UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

Grup de Recerca en Dinàmica No Lineal, Òptica No Lineal i Làsers

Polarization square-wave switching in orthogonally delay-coupled semiconductor lasers

Cristina Masoller

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Fifth Rio de la Plata Workshop on Laser Dynamics and Nonlinear Photonics, Colonia, Uruguay, December 2011

Outline

- DONLL research group @ UPC
- Square waves
  - Semiconductor lasers: edge-emitting & VCSELs
  - SWs induced by polarization rotated optical feedback
  - SWs induced by polarization rotated optical coupling
- Summary

UPC

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONA**TECH**

- www.upc.edu
- The UPC is the main technical university in Catalonia, and 1of 3 largest technical universities in Spain.
- Campus in **8** Catalan towns (2 campuses in Barcelona)
- DONLL research group based in Campus Terrassa

Group on Dinamica, Optica NoLineal & Lasers

http://donll.upc.edu/

People

9 faculty

3 posdocs

10 phd students

several undergrads

DONLL group et al
November 2011

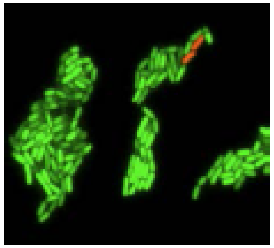
Research Objectives

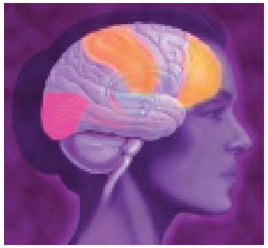
Study of the mechanisms and consequences of ***nonlinear phenomena*** in different fields:

- **Photonics:**

  Nonlinear Optics and Nonlinear Dynamics

- **Neuroscience**
- **System's biology**





- **Others:**

  Nonlinear electronics, Nonlinear acoustics, Cold atoms, Neuronal networks, Fracture dynamics in solids,…

Photonics

Spatially modulated materials

Linear & nonlinear light propagation phenomena

Kestutis Staliunas
José F. Trull
Crina Cojocaru
Ramon Herrero
Muriel Botey
Ramon Vilaseca

Cristian Nistor
Vito Roppo
Lina Maigyte
Nikhil Kumar

Semiconductor laser dynamics

Nonlinear light dynamics

Cristina Masoller
M. Carme Torrent
Jordi García Ojalvo
Ramon Vilaseca

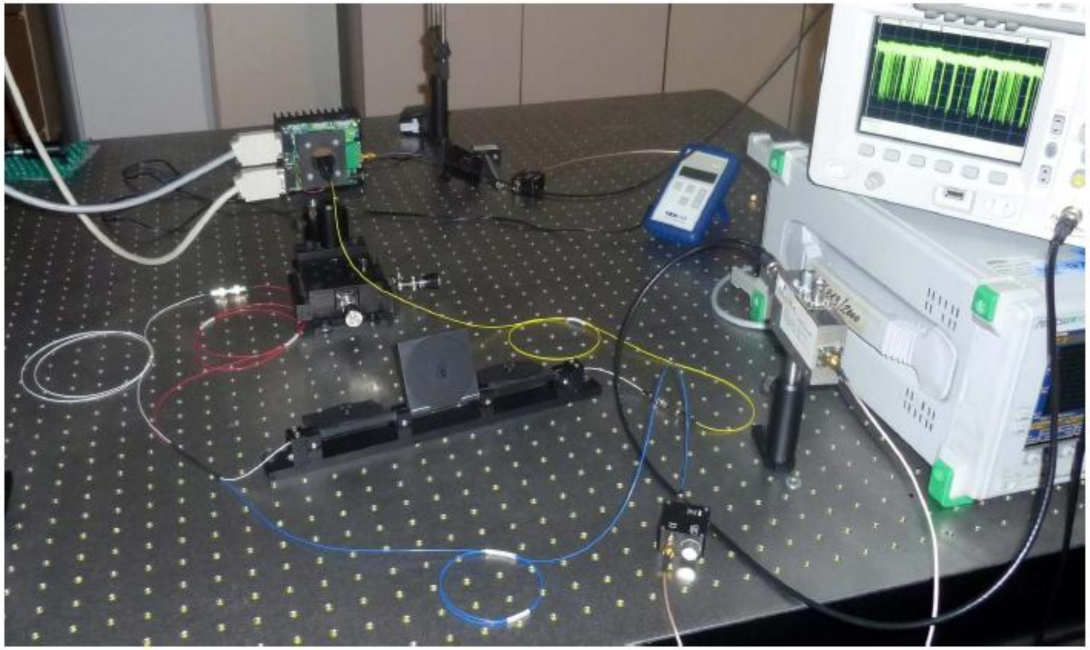
Jordi Tiana
Jordi Zamora
Andrés Aragoneses

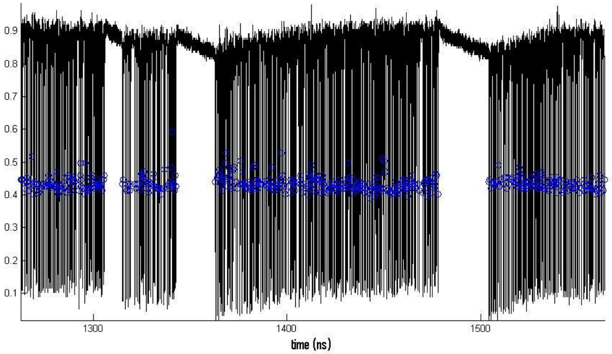
Other configurations or problems

Nonlinear light dynamics

Carles Serrat
Kestutis Staliunas
Ramon Herrero
Muriel Botey
Ramon Vilaseca
Josep Lluís Font
Juanjo Fernández

Semiconductor Laser dynamics





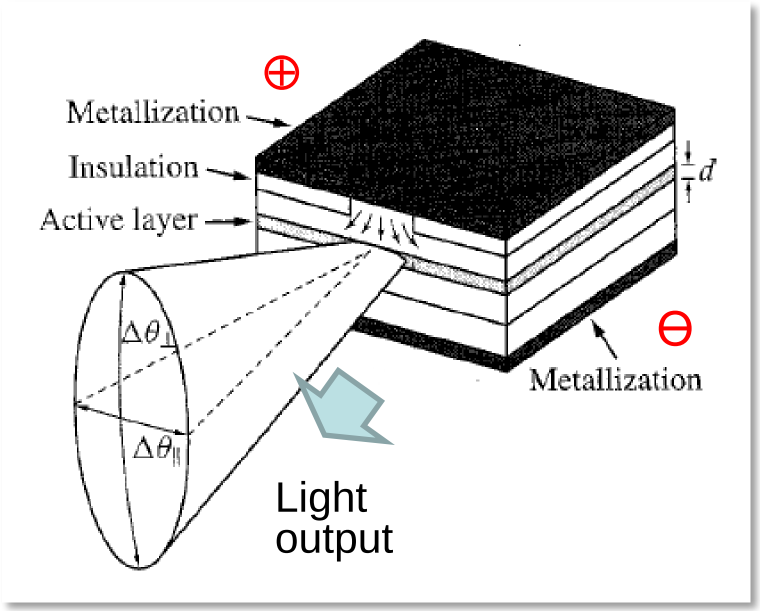
Recent efforts in Terrassa have been focused on

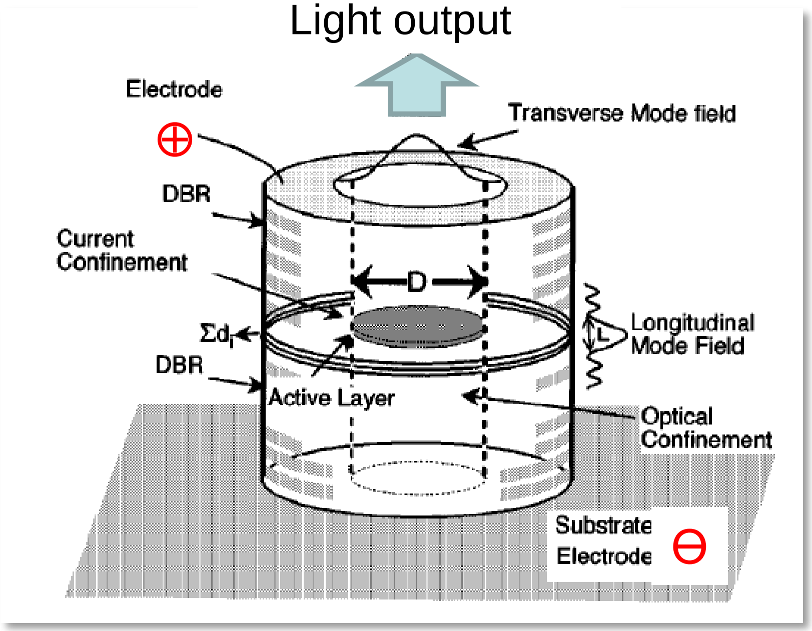
- quantifying the dynamical complexity of the output of a semiconductor laser with optical feedback
- detecting signatures of deterministic dynamics in the LFFs using *nonlinear time series methods* (via symbolic representation of events)

Semiconductor lasers: two types of geometries

Edge-Emitting lasers (EELs)

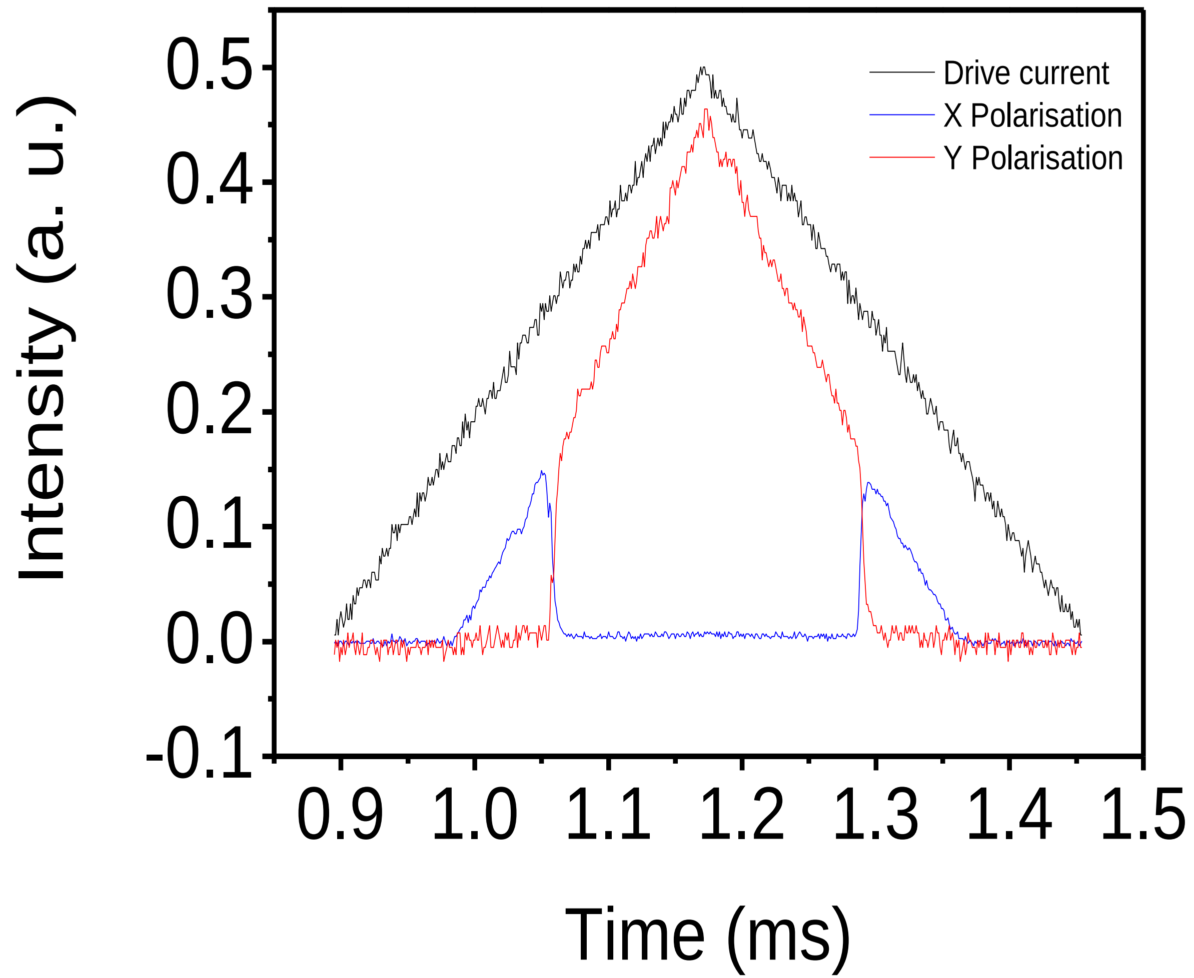
Vertical-Cavity Surface-Emitting Lasers (VCSELs):





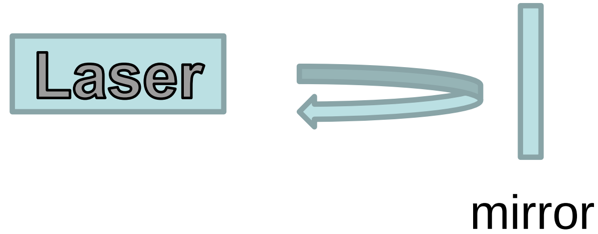
with different polarization properties

VCSELs: Polarization switching, bi-stability and hysteresis



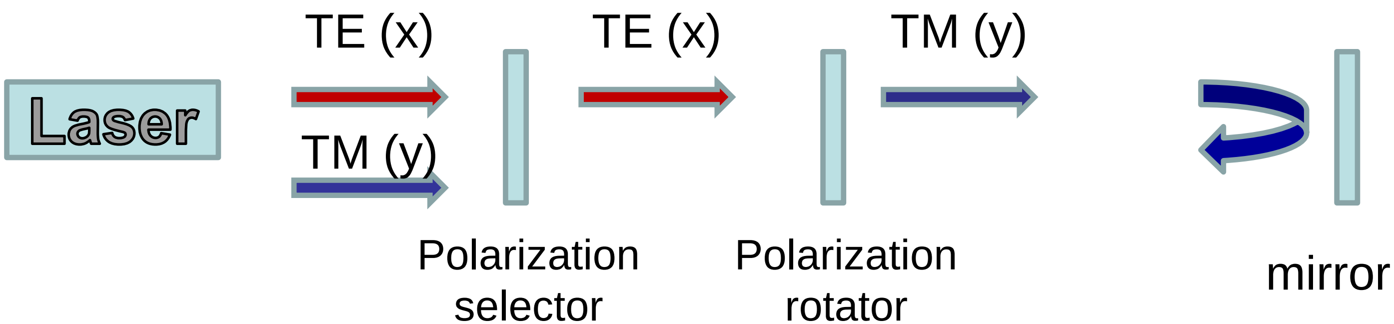
Time delayed optical feedback: two setups

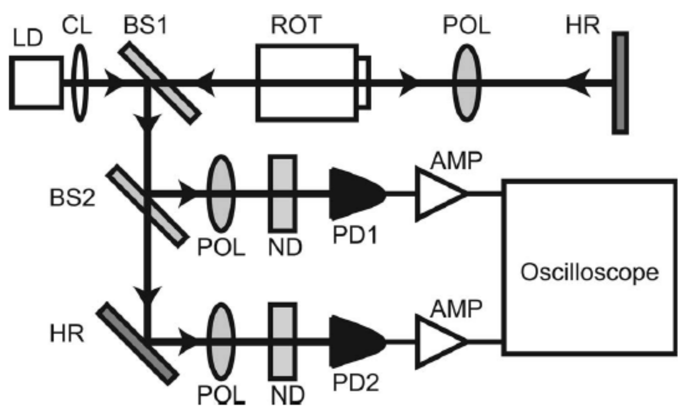
Isotropic optical feedback:



Polarization-rotated optical feedback:

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



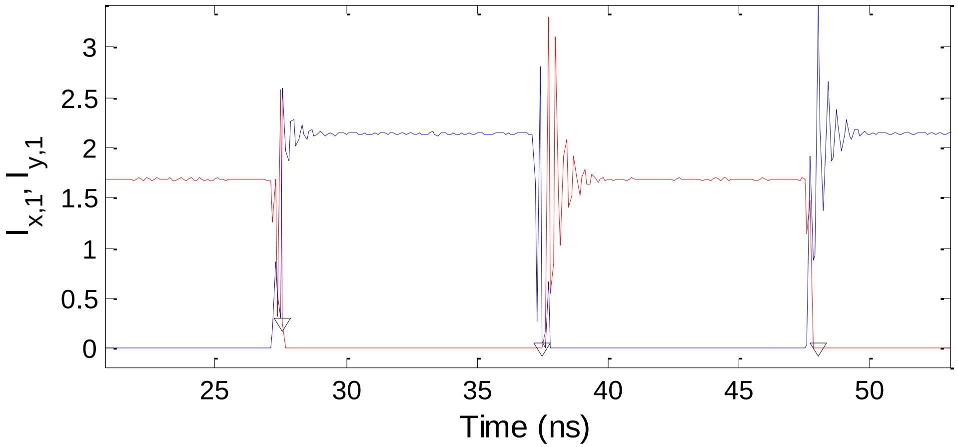


Gavrielides et al, Opt. Lett. 31, 2006 (2006)

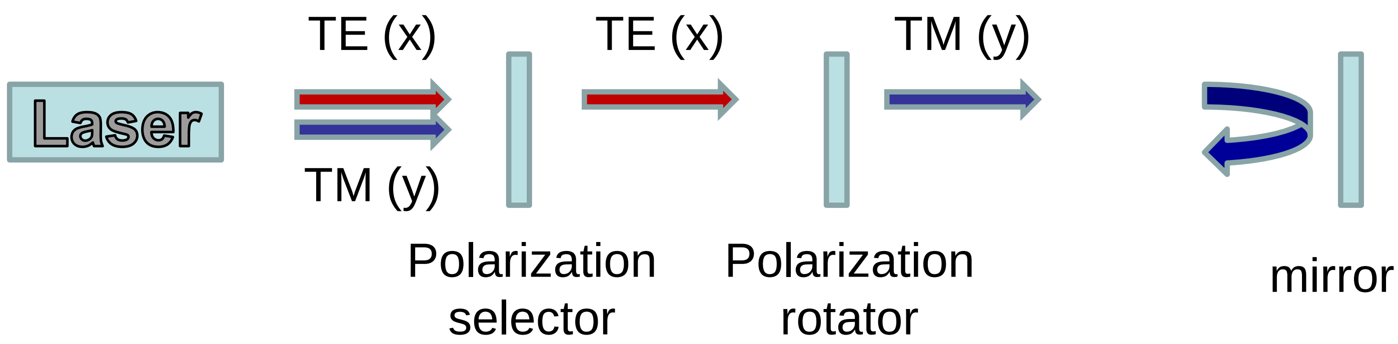
Motivation for studying polarization-rotated feedback or coupling?

Besides providing insight into semiconductor laser physics and models, these schemes can

- produce optical square-waves with GHz repetition rates without the need for high-speed electronics,
- Sharp and fast rising and falling edges



Model for polarization-rotated feedback



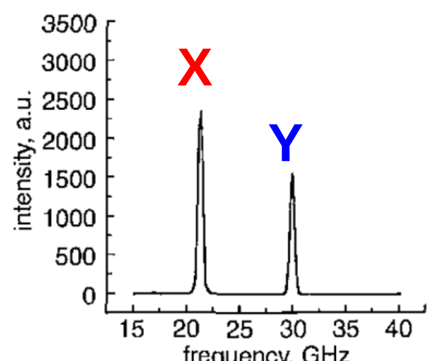
$$\frac{dE_x}{dt} = \frac{1}{2\tau_p}(1+i\alpha)(N-1)E_x + \sqrt{2\beta_{sp}}\xi_x(t)$$

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

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

Polarization-rotated feedback

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

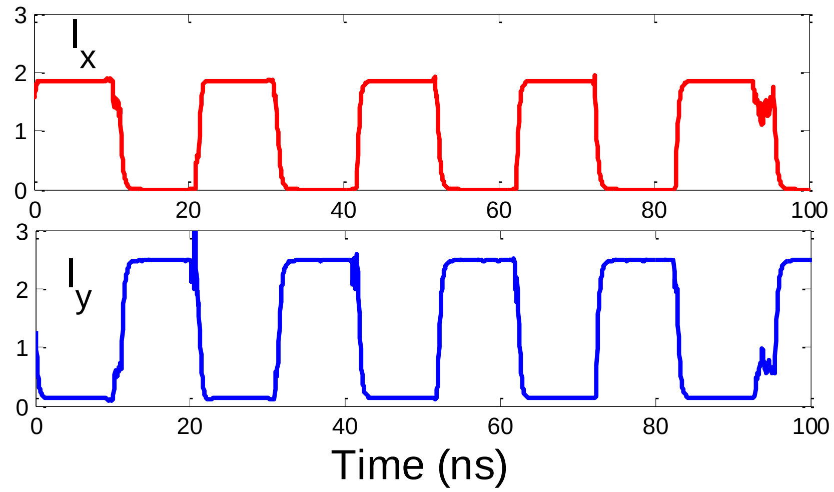


Adapted from Hong et al, Elec. Lett. 36, 2019 (2000)

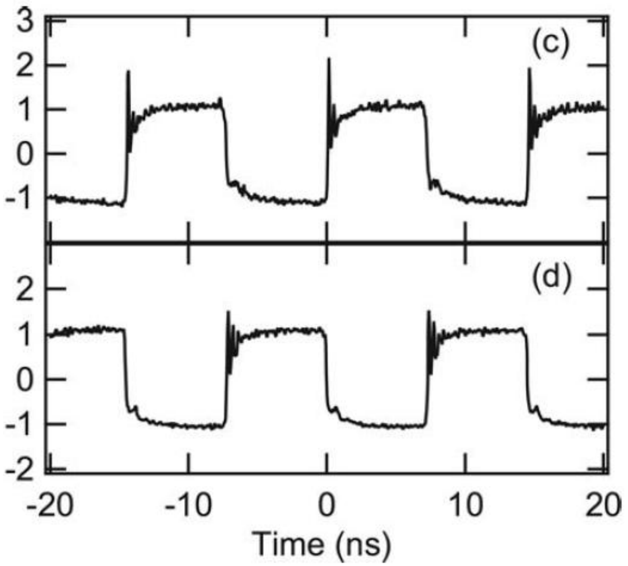
Feedback-induced polarization square-wave switching

Simulations
τ=10 ns

Periodicity: 2τ

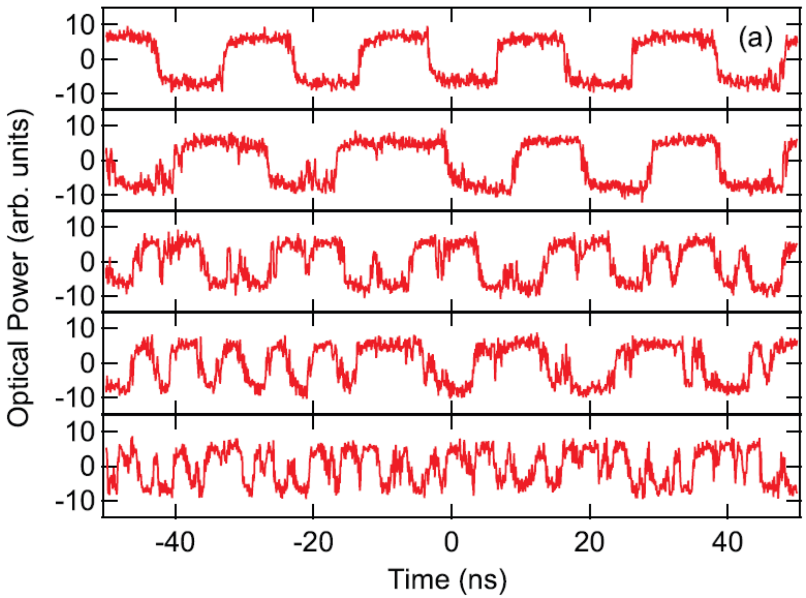


Experimental observations (EELs)
Gavrielides et al, Opt. Lett. 31, 2006 (2006)



Experimental observations with VCSELs

Noisy and unstable SWs:

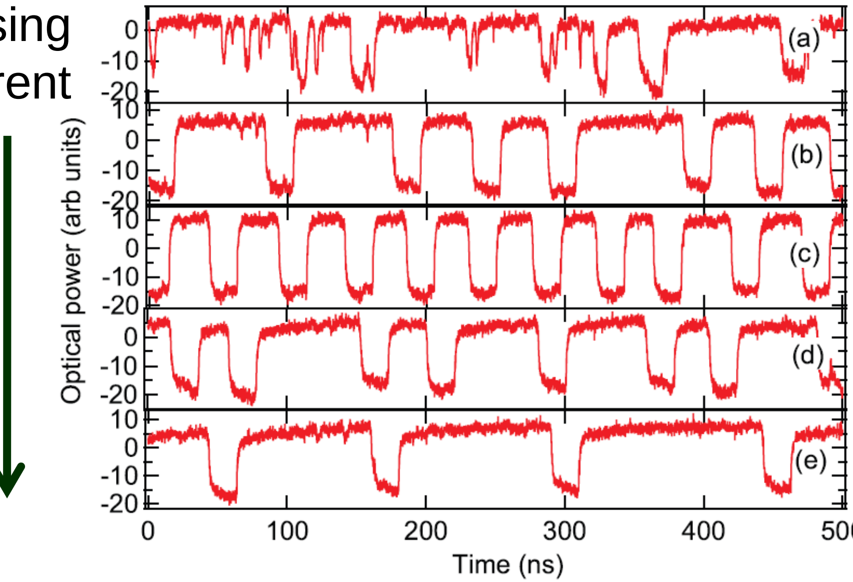


Time traces taken under identical conditions

Sukow et al, submitted (2011)

Influence of the laser current:

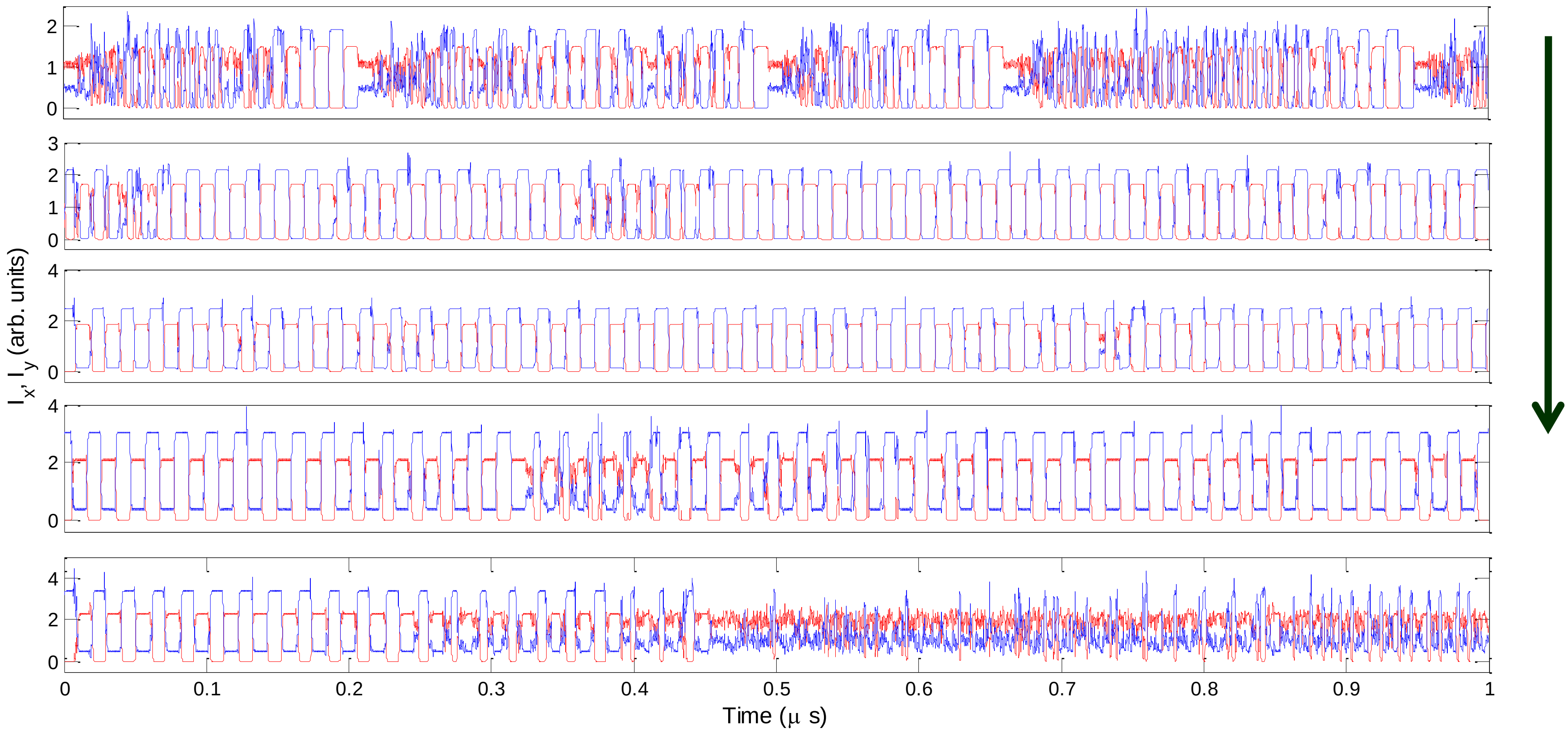
Increasing current



Optimal regularity at a certain current value

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

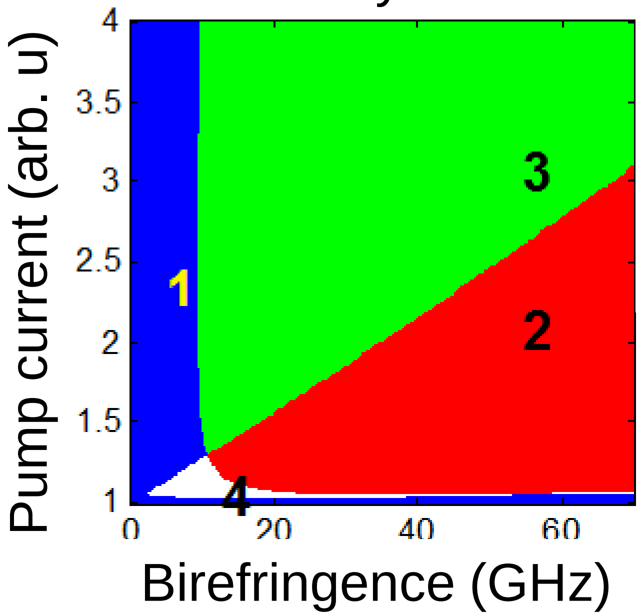
Influence of the injection current: Increasing μ

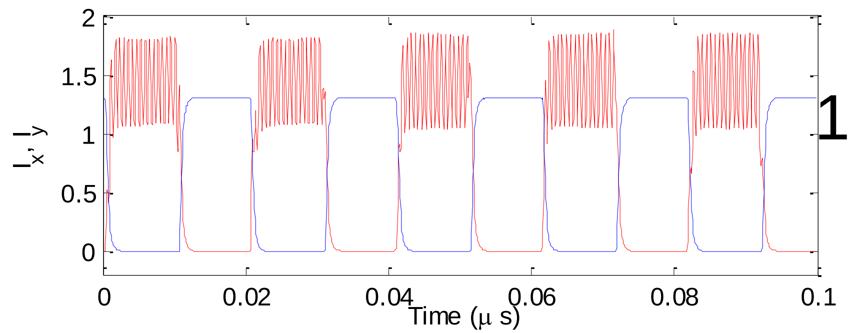


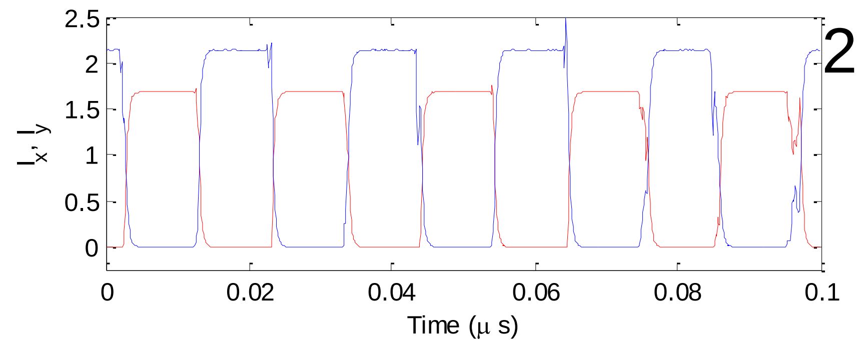
Sukow et al, submitted (2011)

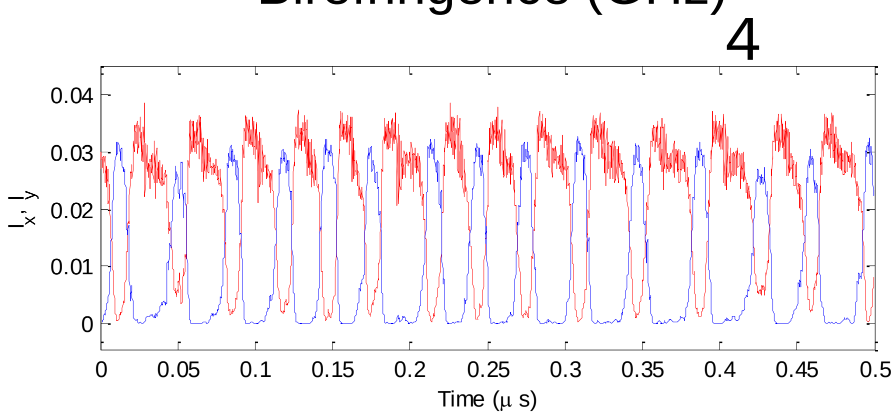
SWs in relation with the parameter region where the solitary VCSEL is mono-stable

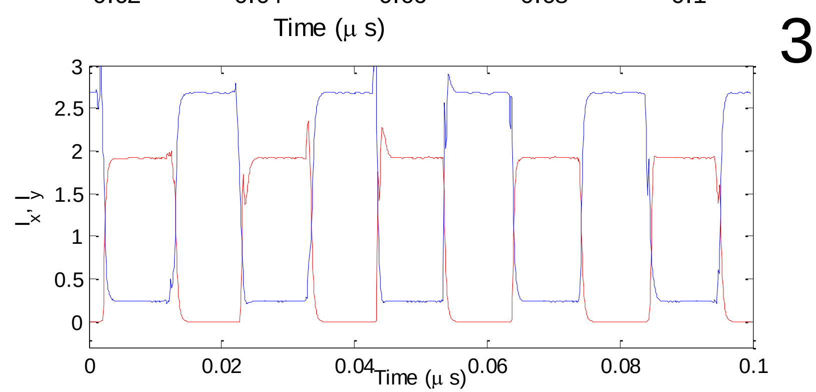
Stability of the solitary modes:



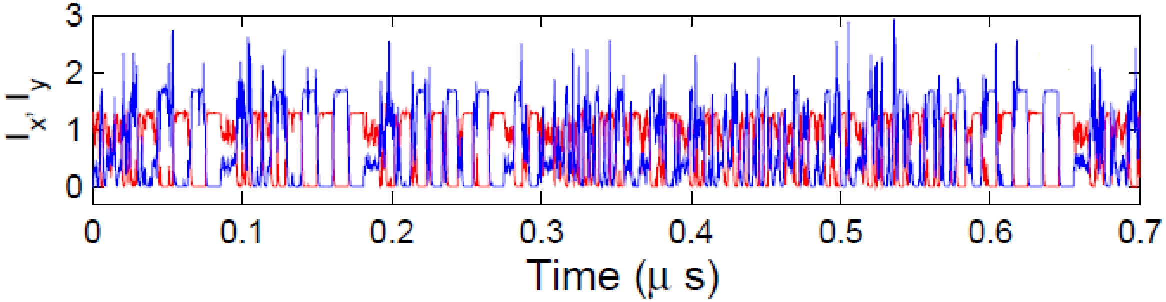






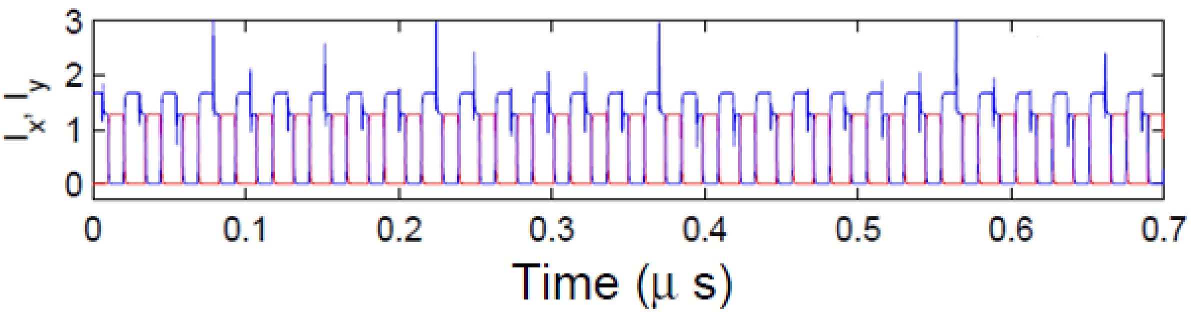


Influence of noise (I)



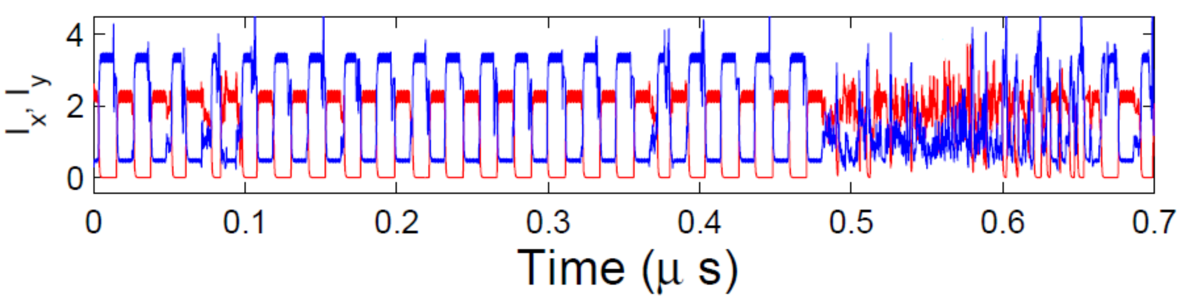
$\mu = 2.3$ *Pump current parameter*

$\beta_{sp} = 10^{-4}\,\text{ns}^{-1}$ *Noise strength*



$\mu = 2.3$

$\beta_{sp} = 0$



$\mu = 3.8$

$\beta_{sp} = 0$

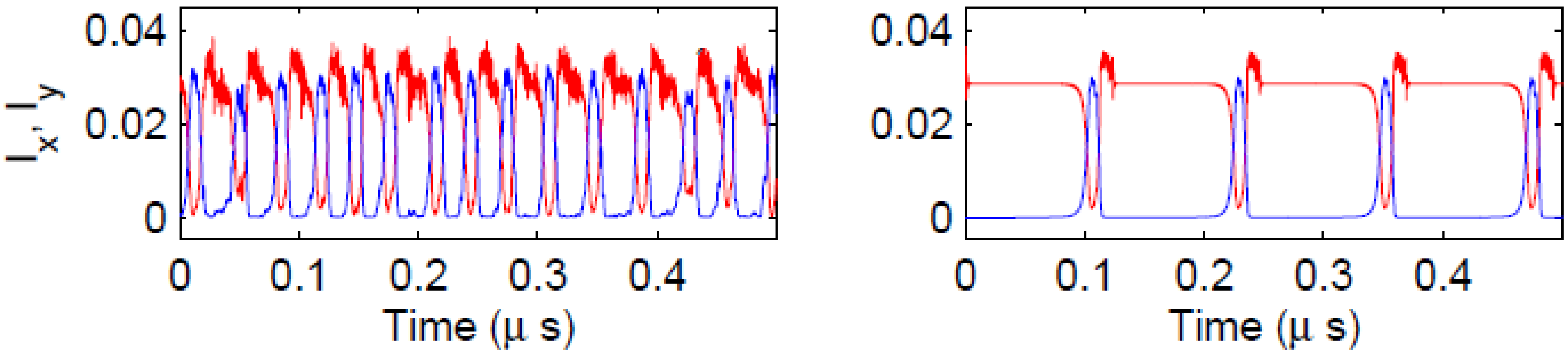
- *Al low pump current the degradation of the SWs is mainly noise-induced.*
- *At higher pumps, the SW degradation also has a deterministic origin*

Influence of noise (II)

$\mu = 1.03$

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

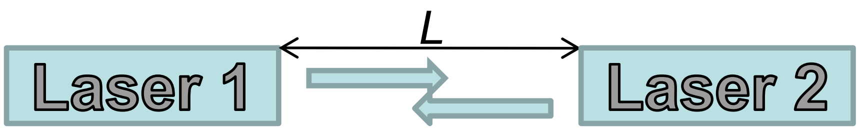
$\beta_{sp} = 0$



- *For parameters near the bistability boundaries square-wave switching can be noise-induced.*

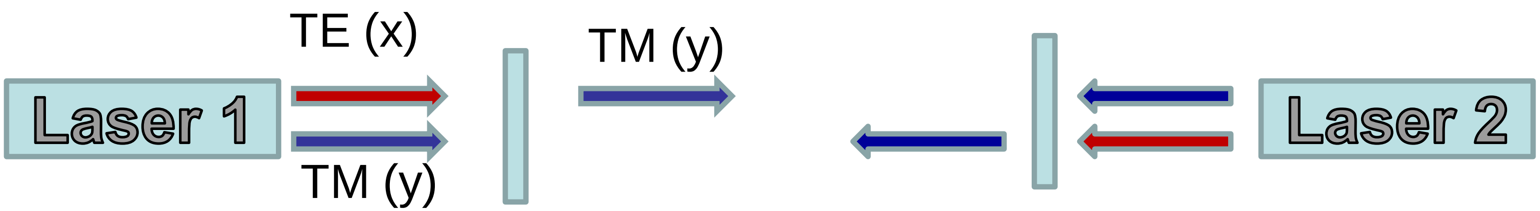
Time delayed mutual coupling

Isotropic coupling



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

Polarization-rotated coupling

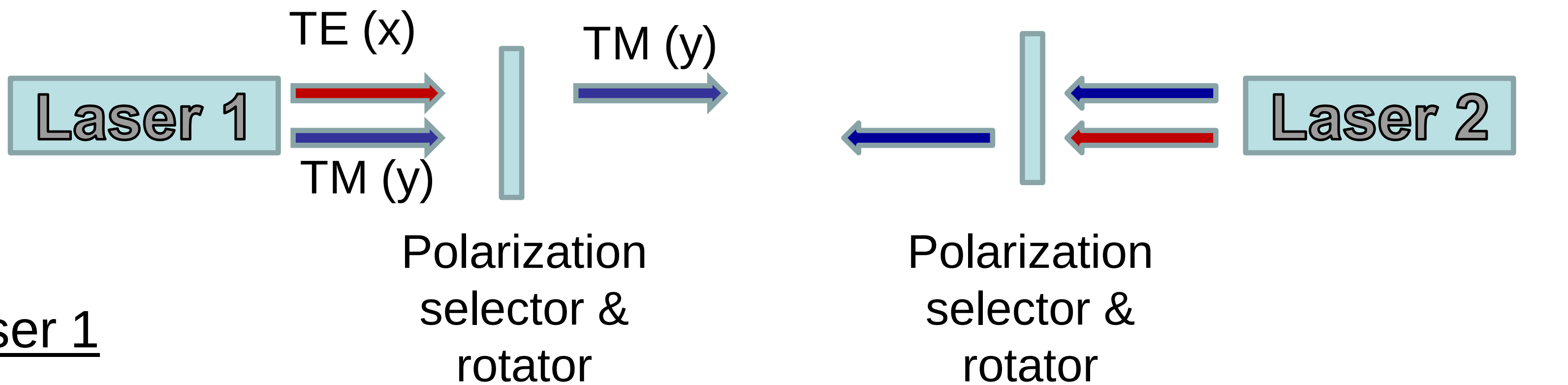


Polarization selector & rotator

Polarization selector & rotator

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

Model for polarization-rotated coupling



Laser 1

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

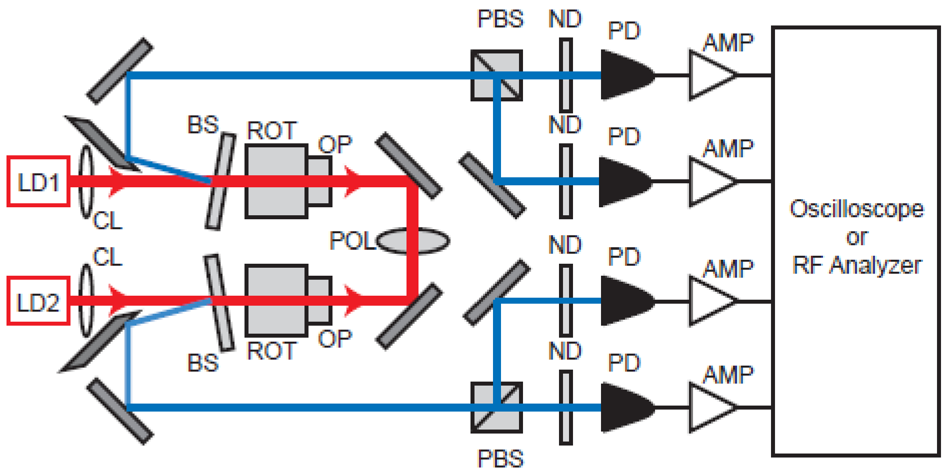
$$\frac{dE_{1,y}}{dt} = \frac{1}{2\tau_p}(1+i\alpha)(N_1-1-\underline{\gamma_a})E_{1,y} + i\underline{\gamma_p}E_{1,y} + \sqrt{2\beta_{sp}}\xi_{1,y}(t) + \underbrace{\eta E_{2,x}(t-\tau)e^{-i\omega_0\tau}}$$

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

Polarization-rotated coupling

And vice-versa for laser 2

Experimental observations (EELs)

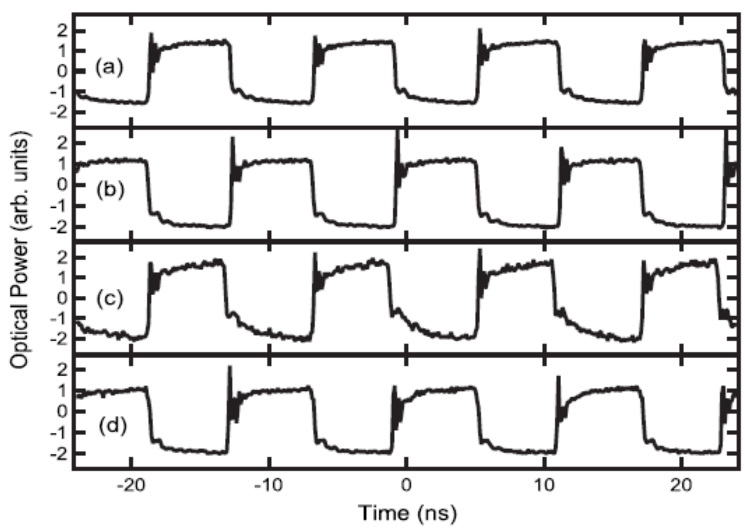


I_{1x}

I_{1y}

I_{2x}

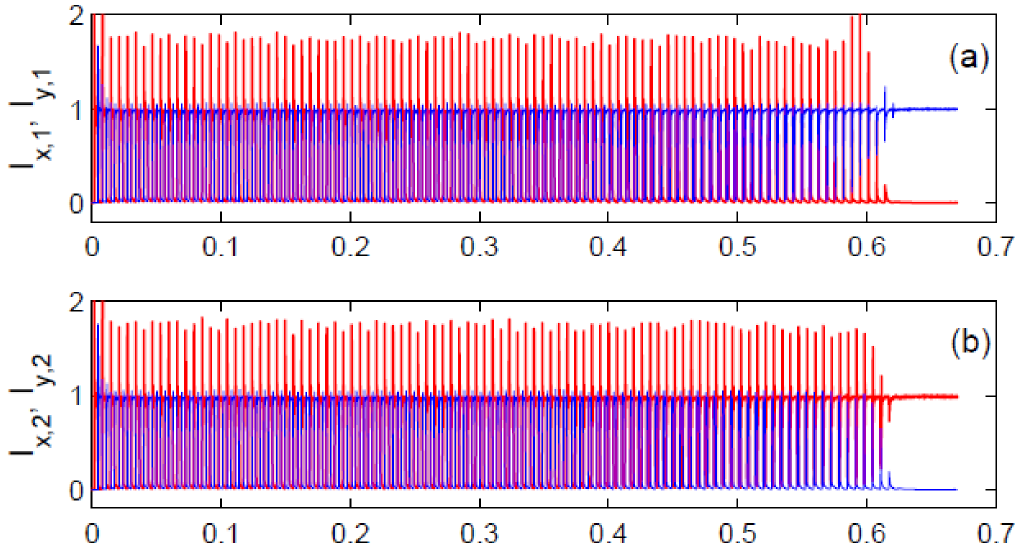
I_{2y}



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

Numerical simulations (EELs)

Polarization square-wave switching is a transient dynamics:



‘Injected laser’

‘Solitary laser’

Stationary state: master-slave unidirectional coupling, Laser 2 → Laser 1

‘Injected laser’

‘Solitary laser’

Polarization selector & rotator

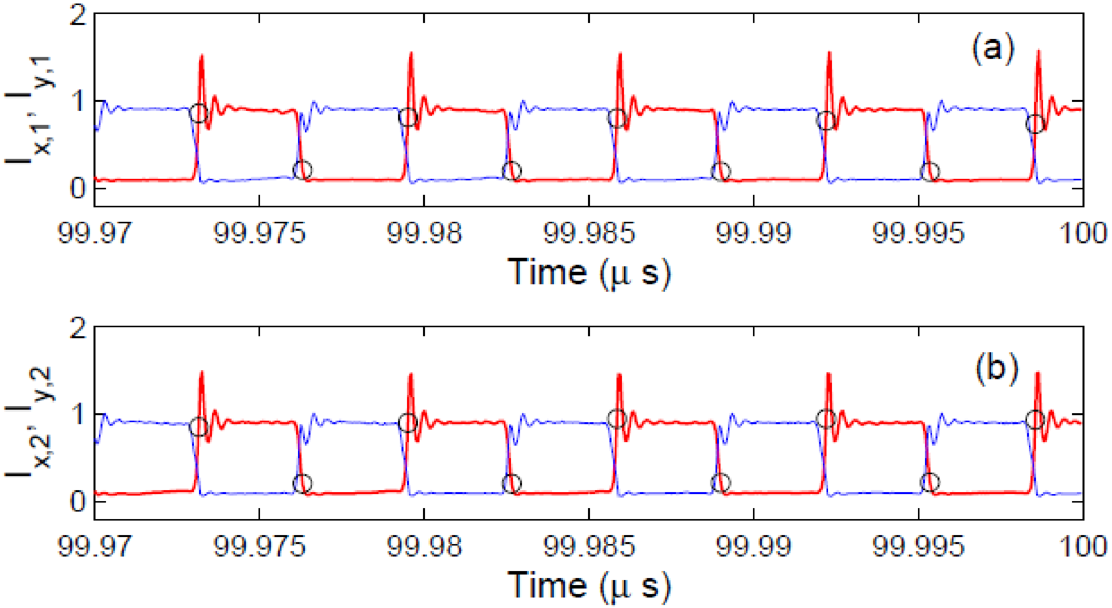
Polarization selector & rotator

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

Transient vs stationary square-wave switching

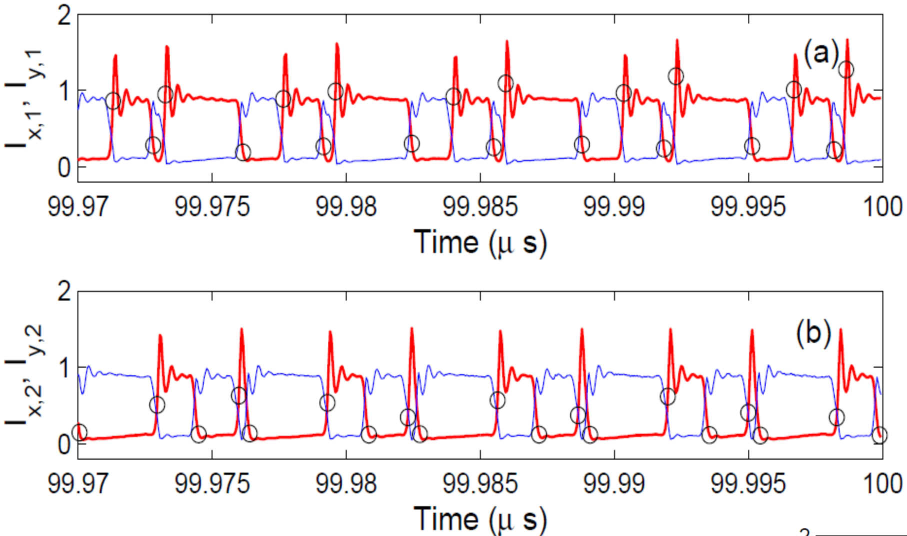
However, by including in the model nonlinear gain saturation (self and cross saturation coefficients), in certain parameter regions, regular square-wave switching becomes a stable dynamics.

Symmetrical switching

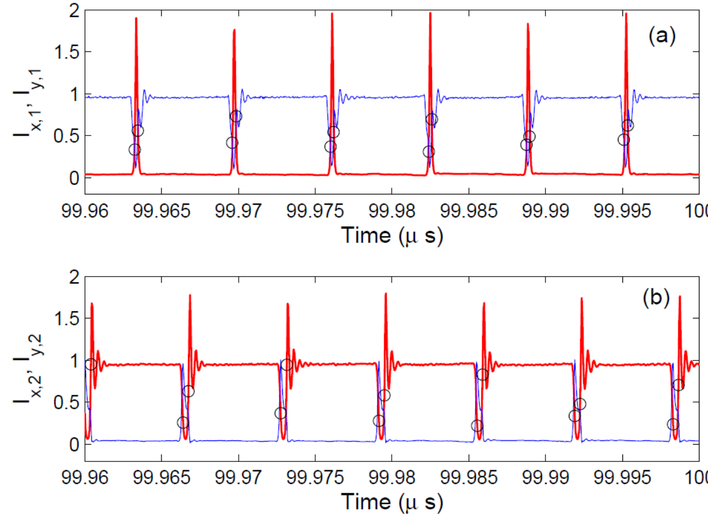


Multi-stability in the form of various types of coexisting waveforms

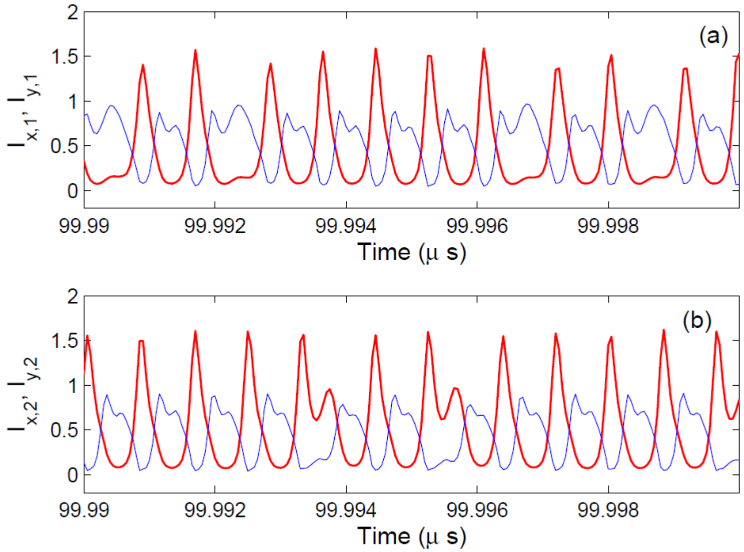
Nonsymmetrical switching



Nonsymmetrical pulses

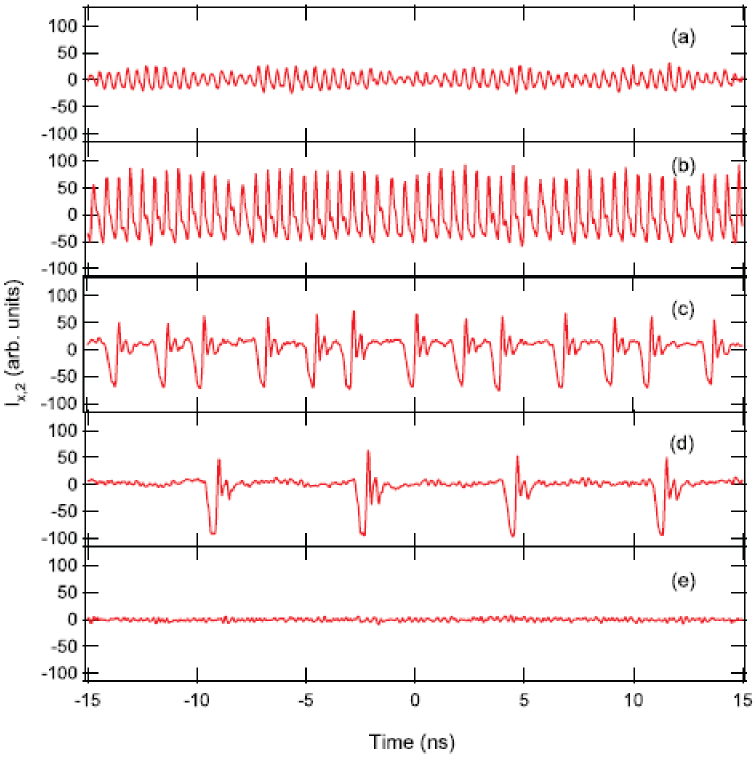


Nonsymmetrical oscillations

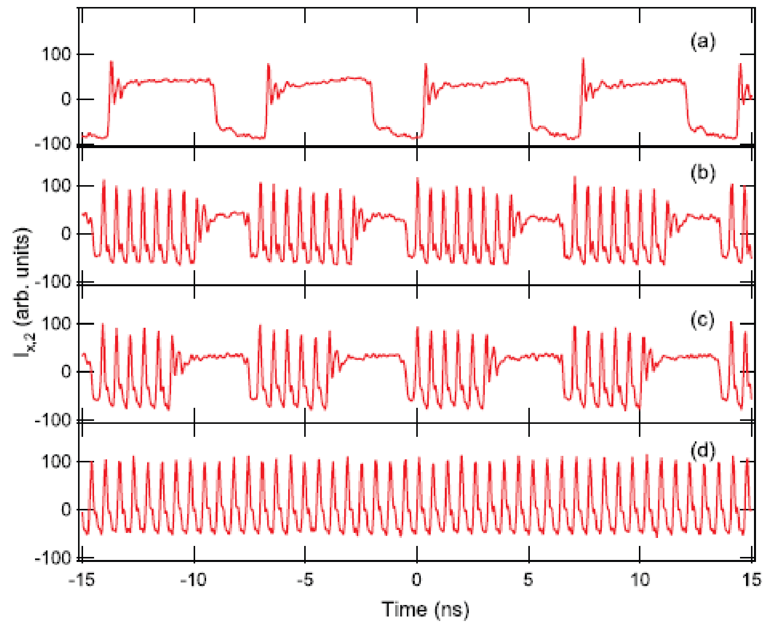


Experimental observations

For increasing coupling strength



Multistability of coexisting solutions



Time traces of the intensity of one mode of one laser

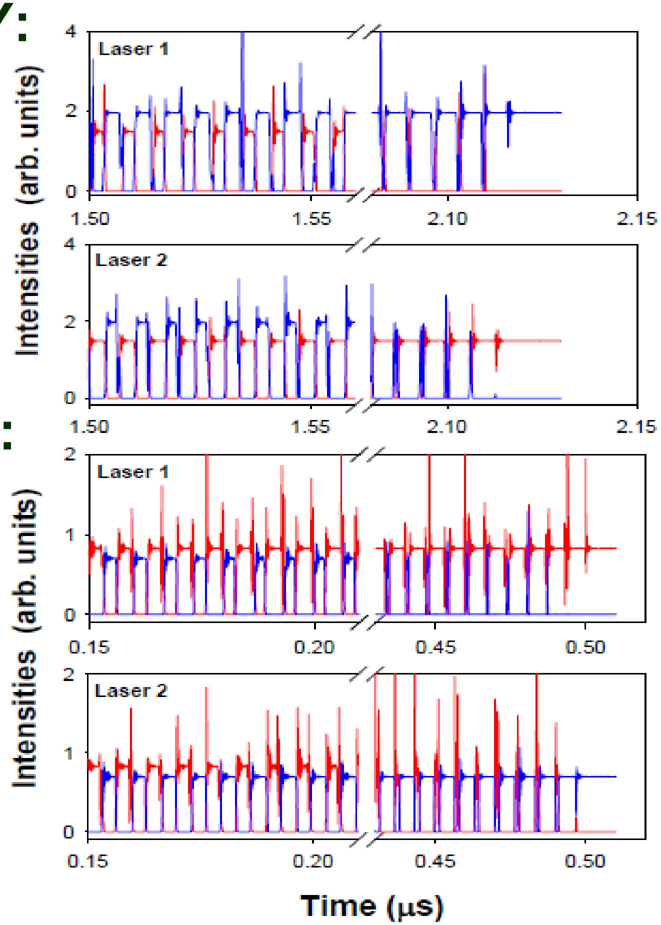
C. Masoller, D. Sukow, A. Gavrielides & M. Sciamanna, PRA 84, 023838 (2011)

Numerical simulations with VCSELs

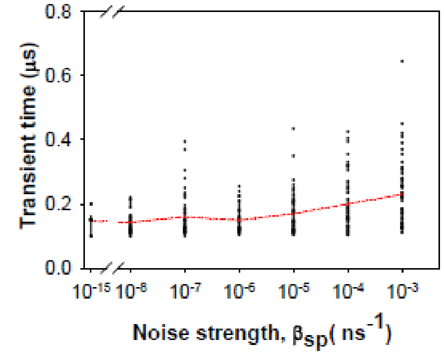
The square waves are only a transient dynamics:

X →Y:

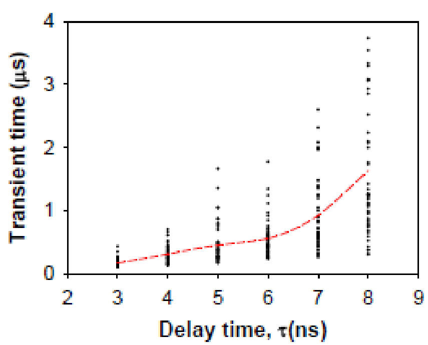
Y →X:

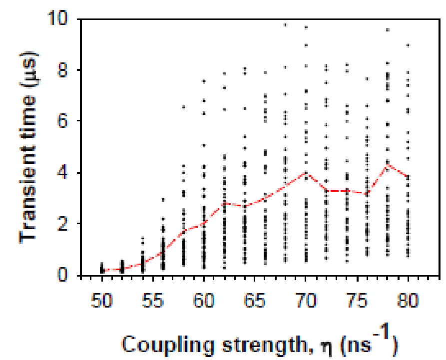


The average transient time is almost unaffected by the noise strength:



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: good agreement between experimental observations and numerical simulations (when the model includes gain saturation terms).
- In VCSELs: good agreement between simulations and experiments in the feedback scheme, no experiments available so far on the mutual coupling scheme.

THANK YOU FOR YOUR ATTENTION

Acknowledge: EOARD grant FA8655-10-1-3075