Thermal effects in the polarization-resolved light-current characteristics of vertical-cavity surface-emitting lasers

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Outline of the talk

- Overview of VCSELs
- Polarization switching
- Theoretical framework: spin-flip model extended to account for thermal effects
- Results
- Summary and conclusions
Vertical Cavity Surface Emitting Laser

- 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 1990’s.
- 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.
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*

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

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

Frequency split due to material birefringence
Thermal saturation

Oxide aperture diameter

Solid line: cw operation

☐, +: fast current variation

Adapted from C. Degen et al, APL, 76 (2000)
Model for studying VCSEL polarization

**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:

\[
\begin{align*}
E_x &= (E_+ + E_-)/\sqrt{2} \\
E_y &= -i(E_+ - E_-)/\sqrt{2} \\
N &= (N_+ + N_-)/2 \\
n &= (N_+ - N_-)/2
\end{align*}
\]
The SFM model predicts two types of polarization switching:

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

\[ \mu = K \left( \frac{I}{I_o} - 1 \right) \]

- **Large birefringence**  
  \[ Y \rightarrow X \]

- **Small birefringence**  
  \[ X \rightarrow Y \]
SFM model extended to account for thermal effects

Masoller & Torre OPTICS EXPRESS 16, 21282 (2008)

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

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

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

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

Temperature dependent gain-cavity offset

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

P. V. Mena, et al, J. Lightwave Technol. 17, 2612 (1999);
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 \( d\lambda_g / dT \approx 0.27 \text{ nm/}^0\text{K} \)
- Thermal red-shift of the cavity resonance \( d\lambda_c / dT \approx 0.07 \text{ nm/}^0\text{K} \)
- \( \delta_0 = \) 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

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

Decay to fixed substrate temperature

Non-radiative recombination heating

Joule heating

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

LI curve: influence of the device size

**Aperture diameter**

![Graphs showing output power vs. injection current for different aperture diameters](image-url)
LI curve: influence of the substrate temperature
Polarization-resolved LI curve

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

Second, thermal induced PS

Large birefringence

\[ Y \rightarrow X \]

Small birefringence

\[ X \rightarrow Y \]
Increasing the speed of the current ramp

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

\[ \Delta T = 5 \mu s \]

\[ \Delta T = 50 \mu s \]

A fast enough current ramp avoids thermal saturation

**Large birefringence**  
\[ Y \rightarrow X \]

**Small birefringence**  
\[ X \rightarrow Y \]
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 ($I_{th}$) and of the polarization switching current ($I_{ps}$) on the substrate temperature ($T_s$) and on the RT gain-cavity offset ($\delta_0$).

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

Thank you for your attention!

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