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

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Outline of the talk

- Motivation: brief overview of semiconductor lasers and time-delay effects
- Polarization rotation: self-feedback and mutual coupling configurations
- Results
- Conclusions

Symposium on Time-Delayed Systems, ENOC 2011, Roma, Italy, July 27
Semiconductor lasers

- Today are widely used in optical fiber communication systems
- Also used in: laser printers, scanners, CDs, DVDs, sensors, etc.
- Nonlinear devices.

Edge-Emitting laser (EEL):

Vertical-Cavity Surface-Emitting Lasers (VCSEL):

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Time delayed optical feedback & mutual coupling

Optical feedback

\[ \tau = \frac{2L}{c} \]

Mutual coupling

\[ \tau = \frac{L}{c} \]
Motivation: why is important to study time delayed effects in semiconductor lasers?

Practical applications:

- controlled optical feedback is commonly used to improve the laser performance (reduce the threshold, linewidth and intensity noise);
- synchronized laser arrays can give high output powers ($I = |E|^2$ and if the lasers are synchronized, $E_{\text{tot}} = \sum E_i$).

However, time-delayed feedback and coupling can induce instabilities that degrade the lasers’ performance.

But… these instabilities can also be exploited for novel applications, such as fast all-optical random number generators.

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Time delayed optical feedback: two configurations

Isotropic optical feedback:

Polarization-rotated optical feedback:

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

Why is interesting to study polarization-rotated feedback or coupling?

Because it can result in all-optical square-wave switching.
Isotropic optical feedback: The Lang-Kobayashi model

\[ \frac{dE}{dt} = \frac{1}{2\tau_p} (1 + i\alpha)(N - 1)E + \eta E(t - \tau)e^{-i\omega_0\tau} + \sqrt{2\beta_{sp}} \xi(t) \]

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

**Model**

**Laser** \[ \xrightarrow{\tau} \] mirror

- Solitary laser
- \(|E|^2 \propto \) to the laser intensity
- \(N \propto \) the carrier density
- 4 parameters: \(\alpha, \tau_p, \tau_N, \mu\)

\(\eta\): feedback strength
\(\omega_0\tau\): feedback phase

(only one reflection in the external cavity)

spontaneous emission noise
Two new parameters represent the anisotropies between the two polarizations: $\gamma_a$ and $\gamma_p$.

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

\[
\frac{dE_y}{dt} = \frac{1}{2\tau_p} (1 + i\alpha)(N - 1 - \gamma_a)E_y + i\gamma_p E_y + \sqrt{2\beta_{sp}}\xi_y(t) + \eta E_x(t - \tau)e^{-i\omega_{\text{res}}\tau}
\]

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

Adapted from Hong et al, Elec. Lett. 36, 2019 (2000)
Dynamics under strong feedback: polarization square-wave switching

Simulations
$\tau = 10 \text{ ns}$

Periodicity: $2\tau$

Experimental observations (EELs)
Noisy and unstable SWs:

Influence of the laser current:

Increasing current

Optimal regularity for certain current value

Time traces taken under identical conditions

Sukow et al, submitted (2011)
Simulations based on the **spin-flip model** for VCSELs
(Martín-Regalado et al, JQE 1997)

Influence of the injection current:

Increasing $\mu$

Sukow et al, submitted (2011)
Isotropic coupling

\[ \tau = \frac{L}{c} \]

Polarization-rotated coupling

TE (x) is the natural lasing polarization of the solitary lasers.
Model: isotropic mutual coupling

identical lasers

Laser 1

\[
\frac{dE_1}{dt} = \frac{1}{2\tau_p} (1 + i\alpha)(N_1 - 1)E_1 + \eta E_2(t - \tau)e^{-i\omega_0\tau} + \sqrt{2\beta_{sp}} \xi_1(t)
\]

\[
\frac{dN_1}{dt} = \frac{1}{\tau_N} \left[ \mu - N_1 - N_1|E_1|^2 \right]
\]

Laser 2

\[
\frac{dE_2}{dt} = \frac{1}{2\tau_p} (1 + i\alpha)(N_2 - 1)E_2 + \eta E_1(t - \tau)e^{-i\omega_0\tau} + \sqrt{2\beta_{sp}} \xi_2(t)
\]

\[
\frac{dN_2}{dt} = \frac{1}{\tau_N} \left[ \mu - N_2 - N_2|E_2|^2 \right]
\]
Model for polarization-rotated coupling

Laser 1

Polarization selector & rotator

Polarization selector & rotator

Laser 2

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

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

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

And vice-versa for laser 2

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Experimental observations (EELs)

Sukow et al, PRE 81, 025206R (2010)
Numerical simulations (EELs)

Polarization square-wave switching is a transient dynamics:

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

C. Masoller  Masoller et al, accepted in PRA
Transient vs stationary square-wave switching

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

\[ g_{x,i} = \frac{N_i}{1 + \epsilon_{xx} I_{x,i} + \epsilon_{xy} I_{y,i}} \]
\[ g_{y,i} = \frac{N_i}{1 + \epsilon_{yx} I_{x,i} + \epsilon_{yy} I_{y,i}} \]

symmetrical switching:

Masoller et al, accepted in PRA
Multi-stability in the form of various types of coexisting waveforms

Nonsymmetrical switching

Nonsymmetrical pulses

Nonsymmetrical oscillations
For increasing coupling strength

Multistability of coexisting solutions

Time traces of the x-intensity of one laser

Masoller et al, accepted in PRA
Numerical simulations with VCSELs

The square waves are only a transient dynamics:

\[ X \to Y: \]

\[ Y \to X: \]

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

And increases with the coupling parameters:

Torre et al, submitted (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.

- Future work: analysis of the relationship between the average duration of the transient time and the stability of the x- and y- polarizations of the solitary lasers.

THANK YOU FOR YOUR ATTENTION