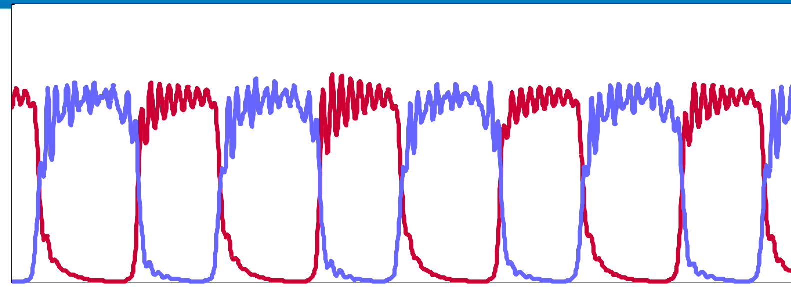

Interplay of bistability, noise and delay in semiconductor lasers: complex dynamics and applications

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SIAM Conference on Applications of Dynamical Systems, Snowbird, Utah, US, May 2013

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Outline

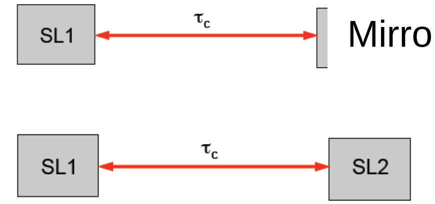
- Introduction
  - Semiconductor lasers
  - Edge-emitting lasers and vertical-cavity lasers
  - Time-delayed feedback and time-delayed coupling

- All-optical square wave switching
  - Induced by optical feedback
  - Induced by optical coupling

- Conclusions and perspectives

Why semiconductor lasers?

- SLs have many advantages:
  - are compact, fast, reliable, inexpensive
  - wide range of wavelengths



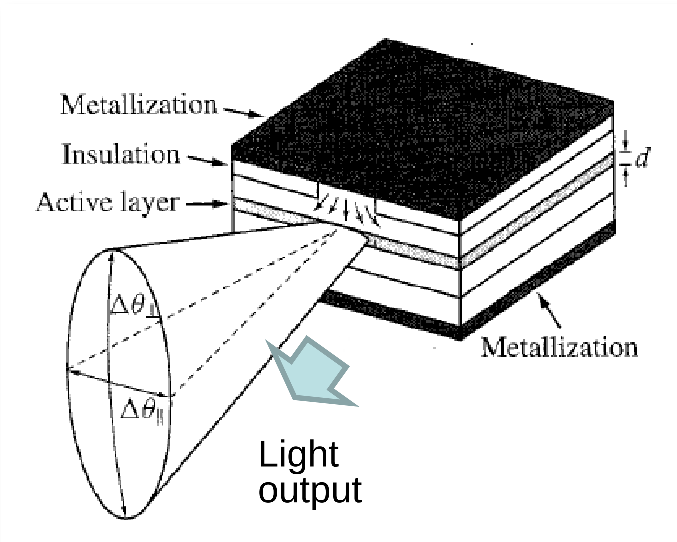
- Nowadays are used in
  - Telecommunications
  - Data storage (CDs, DVDs)
  - Barcode scanners, printers, mouse
  - Sensing & material processing
  - Life sciences

- Under optical feedback or coupling: **nonlinear dynamics**.
- Complex interplay of:
  - delay
  - noise
  - nonlinearity
- that can be exploited for applications.

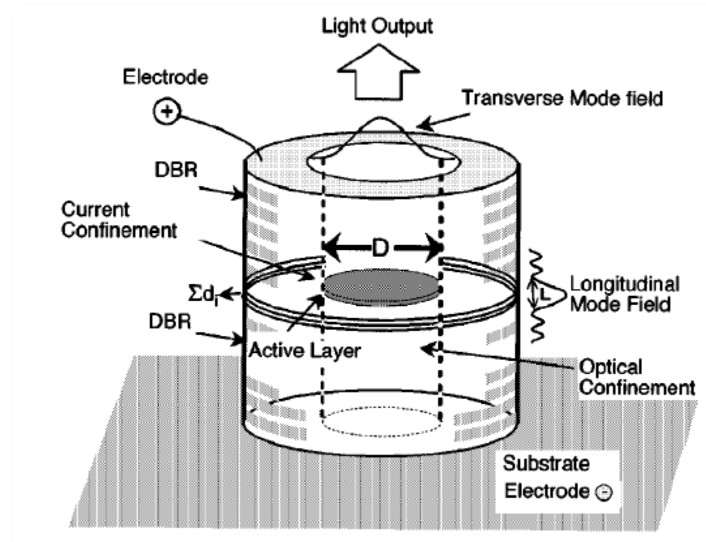
Goal: to induce all optical switching with GHz repetition rates without the need of high-speed electronics

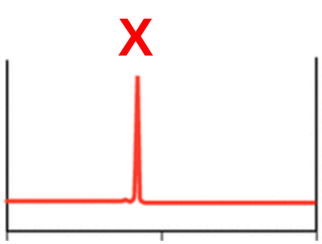
Semiconductor lasers

Edge-Emitting (EELs)

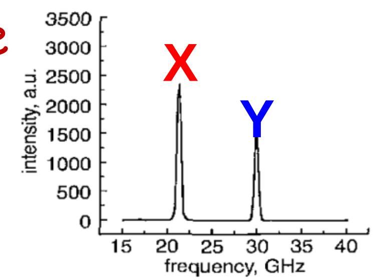


Vertical-Cavity (VCSELs):





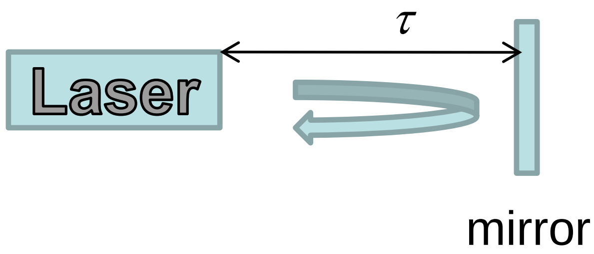
these lasers have different polarization properties



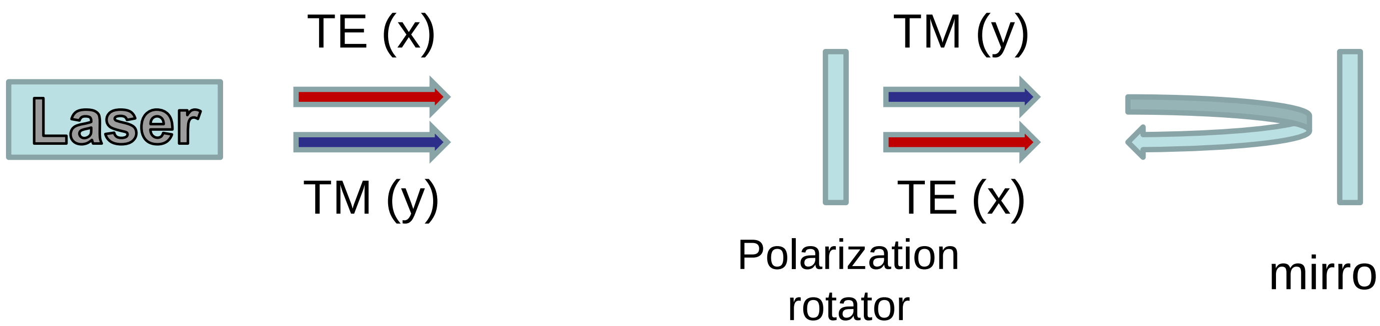
Hong et al, Elec. Lett. (2000)

Time-delayed feedback

- Isotropic

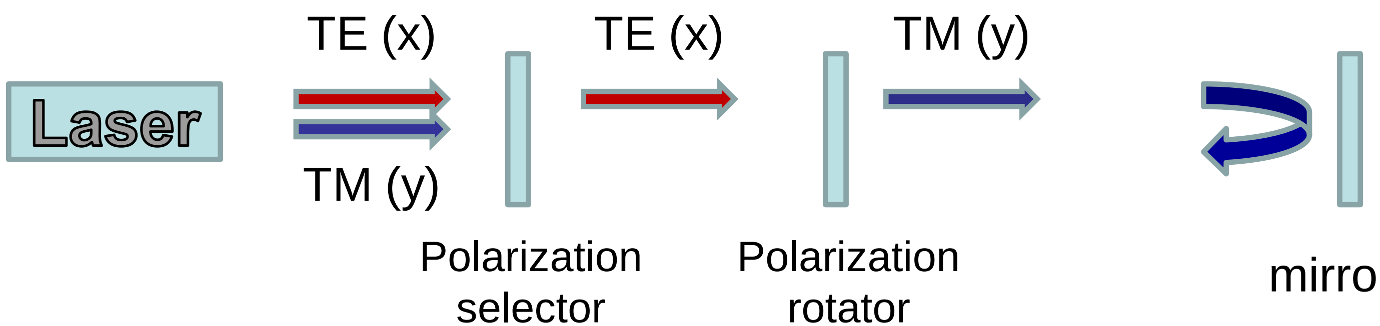


- Orthogonal



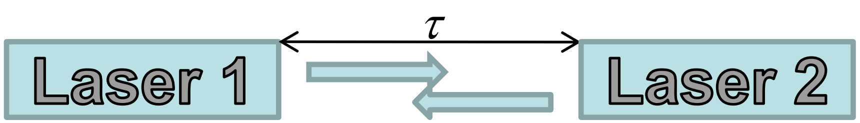
- Polarization-rotated

(TE (x) is the polarization of the light emitted by the laser without feedback)



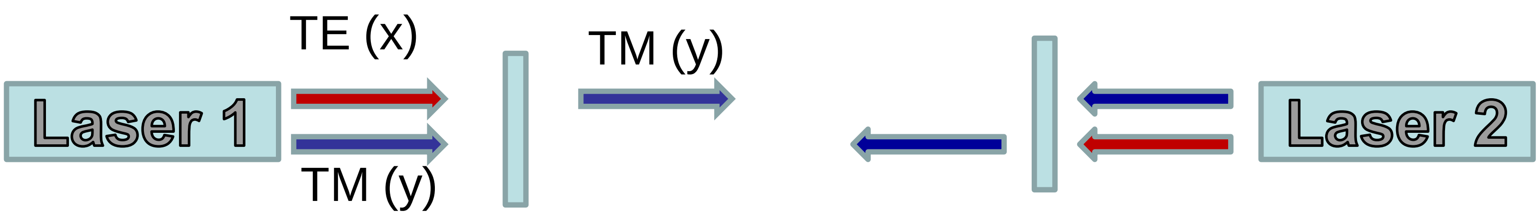
Time-delayed coupling

- Isotropic



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

- Polarization-rotated

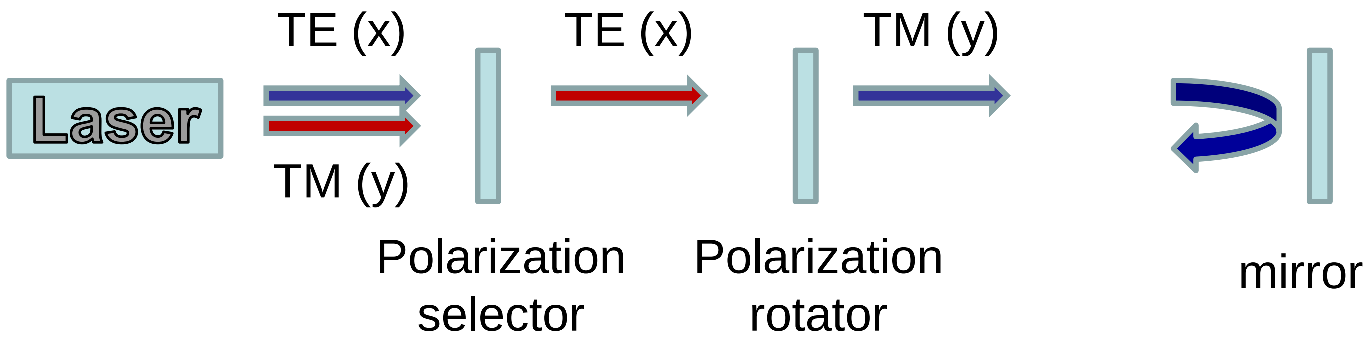


(TE (x) is the polarization of the light emitted by the lasers without coupling)

Polarization selector & rotator

Polarization selector & rotator

Governing equations



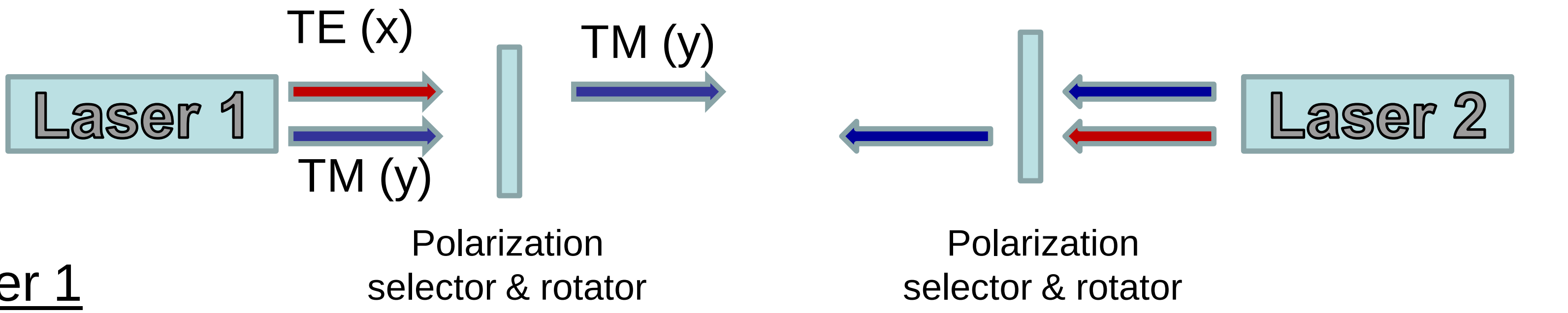
$$\frac{dE_x}{dt} = \frac{1}{2\tau_p}(1+i\alpha)(N-1)E_x + \sqrt{2\beta_{sp}}\xi_x$$

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

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

γ_a and γ_p represent anisotropies between the two polarizations

Coupled lasers model



Laser 1

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

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

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

And the same for <u>laser 2</u>

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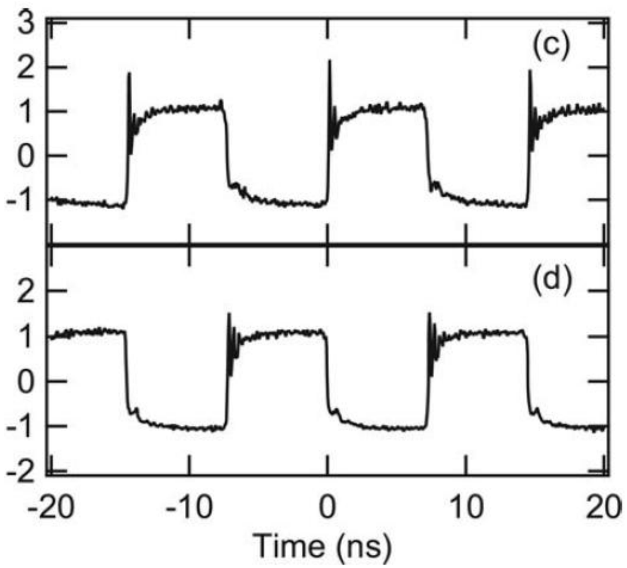
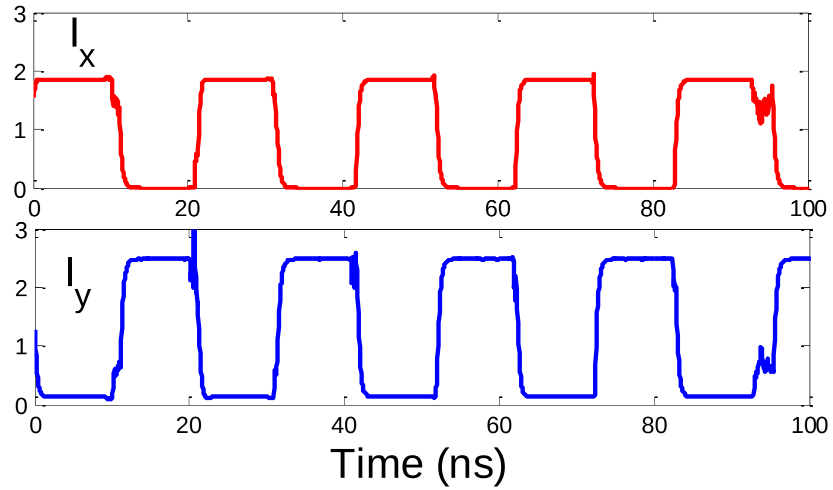
Square-wave switching in edge-emitting lasers

Experimental observations

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



Simulations



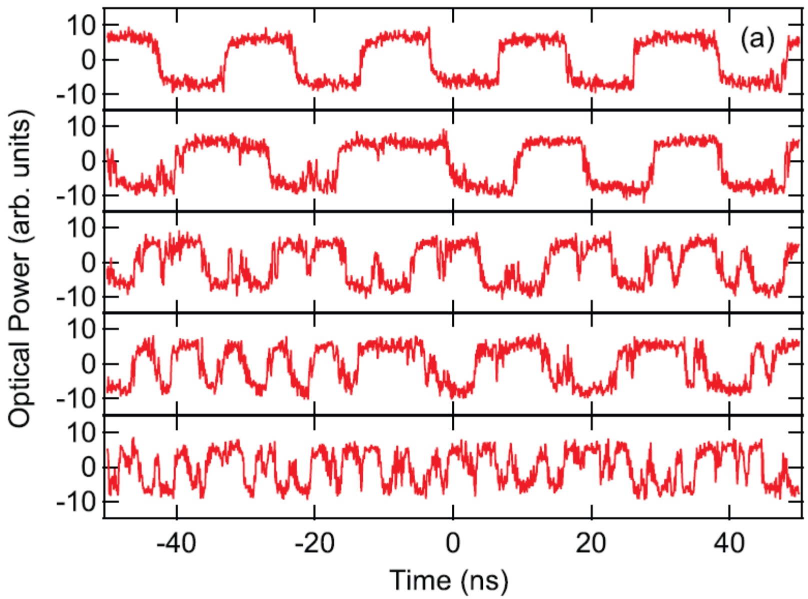
Periodicity: 2τ (τ=10 ns)

- sharp rising and falling edges

Interpretation: polarization self-modulation is a time-dependent solution that connects two fixed points that are orthogonally polarized

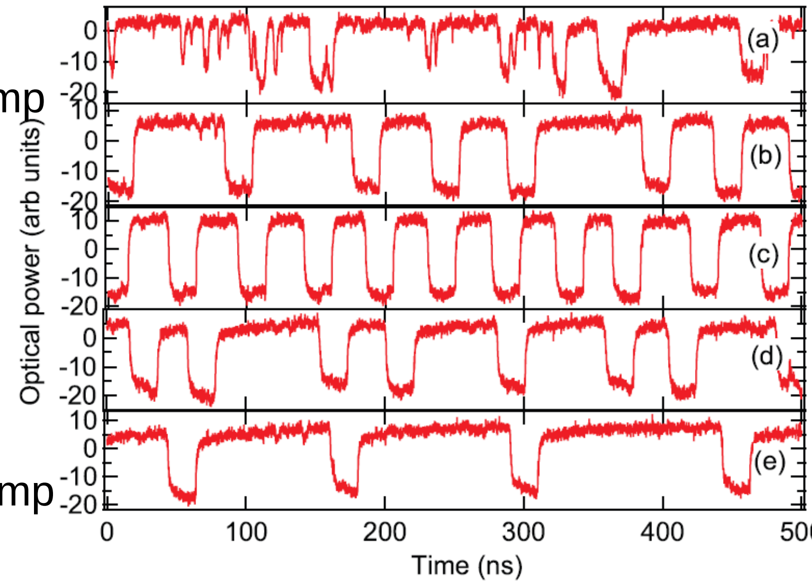
Square wave switching is noisier in vertical-cavity lasers

Time traces obtained under identical conditions:



Influence of the pump current:

Low pump



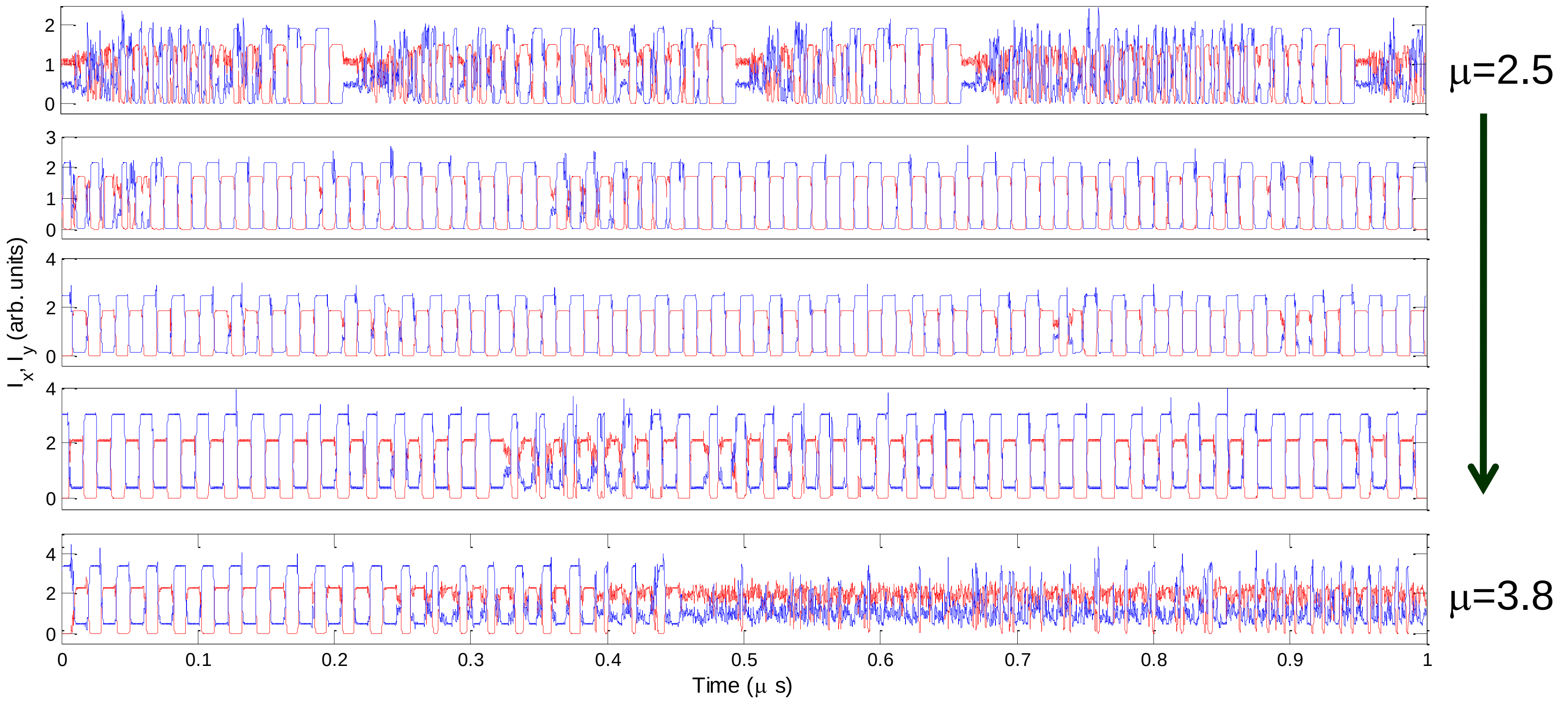
High pump

Optimal switching regularity at an optimal current value

D. Sukow, T. Gilfillan, B. Pope, M. S. Torre, A. Gavrielides, C. Masoller, *Phys. Rev. A 86, 033818 (2012)*

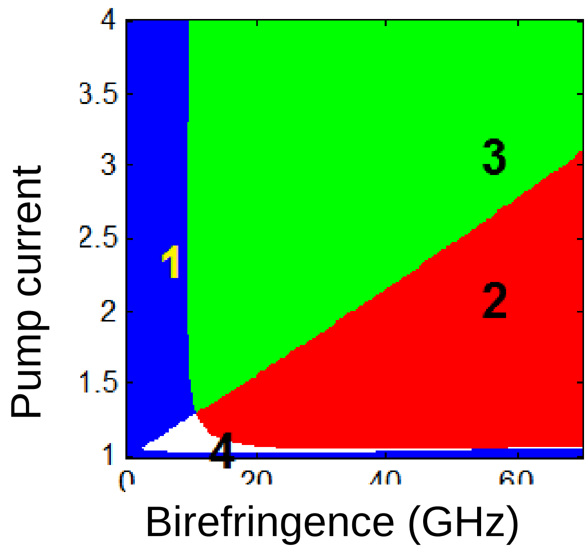
Simulations in good agreement with observations

Increasing the pump current parameter:

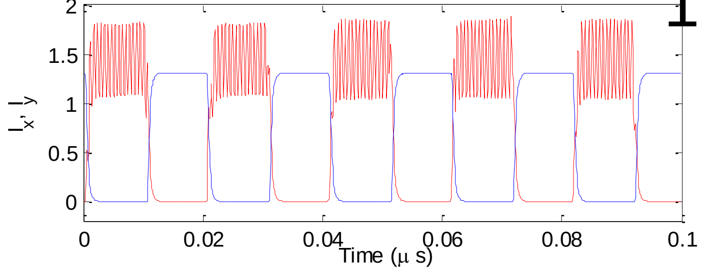


Various types of switching

Stability of X, Y without feedback: **Red: X**, **Blue: Y**, White: both, Green: none



1



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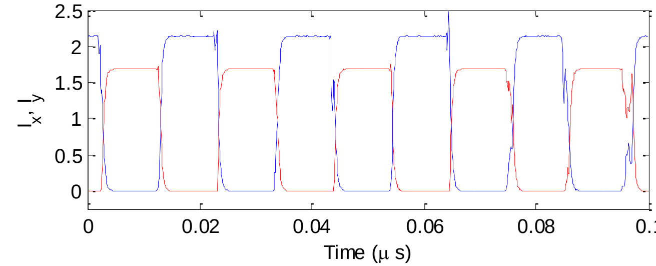

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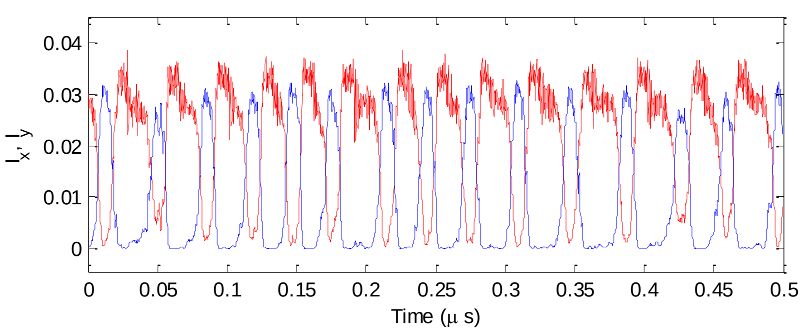

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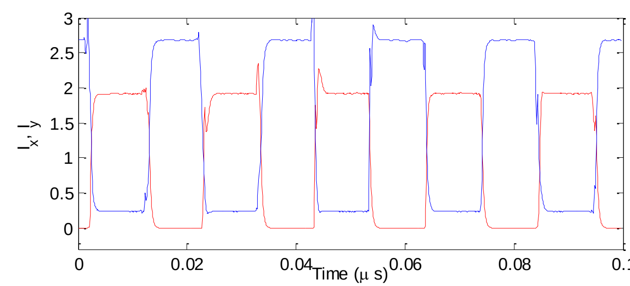

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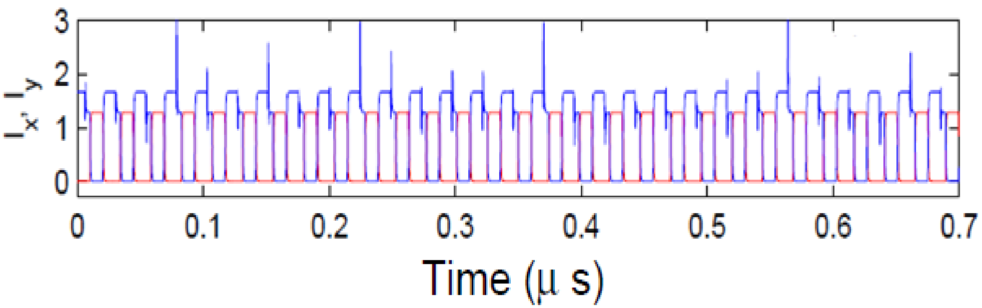
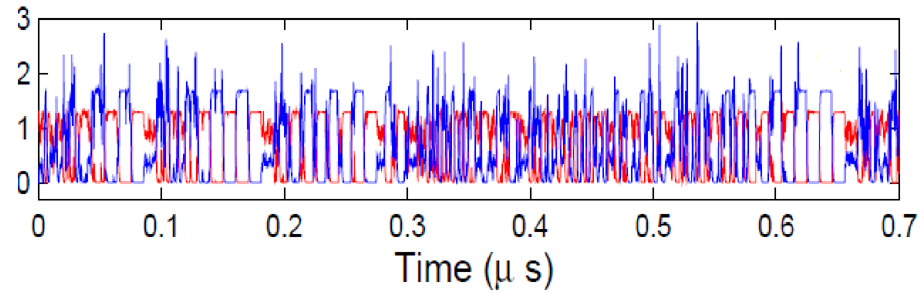
Influence of spontaneous emission noise

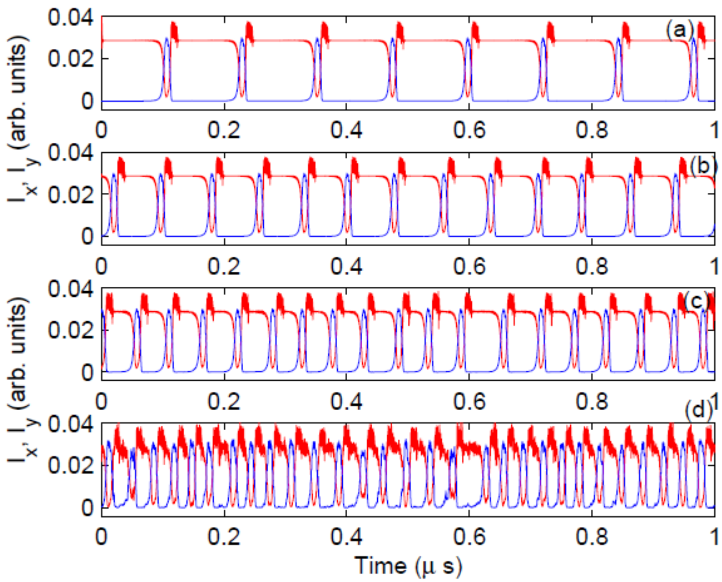
No noise:



Including noise:



At lower pump, increasing the noise strength:



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

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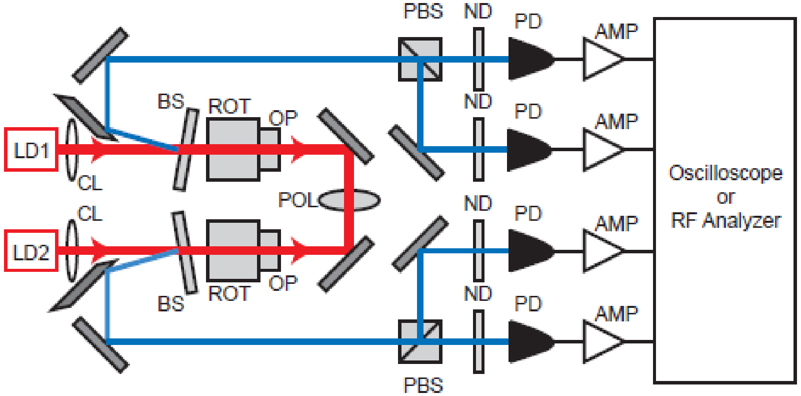
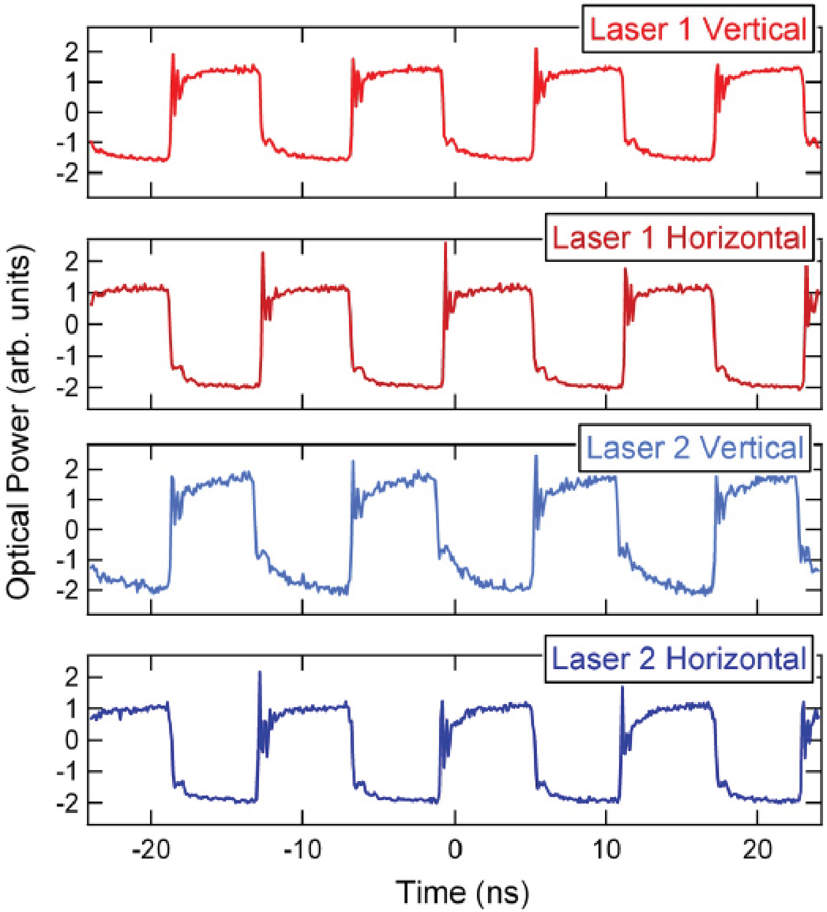
In two coupled edge-emitting lasers





Interpretation: polarization self-modulation is a time-dependent solution that connects two fixed points ("pure modes") in which the lasers are orthogonally polarized.

Pure mode A:

$I_{1,x} = I, \quad I_{1,y} = 0$

$I_{2,x} = 0, \quad I_{2,y} = I$

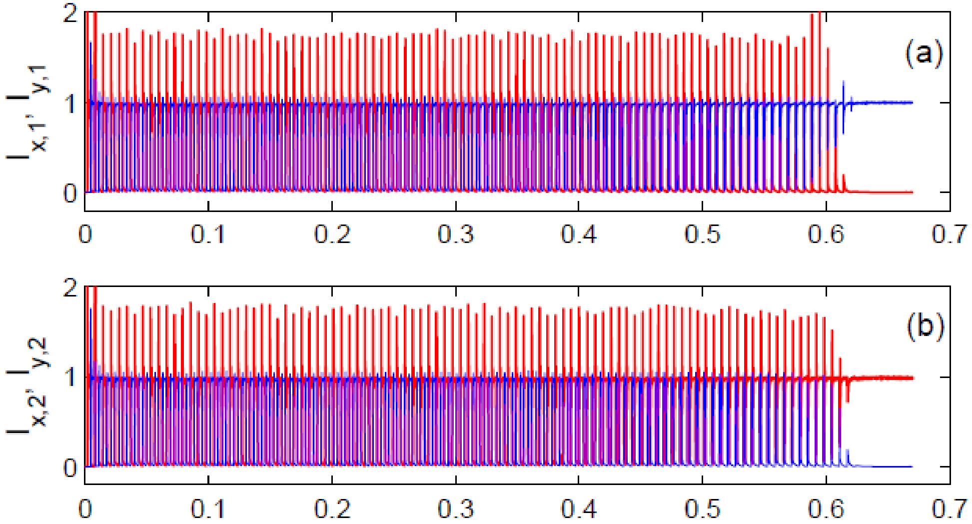
Pure mode B:

$I_{1,x} = 0, \quad I_{1,y} = I$

$I_{2,x} = I, \quad I_{2,y} = 0$

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

Simulations: transient SWs



'Injected laser'

'Master laser'

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

<u>Stationary state</u>:

$I_{1,x}= 0$, $I_{1,y}= I$
$I_{2,x}= I$, $I_{2,y}= 0$
(pure mode B)

unidirectional coupling: Laser 2 → Laser 1

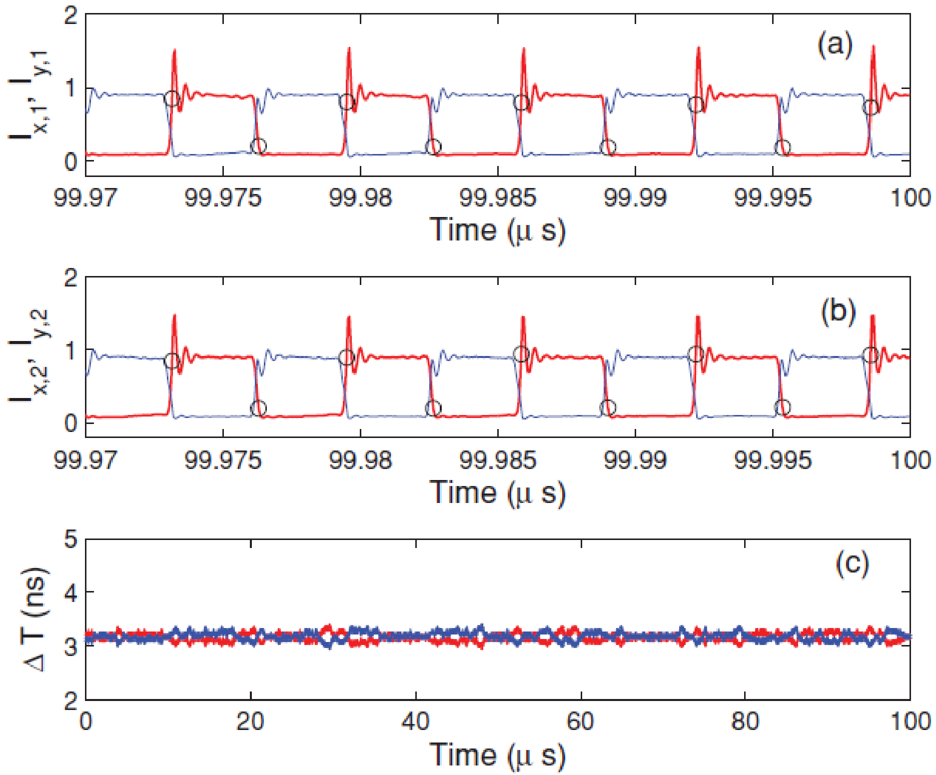
Transient or stable switching?

The SWs are stable if the model includes

- nonlinear gain saturation (self and cross saturation coefficients)
- frequency detuning

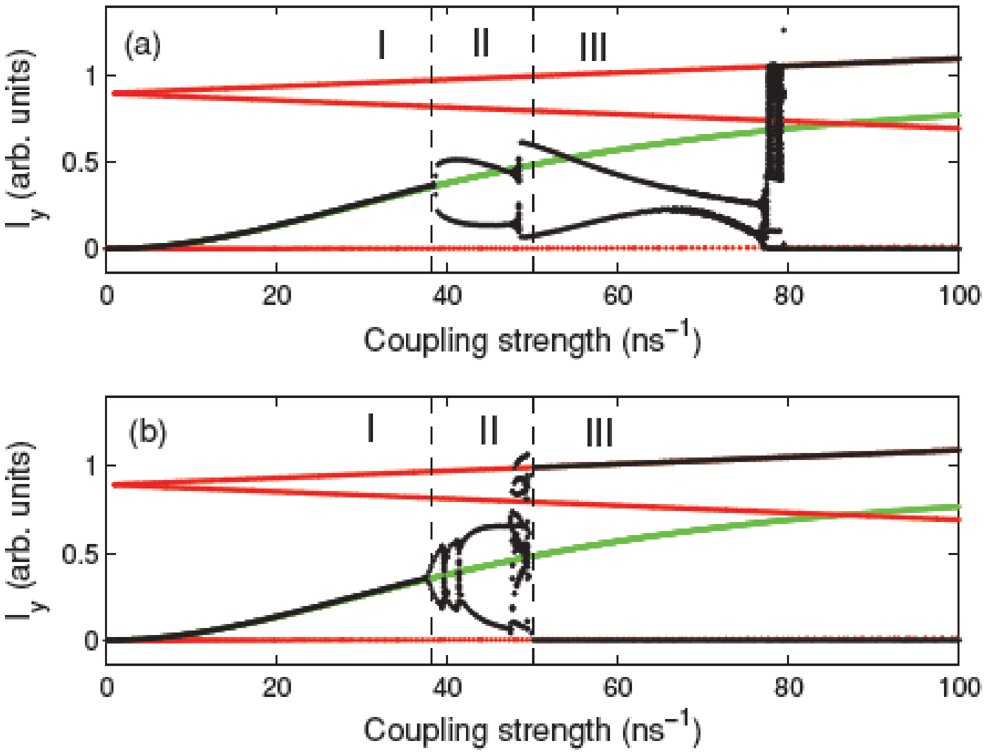
Even in the absence of noise.

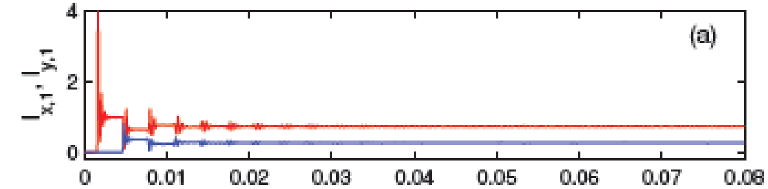
BUT only in **narrow** parameter regions

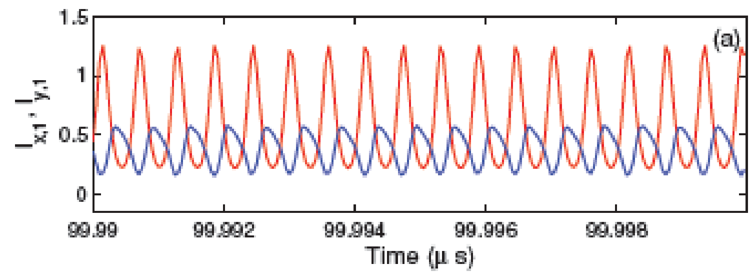


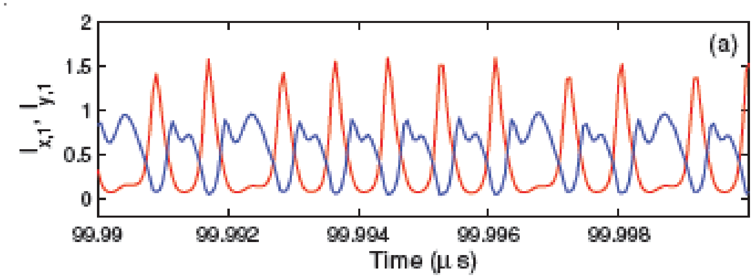
C. Masoller, D. Sukow, A. Gavrielides & M. Sciamanna, Phys. Rev. A 84, 023838 (2011)

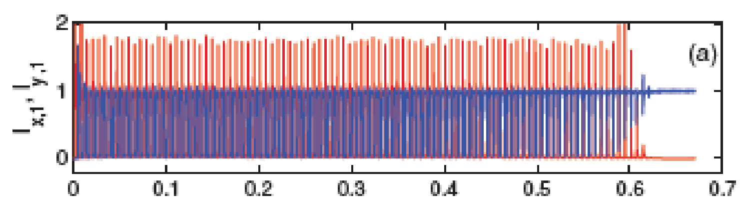
Bifurcation analysis









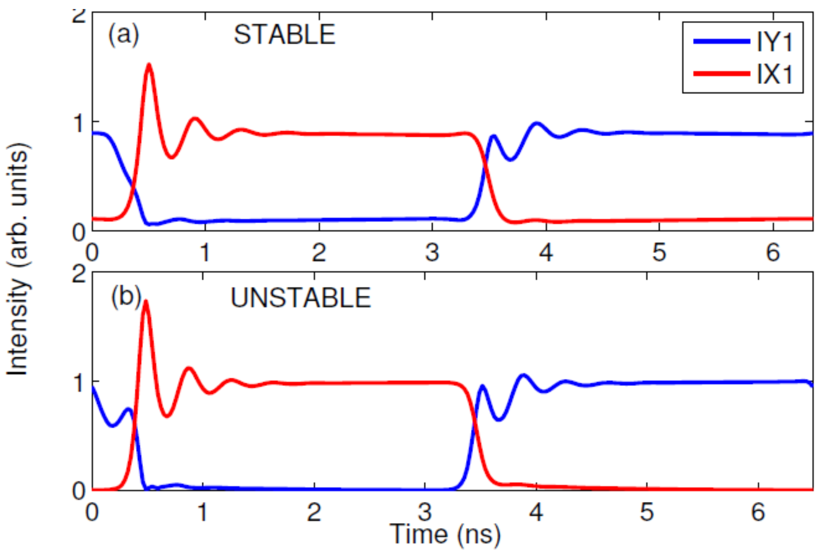


- ❑ Region I: : steady-state (mixed mode)
- ❑ Region II: multistability + square-waves
- ❑ Region III: steady-state (pure mode)

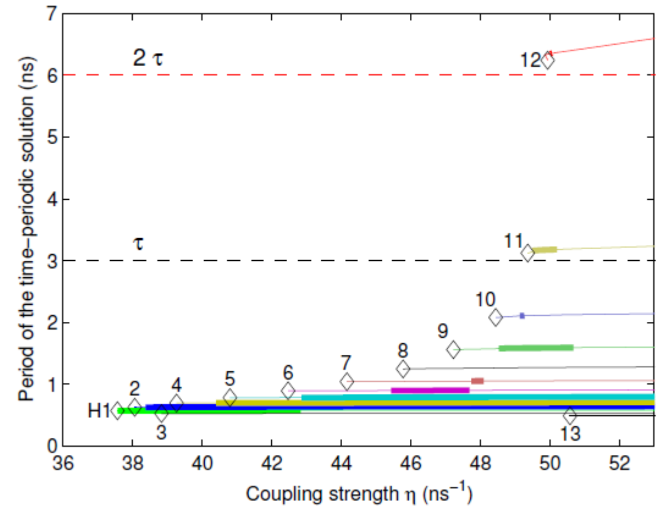
M. Sciamanna, M. Virte, C. Masoller, and A. Gavrielides, Phys. Rev. E **86**, 016218 (2012).

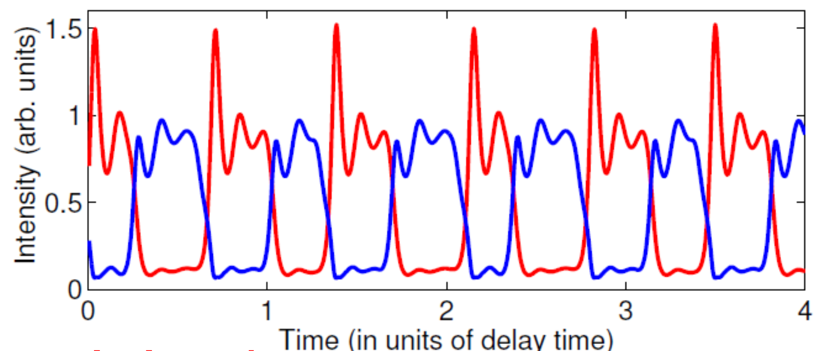
Stable and unstable SWs with different periods

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



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

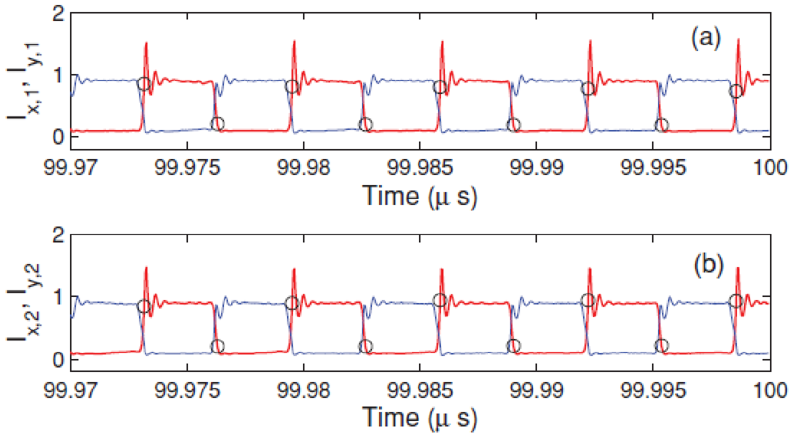




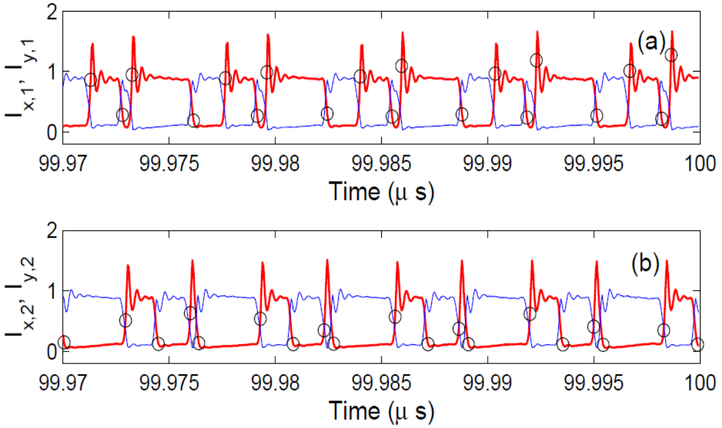
Period ≈2τ/3

Multistability: coexistence of symmetrical and non-symmetrical wave forms

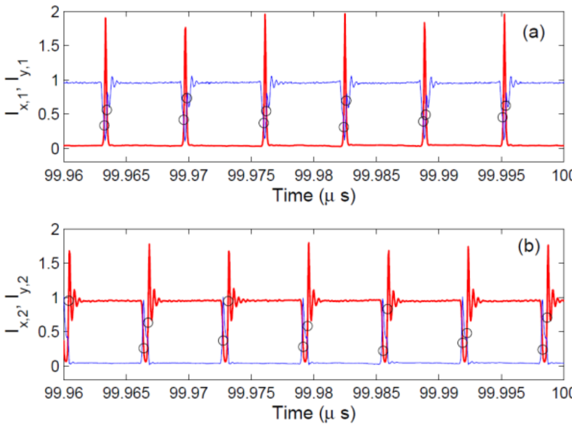
Symmetrical switching



Nonsymmetrical switching

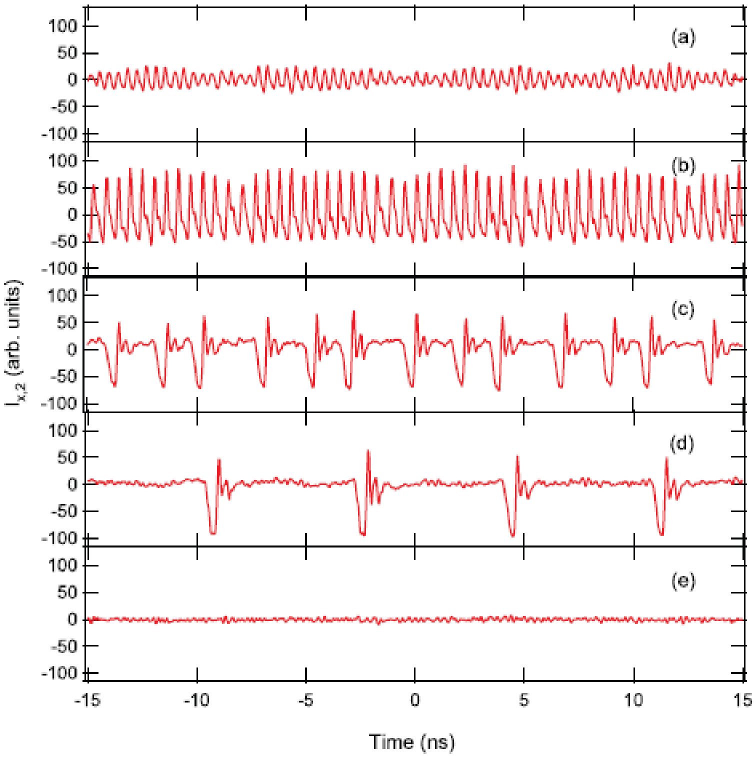


Nonsymmetrical pulses

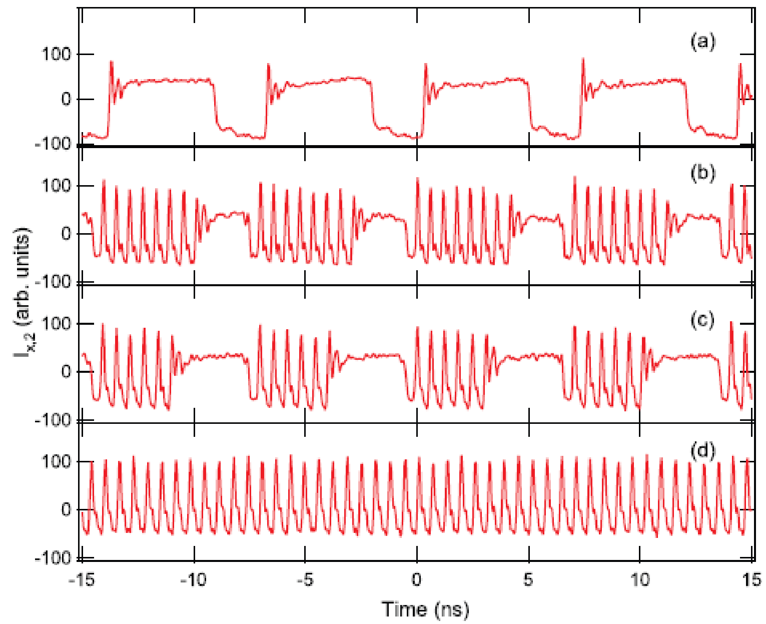


Experimental observations

Increasing coupling:



Coexisting solutions:

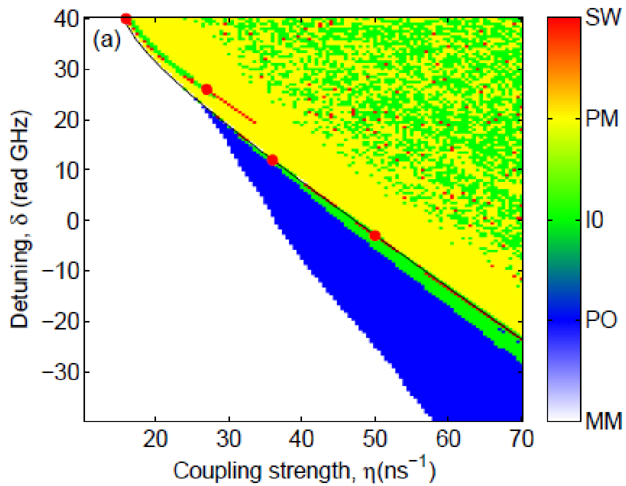


Time traces of the intensity of one mode of one laser

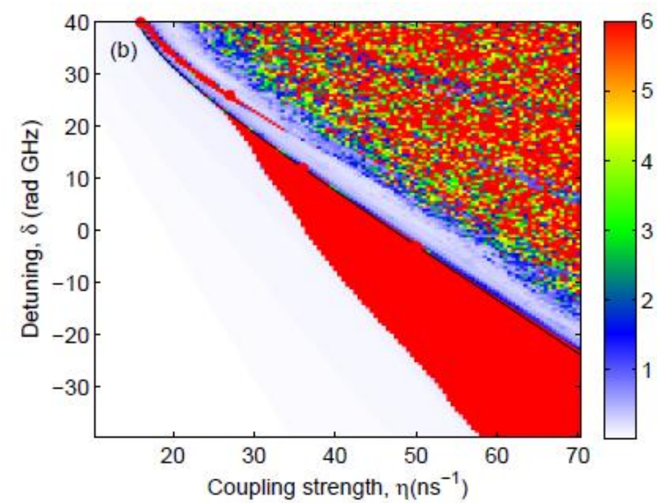
C. Masoller, D. Sukow, A. Gavrielides & M. Sciamanna, PRA 84, 023838 (2011)

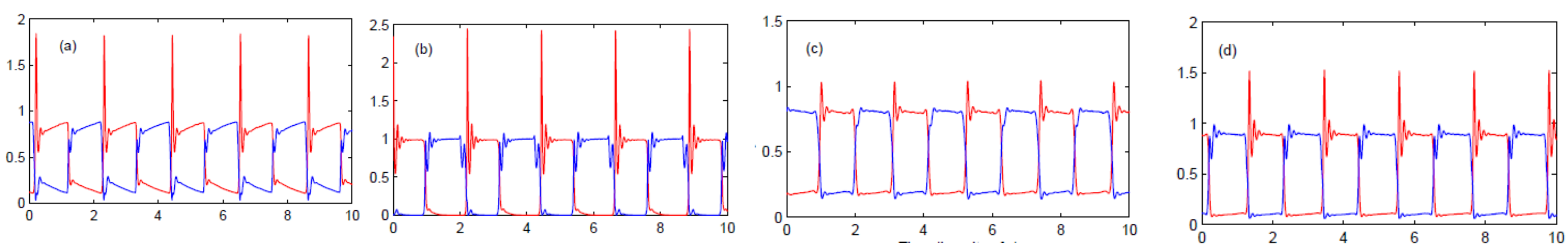
Two parameter study

Dynamical regimes



Transient time

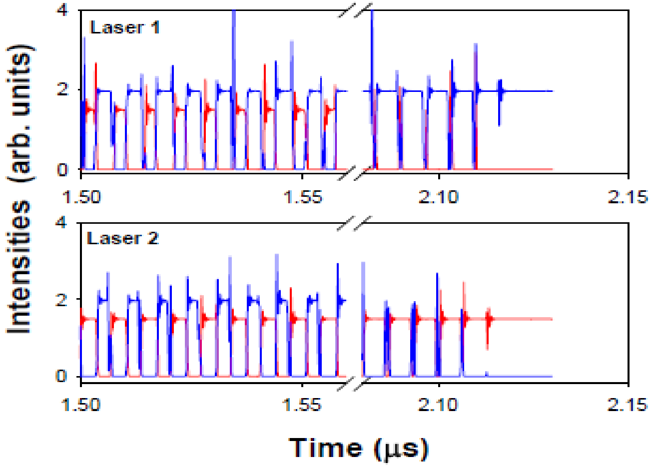




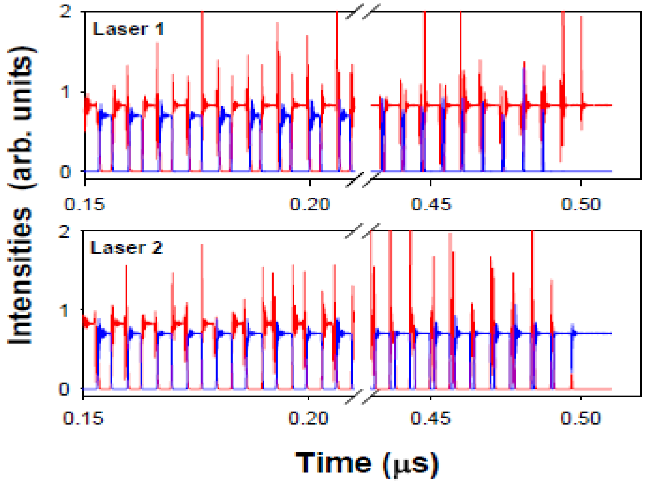
C. Masoller, A. Gavrielides & M. Sciamanna, to appear in Phil. Trans. Royal Soc. A, topical issue on time-delayed systems (2013)

In coupled vertical cavity lasers: only transient switching

X →Y:



Y →X:



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

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Summarizing

- Delay-induced all-optical square-wave (SW) switching via polarization-rotated feedback or coupling.
- GHz repetition rates fully controlled by the delay time.
- With feedback: regular SWs in EELs; noisier in VCSELs.
- In coupled EELs: narrow regions of stable SWs even in the absence of noise.
- In coupled VCSELs: only transient SWs (no experiments available).
- Future work: characterization of the influence of noise in the duration of the transient time and identification of optimal parameters for stable and regular SWs.

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THANK YOU FOR YOUR ATTENTION