Negative hysteresis and thermal effects in vertical-cavity surface-emitting lasers

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Tandil, Argentina, December 2010
Outline of the talk

- UPC & DONLL presentation
- Overview of semiconductor lasers and VCSELs
- VCSEL model
- Thermal effects, current modulation, hysteresis
- Experimental results (Alan Shore, Bangor, UK)
- Summary and conclusions
The UPC is the main technical university in Catalonia, and one of three largest technical universities in Spain.

Students: 29,041 (undergrad)
10,141 (grad and posgrad)

2,752 PDI (research and teaching)
1,629 PAS (administration and technical staff)

236 research groups

Campus in 8 catalan towns, 23 schools (engineering, architecture, etc)

- Barcelona
  - Campus Diagonal Nord
  - Campus Diagonal Sud
- Castelldefels
- Igualada
- Manresa
- Mataro
- Sant Cugat
- Terrassa
People

11 faculty
2 posdocs
7 phd students
several undergrads

DONLL group
with invited members of DFEN (11/08)
Research lines

- Nonlinear phenomena in materials and photonics
  - Laser dynamics
  - Photonic crystals
  - Fracture
  - Stochastic and complex systems

- Nonlinear and stochastic dynamics in biophysics
  - Gene regulation
  - Intracellular signaling and coupling
  - Neuronal networks
  - Brain dynamics
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Semiconductor lasers

- SLs were invented more than 40 years ago.
- Today are widely used in optical fiber communication systems
- Also used in: laser printers, scanners, CDs, DVDs, sensors, etc.

With Marita, since we meet in Cartagena (OPTILAS 1998) we have been studying a wide variety of nonlinear phenomena in semiconductor lasers:

- Optical injection, optical feedback, current modulation, synchronization of delay-coupled lasers
- Multi-mode competition (various transverse modes, two orthogonal polarization modes)
VCSEL: a microcavity device (thickness of active layer ~ 30 nm), electrically pumped.

Presented by Soda et al (1979), CW RT operation achieved in 1988 (Koyama et al), commercialized in the late 1990s.

Today used for: optical fiber communication systems & sensors; also scientific use (spectroscopy, laser pumping and instrumentation).


Adapted from Suematsu and Iga, JLT 26(9) 1132 (2008)
Advantages:

- single-mode emission (very thin active layer)
- excellent beam quality (circular cross section)
- low threshold current (< 2-4 mA, V~0.4 μm³ vs. > 10 mA, 60 μm³)
- high efficiency, compact, etc.
Thermal saturation

- Solid line: cw operation
- fast current variation: 2 μs (□) and 0.2μs (⊕)

Oxide aperture diameter

- 4 μm
- 11 μm

Adapted from C. Degen et al, APL, 76 (2000)
Two orthogonal linearly polarized states

“Current-driven” Polarization Switching

Stochastic Polarization Switching

VCSEL Drawbacks:
- Unstable polarization states
- Transverse mode instabilities
- temperature-sensitive wavelength and output characteristics

Frequency split due to material birefringence

Adapted from J. Kaiser et al, JOSAB 19, 672 (2002)

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

Four-level SFM Model
San Miguel et al, PRA 54, 1728 (1995),

The spin-flip model (SFM) assumes a four-level system in which electrons with spin down (up) yield optical transitions with right (left) circularly polarized light:

\[
\frac{dE_\pm}{dt} = \kappa (1 + i \alpha)(N_\pm - 1)E_\pm - (\gamma_a + i \gamma_p)E_\mp + F_\pm(t)
\]

\[
\frac{dN_\pm}{dt} = -\gamma_N(N_\pm - \mu) - \gamma_j(N_\pm - N_\mp) - 2\gamma_N N_\pm |E_\pm|^2
\]

These equations can be rewritten in terms of two LINEARLY POLARIZED COMPONENTS X, Y coupled to the total carrier density and the carrier difference:

\[
E_x = (E_+ + E_-)/\sqrt{2} \\
E_y = -i(E_+ - E_-)/\sqrt{2} \\
N = (N_+ + N_-)/2 \\
n = (N_+ - N_-)/2
\]

Total carrier density
Carrier difference
Linearly polarized components
Spontaneous recombination
Carrier injection
spin-flip rate
Stimulated recombination
dichroism
birefringence
Spontaneous emission noise
The SFM model predicts two types of polarization switching:

- **Low-frequency X polarization:** red;
- **High-frequency Y polarization:** blue

**Large birefringence**

\[ Y \rightarrow X \]

**Small birefringence**

\[ X \rightarrow Y \]

\[ \mu = K \left( \frac{I}{I_o} - 1 \right) \]
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SFM model extended to account for thermal effects
Masoller & Torre Optics Express 16, 21282 (2008)

\[
\frac{dE_\pm}{dt} = \kappa(1+i\alpha)[g(\omega_\pm,T)N_\pm - 1]E_\pm - (\gamma_a + i\gamma_p)E_\mp + F_\pm(t)
\]

\[
\frac{dN_\pm}{dt} = -\gamma_N(N_\pm - \mu) - \gamma_j(N_\pm - N_\mp) - 2\gamma_N g(\omega_\pm,T)N_\pm |E_\pm|^2
\]

temperature dependent spin-flip rate

\[
\gamma_j = \gamma_{j,0} T/T_0
\]

Temperature dependent gain-cavity offset

\[
g(\omega, T) = \frac{T_0/T}{1 + [\delta(T) - \omega]^2 / \Delta \omega_g^2(T)}
\]

\[
\delta = \omega_g - \omega_c
\]

Frequency and temperature dependent gain

\[ g(\omega, T) = \frac{T_0/ T}{1 + [\delta(T) - \omega]^2 / \Delta \omega_g^2(T)} \]

- Thermal red-shift of the gain peak \( d\lambda_g/dT \approx 0.27 \text{ nm/K} \)
- Thermal red-shift of the cavity resonance \( d\lambda_c/dT \approx -0.07 \text{ nm/K} \)
- \( \delta_0 = \) gain-cavity offset at room temperature \( T_0 \)
- Thermal increase of the gain bandwidth \( \Delta \omega_g^2(T) = \Delta \omega_g^2(0)(T/T_0) \)
Temperature rate equation

\[
\frac{dT}{dt} = -\gamma_T (T - T_s) + Z (N / K + 1) + P (I / I_0)^2
\]

Z, K and P are size-dependent parameters. Values are given for a VCSEL of aperture diameter of 10 \( \mu \text{m} \) emitting at \( \lambda_0 = 850 \text{ nm} \).

**Decay to fixed substrate temperature**

**Non-radiative recombination heating**

**Joule heating**

**Parameter values**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k )</td>
<td>41.7 ( \text{ns}^{-1} )</td>
</tr>
<tr>
<td>( \gamma_N )</td>
<td>2.7 ( \text{ns}^{-1} )</td>
</tr>
<tr>
<td>( \gamma_{j,0} )</td>
<td>100 ( \text{ns}^{-1} )</td>
</tr>
<tr>
<td>( \gamma_T )</td>
<td>0.01 ( \text{ns}^{-1} )</td>
</tr>
<tr>
<td>( \gamma_\alpha )</td>
<td>0.4 ( \text{ns}^{-1} ), ( \gamma_p )</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>3</td>
</tr>
<tr>
<td>( \beta_{sp} )</td>
<td>10(^{-4}) ( \text{ns}^{-1} )</td>
</tr>
<tr>
<td>( K )</td>
<td>7.5</td>
</tr>
<tr>
<td>( Z )</td>
<td>0.42 ( ^{0}\text{K/\text{ns}} )</td>
</tr>
<tr>
<td>( P )</td>
<td>1.68 \times 10^{-3} ( ^{0}\text{K/\text{ns}} )</td>
</tr>
</tbody>
</table>

Results: influence of the device size

In good agreement with experiments
LI curve: temperature variation of the laser threshold

Parabolic-like variation of the threshold, also in good agreement with experiments

Polarization-resolved LI curve

Low-frequency X polarization: red; high-frequency Y polarization: blue

Large birefringence: Y → X

Small birefringence: X → Y

Injection current (mA)

Ts = -20 °C

Ts = 0 °C

Thermal PS
Effect of the current variation

Large birefringence: $Y \rightarrow X$

Small birefringence: $X \rightarrow Y$

$\Delta T = 50 \mu s$

$\Delta T = 5 \mu s$

$\Delta T = 1 \mu s$

With a fast current ramp thermal effects do not have time to act.
Dynamical Hysteresis

\[ \dot{x} = x(A - x) \]

\[ s_i A = A_0 + bt \]

Example: laser turn-on

\begin{align*}
\text{Injection current / mA} \\
\text{Power / mW}
\end{align*}

\text{Pump (V)}

\text{Laser Intensity (V)}

\text{Adapted from J. Kaiser et al, JOSAB 19, 672 (2002)}

\text{Adapted from Tredicce et al, Am. J. Phys. 72, 800 (2004)}

\text{x=0 stable if A<0}

\text{x=A stable if A>0}
Dynamical hysteresis in VCSELs

\[ \Delta T = 0.1 \, \mu s \]
Dynamical hysteresis

$\Delta T = 0.1 \mu s$

$\Delta T = 1 \mu s$

Laser current

Intensity

PS $\downarrow$

PS $\uparrow$
Dynamical hysteresis

\[ \Delta T = 0.1 \, \mu s \]

\[ \Delta T = 1 \, \mu s \]

\[ \Delta T = 10 \, \mu s \]

“quasi-static” variation

Normal hysteresis: \( I_{on} > I_{off} \)
Dynamical Hysteresis and Thermal Effects in Vertical-Cavity Surface-Emitting Lasers

Maria Susana Torre and Cristina Masoller

Normal hysteresis
$I_{on} > I_{off}$

Negative hysteresis
$I_{on} < I_{off}$
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Thermal effects and dynamical hysteresis in the turn-on and turn-off of vertical-cavity surface-emitting lasers

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Size of the hysteresis cycle

Experiments

Simulations
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Summary and conclusions

- We proposed a modification of the spin-flip model, which incorporates thermal effects, and allows for a dynamic description of temperature variations.

- The model predicts a parabolic-like dependence of the threshold current and of the polarization switching current on the substrate temperature.

- A second PS can also occur during the thermally induced power switch off.

- Dynamical hysteresis occurs due to the laser current variation.

- Negative hysteresis occurs due to the interplay of thermal effects and current variation.

Thank you for your attention!

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