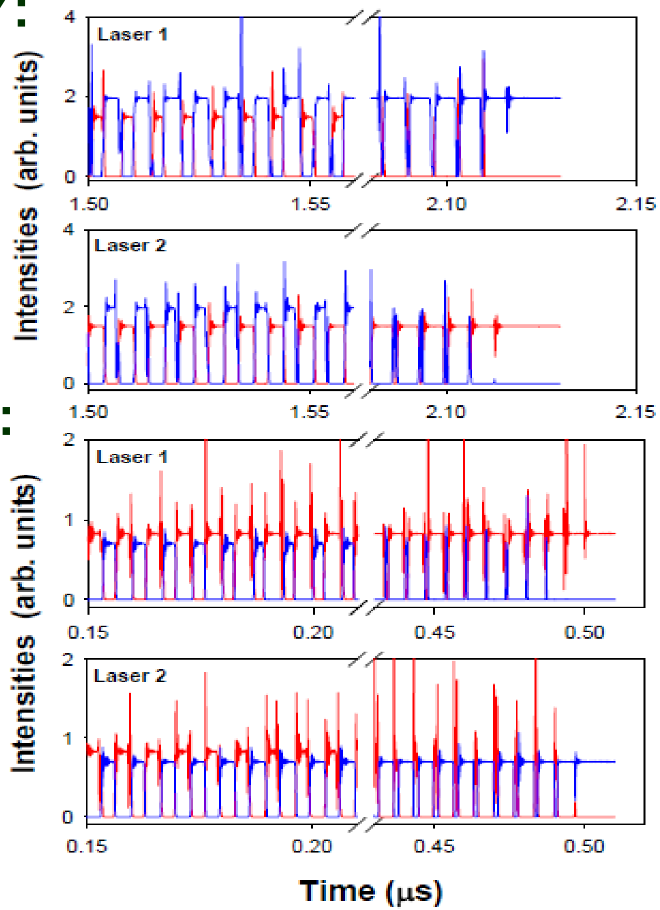
Sciamanna et al, submitted (2012)

Simulations with VCSEL model

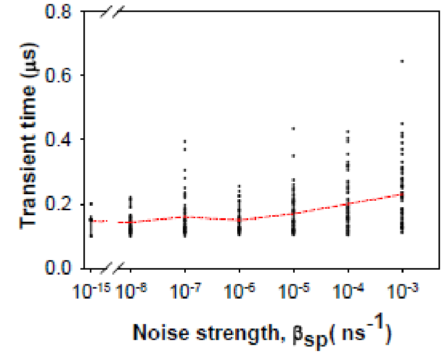
The square waves are only a transient dynamics:

X →Y:

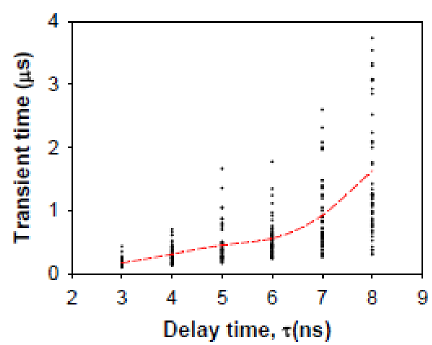
Y →X:

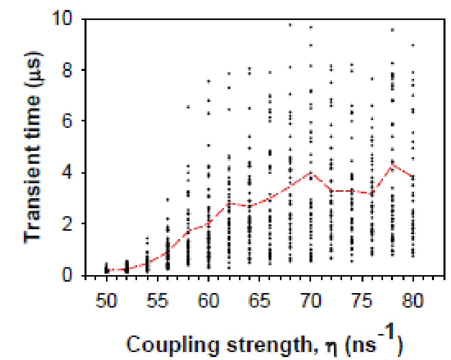


The average transient time is almost unaffected by the noise strength:



And increases with the coupling parameters:





Marita Torre , A. Gavrielides & C. Masoller, Optics Express 19, 20269 (2011)

Summary and future work

- We studied all-optical polarization square-wave switching in semiconductor lasers.
- We considered polarization-rotated time-delayed optical feedback and mutual coupling.
- We considered two types of semiconductor lasers: edge-emitting lasers (EELs) and vertical-cavity lasers (VCSELs).
- In EELs: the inclusion of nonlinear gain saturation in the model yields stable SWs even in the absence of noise.
- In VCSELs: good agreement between simulations and experiments in the feedback scheme, no experiments available yet on the coupling scheme.
- Future work: influence of gain saturation terms and how to enhance the parameter region of stable SW switching

THANK YOU FOR YOUR ATTENTION