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Spin Dynamics and Light Polarization State in Vertical-Cavity Surface-Emitting Lasers

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Thanks:

M. San Miguel, C.R. Mirasso and S. Balle

VISTA
VCSELs for Information Society Technology Applications

- **Goal:**

Semiconductor spin dynamics determining the polarization properties of the light emitted in VCSELs

Semiconductor vs. VCSEL

- **What is a VCSEL?**

A type of semiconductor laser, with a thin QW active layer(s) inserted within a circular micro-cavity

- **Why VCSELs deserve our attention?**

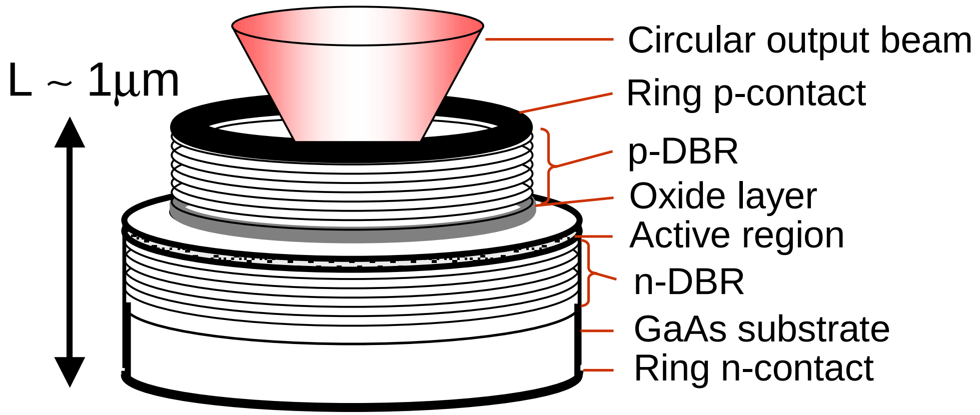
Polarization: *VCSEL vs. EELs*

Advantages:

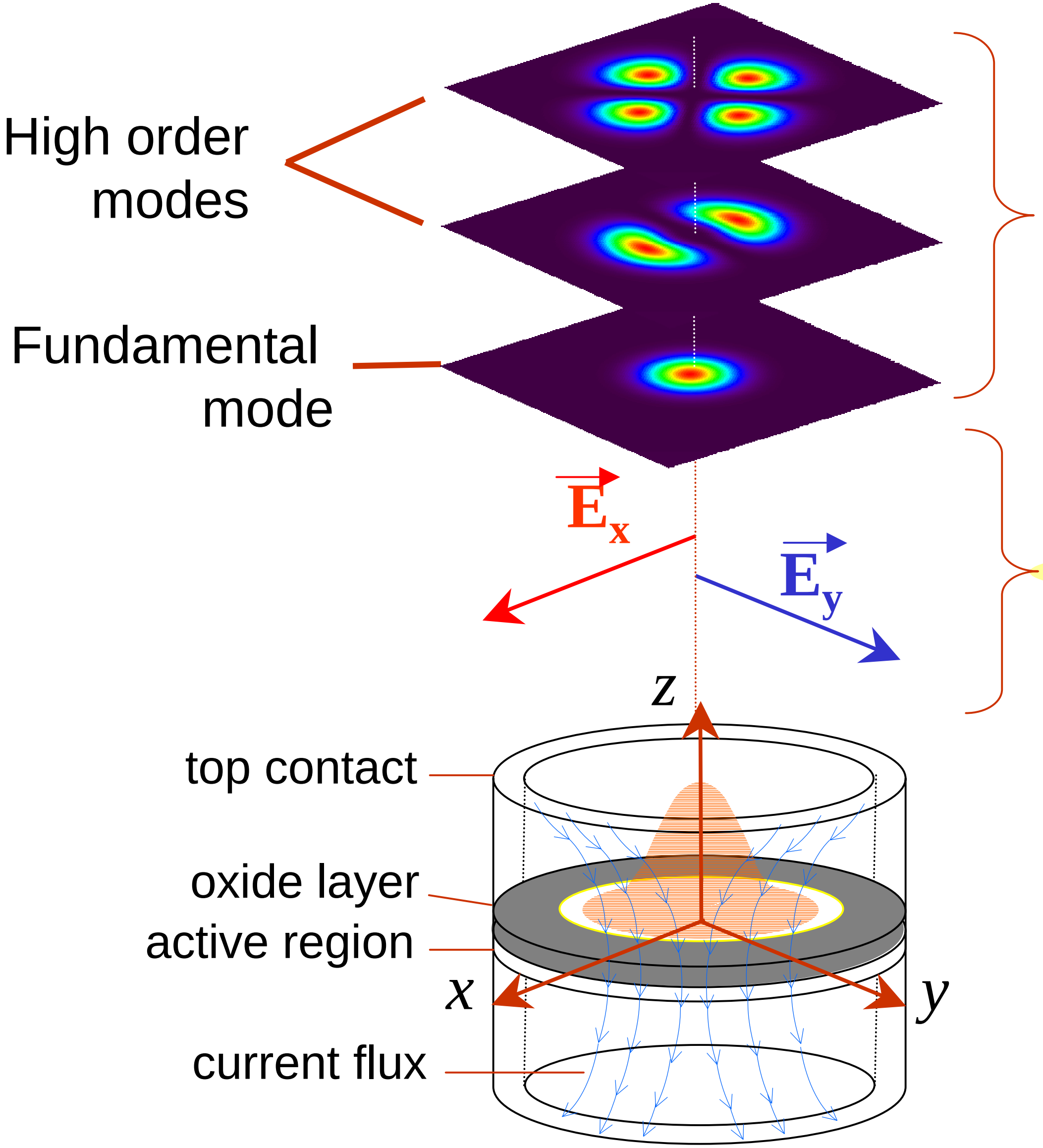
Single-longitudinal mode emission
Circular output beam - Fiber coupling
Cheap manufacturing

Technological applications:

Suitable for integration 2D Arrays
Gigabit Ethernet optical links



Polarization in VCSELs



Transverse Modes

What determines the light polarization state?

A. -Geometric Considerations

Ideal case: Any direction

Real case:

- anisotropies, lattice crystal

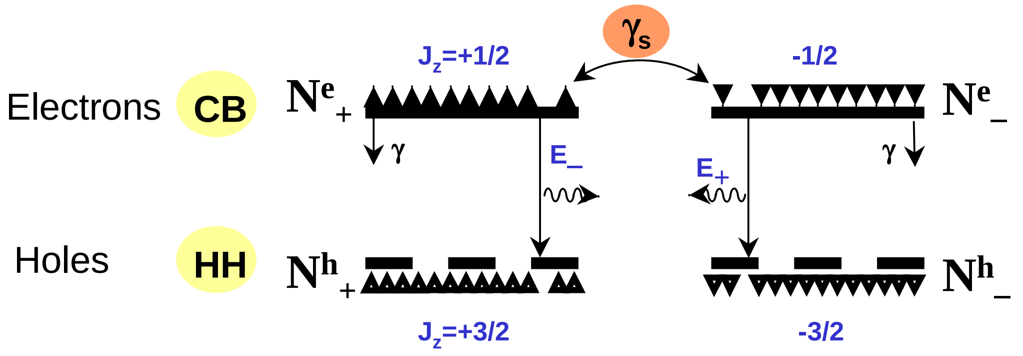
Two preferential directions
x*-*y

“Polarization Switching”

B. - Interaction with the QW material

Spin-Flip Model

• Interaction with the active QW material



spin up & down carrier reservoirs

Population inversion per spin channel: $\mathbf{N_\pm \equiv N^e_\pm - N^h_\pm}$

Total and difference inversions: $D \equiv \mathbf{N_+ + N_-}$ and $d \equiv \mathbf{N_+ - N_-}$

spontaneous recombination rate

injection current

stimulated recombination

Langevin

$$\dot{D}(t) = -\gamma(D-\mu) - \gamma(D+d)|E_+|^2 - \gamma(D-d)|E_-|^2 + F_D(t)$$

$$\dot{d}(t) = -\gamma_s d - \gamma(D+d)|E_+|^2 + \gamma(D-d)|E_-|^2 + F_d(t) .$$

spin flip rate

M. San Miguel, Q. Feng, J.V. Moloney, PRA 54, 1728 (1995)

- •Phenomenological parameter γ_s
- •Possible physical mechanisms in sc:D'yakonov-Perel', Elliot-Yafet, Bir-Aronov-Pikus

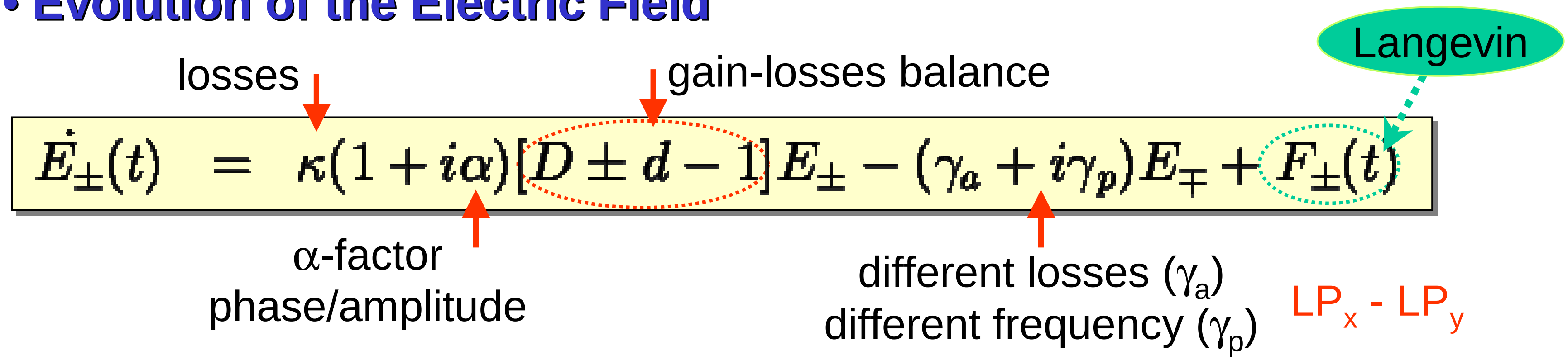
Spin-Flip Model

Laser: <u>Coherent</u> interaction among Spins and Light

Maxwell’s equations. Single longitudinal and transverse mode operation

<u>Natural basis</u>: Circularly polarized states **$E_\pm$**

• Evolution of the Electric Field



losses

gain-losses balance

Langevin

$$\dot{E}_\pm(t) = \kappa(1+i\alpha)[D \pm d - 1]E_\pm - (\gamma_a + i\gamma_p)E_\mp + F_\pm(t)$$

α-factor
phase/amplitude

different losses (γ_a)
different frequency (γ_p)

LP_x - LP_y

• Spontaneous emission

$$F_\pm(t) = \sqrt{\beta_{sp}\gamma(D \pm d)}\,\xi_\pm(t)\,,$$

$$F_{\binom{D}{d}}(t) = \frac{\gamma}{2\kappa}\left[\sqrt{\beta_{sp}\gamma(D+d)}\;E_+\xi_+^*(t) \pm \sqrt{\beta_{sp}\gamma(D-d)}\;E_-\xi_-^*(t) + c.c.\right]$$

fluctuation-dissipation theorem

$$\boxed{\beta_{sp} = \frac{\beta_0}{(1+\alpha^2)}\frac{\kappa}{\gamma}}$$

White Gaussian Noise

$$\langle \xi'_\pm(t)\rangle = 0$$

$$\langle \xi'_\pm(t)\xi'^*_\pm(t')\rangle = 2\delta(t-t')$$

J. Mulet, C.R. Mirasso, M. San Miguel, PRA 64, 023817 (2001).

http://www.imedea.uib.es/PhysDept

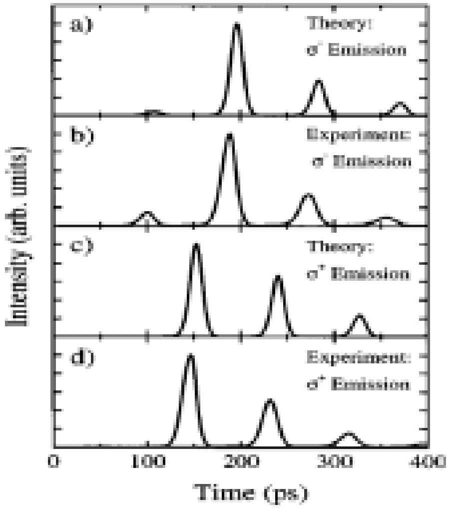
Direct Measures of the Spin Flip Rate

Fingerprints of the spin-flip rate in many polarization related phenomena, providing methods for its experimental determination

◆ Direct methods: Optical pumping

A. Photoluminescence decay in sc *(below threshold)*

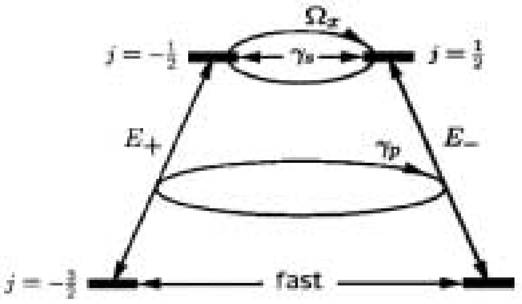
B. Laser emission pulses in VCSELs *(above threshold)*

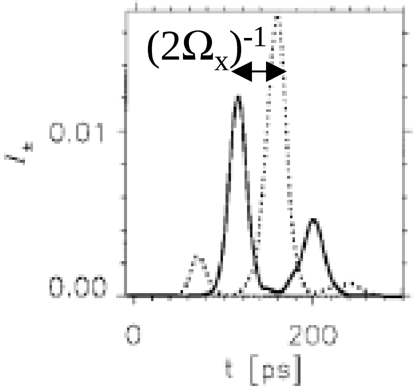


- ***Experiment:*** Optically pumped VCSEL in a transverse magnetic field. Stimulated emission Larmor oscillations 22GHz alternating in polarization B=2T.
  ($In_{0.04}Ga_{0.96}As$ QWs and GaAs/AlAs DBRs) S. Hallstein et al. PRB 56,R7076 (1997)

- ***Spin-Flip Model:*** A. Gahl et al. IEEE JQE 35, 342 (1999)
  including $\eta_{\pm}$, $\boldsymbol{B_x}$, magnetization $\boldsymbol{m}=(0,m_y,m_z)$.

$$\begin{aligned}
\dot{E}_{\pm} &= \kappa(1+i\alpha)(N \pm m_z - 1)E_{\pm} - (\gamma_a + i\gamma_p)E_{\mp} \\
&\quad + \sqrt{\beta\gamma(N \pm m_z)}\,\xi_{\pm} \\
\dot{N} &= \gamma[\eta_+ + \eta_- - (1 + I_+ + I_-)N - (I_+ - I_-)m_z \\
\dot{m}_z &= \gamma(\eta_+ - \eta_-) - [\boxed{\gamma_s} + \gamma(I_+ + I_-)]m_z \\
&\quad - \gamma(I_+ - I_-)N + \Omega_x m_y \\
\dot{m}_y &= -[\gamma_s + \gamma(I_+ + I_-)]m_y - \boxed{\Omega_x m_z}.
\end{aligned}$$





◆ Other indirect methods: Electrical pumping

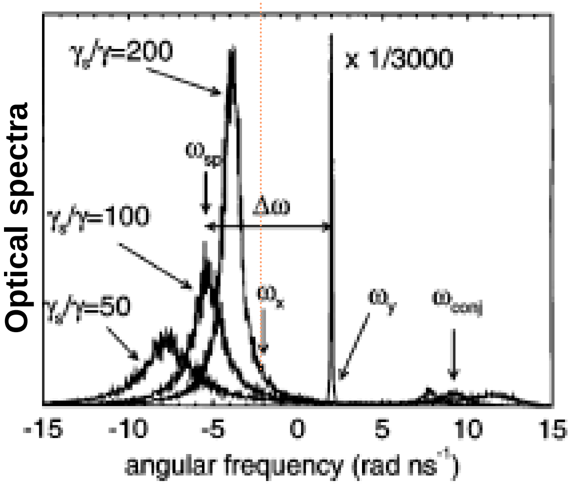
Non-Linear Anisotropies

- Due to Finite Spin-Flip: preference for emission in linearly-polarized states in front of elliptical or circular light.

- Evidences: 1. Peak in the power spectra of $P_\pm$ is not at $2\gamma_p$ *(linear contribution)*

  2. Optical spectra non-lasing component is shifted from $\pm\gamma_p$

H. van der Lem and D. Lenstra. Opt. Lett. 22,1698 (1997).
M.P. van exter, et. al. PRL 80, 4875 (1998).

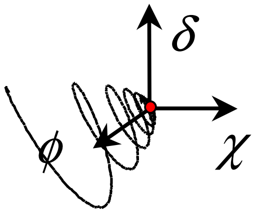


•Two Regimes:

Polarization Relaxation Oscillations (PROs)

χ **-d** oscillate, while ϕ exponential relaxation
Moderat γ_s, small anisotropies, large currents

$$\Omega_{PROs} \approx \sqrt{4\kappa\gamma Q^2 - \frac{(\gamma_s + 2\gamma Q^2)^2}{4}} \qquad Q^2 \approx \frac{\mu - 1}{2}$$

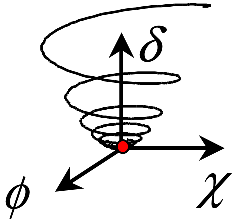


Coupled Oscillations (COs) of the polarization

χ **-**ϕ oscillate, while **d** exponential relaxation
Large γ_s , current close to threshold

$$\Omega_{COs} \approx 2|\gamma_p| \pm \frac{\gamma}{\gamma_s}\alpha\kappa(\mu - 1)$$

Nonlinear birefringence: sensible to the LP solution (±)



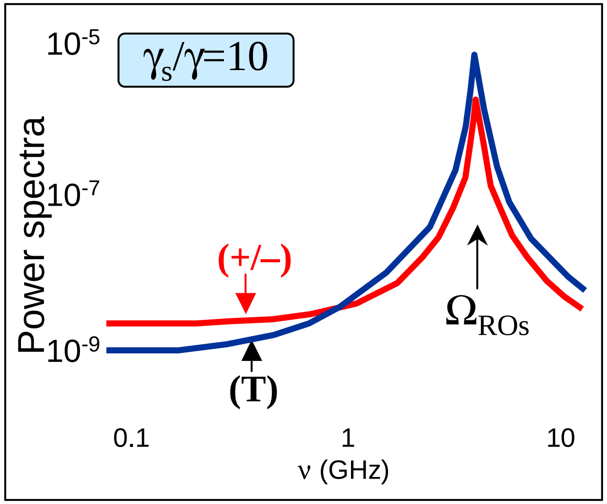
Anticorrelated Polarization Fluctuations

- Power spectra of the circular components and total intensity fluctuations

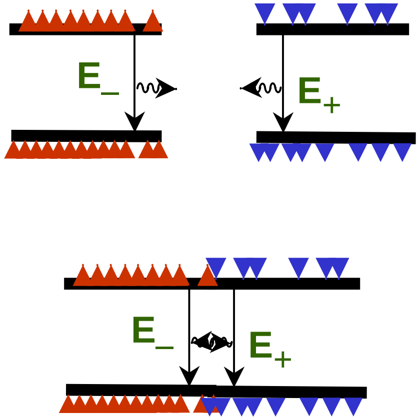
(Anticorrelations appear as a sign of competence for a common gain)

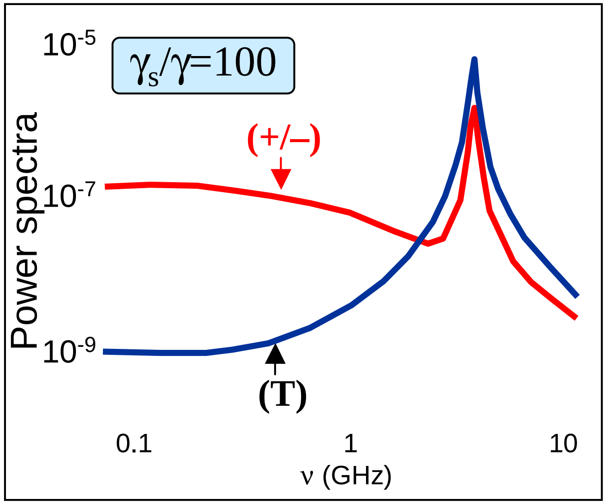
Small spin-flip

Large spin-flip



Two nearly independent spin channels





Only one "common" carrier reservoir

- *Cross-correlation at small frequencies:*

$$C_{+-}(\omega=0)\approx -1+\frac{1}{2Q^4}\frac{[(\gamma_p/\kappa)\Gamma-\varepsilon\alpha]^2}{[\alpha^2+\Gamma^2]}$$

$$\boxed{C_{\pm}+1\propto\frac{1}{\gamma_s^2}}$$

for small anisotropies

J. Mulet, C.R. Mirasso, M. San Miguel, PRA 64, 023817 (2001).

Polarization Switching

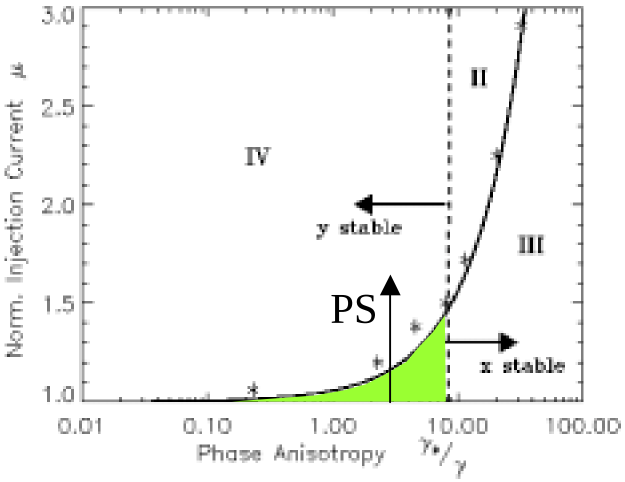
- Polarization switching of non-thermal origin is explained as a phase instability

E_+ E_- *lock* $\Delta\Psi=0$ (LP_x) $\Rightarrow$ E_+ E_- *lock* $\Delta\Psi=\pi$ (LP_y)

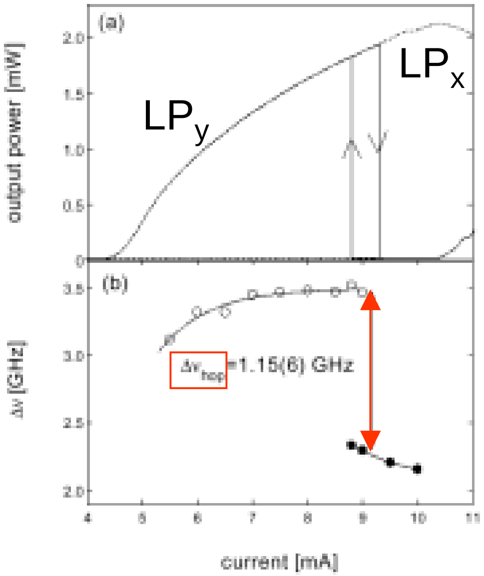
J. Martín-Regalado, et. al IEEE JQE **33**, 765 (1997)

AlGaAs/GaAs VCSEL $\gamma_s=100\ \mathrm{ns}^{-1}$ $\Rightarrow$ $\tau_s \approx 20\mathrm{ps}$

J. Martín-Regalado et al., APL **70**, 3550 (1997)



- Variation of the nonlinear birefringence across a polarization switching



GaAs QW-VCSEL

$$\Delta\nu_{hop} \approx \frac{1}{2\pi}\frac{2\alpha\kappa\gamma(\mu_{sw}-1)}{\gamma_s}$$

Change in nonlinear birefringence

$\alpha=3\text{-}4$, $\kappa=133\text{-}300\ \mathrm{ns}^{-1}$, $\mu_{sw}\approx 2$

$\gamma_s \approx 100\text{-}400\ \mathrm{ns}^{-1}$

$\tau_s \approx 5\text{-}20\mathrm{ps}$

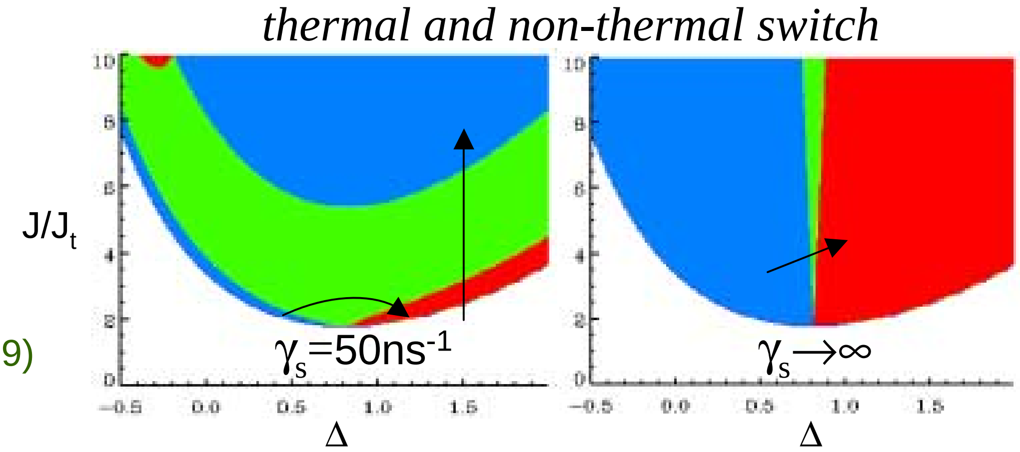
M.P. van Exter, et. al. PRL 80, 4875 (1998)

Polarization Switching and Optical Bistability

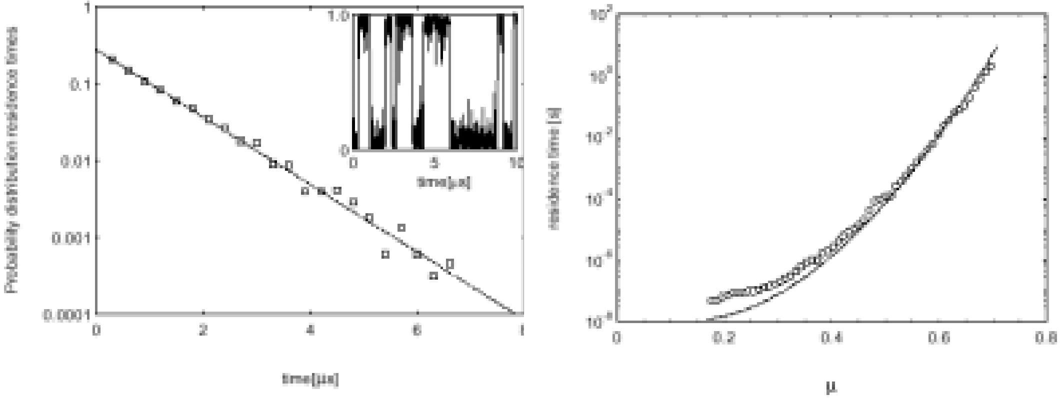
- Polarization stability: optical bistability region coexisting LP_x - LP_y both stable

Dressed SFM
=
Spin Flip
+
QW Susceptibility

S. Balle et al. *Opt. Lett*. **24**, 1121 (1999)



- PS in a bistable region envisioned as a Kramers hopping problem



M. B. Willemsen, et al. *PRL* 82, 4815 (1999).

$$\gamma_{non} = \frac{\gamma}{\gamma_s}\kappa(\mu-1)$$ nonlinear dichroism

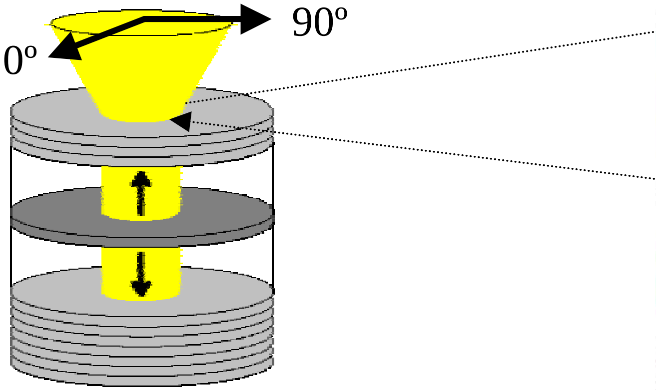
Mean residence time

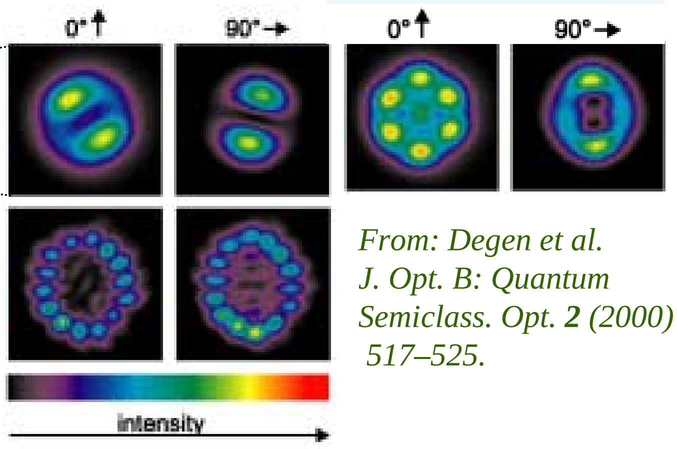
$$\langle T\rangle \approx \gamma_{non}^{-3/2}\exp(\gamma_{non}/4D)$$

$\gamma_s \approx 200\ \mathrm{ns}^{-1}$ $\tau_s \approx 10\mathrm{ps}$

Going Further ...

- Joint interplay of **transverse effects and polarization instabilities** in VCSELs

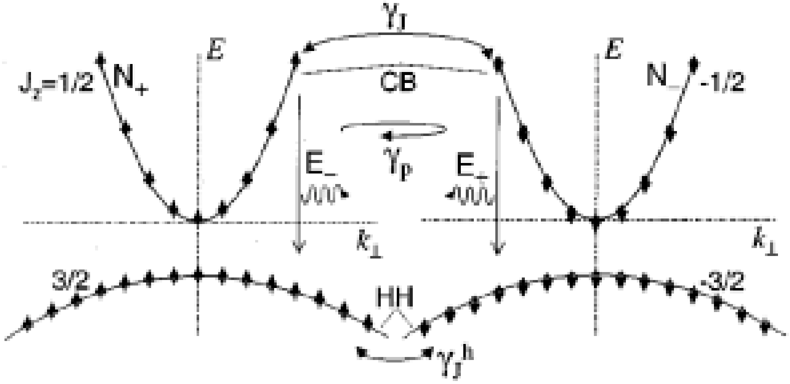




From: Degen et al. J. Opt. B: Quantum Semiclass. Opt. ***2*** *(2000) 517–525.*

•Goal

  - *Use simple but accurate descriptions*
  - Need of a frequency-dependent susceptibility and spin dynamics
  - Interplay of thermal effects and semiconductor dynamics



J. Mulet and S.Balle, IEEE *JQE* **38**, 291 (2002)

The Mesoscopic VCSEL Model

cavity losses

generic QW susceptibility = gain & index

$$\partial_t A_\pm(\vec{r}_\perp;t) = -\kappa A_\pm + i\hat{\mathcal{L}}A_\pm + i\frac{a\Gamma}{2}\chi_\pm\left(\Omega + i\frac{\partial_t A_\pm}{A_\pm}, D_+, D_-\right)A_\pm$$
$$-(\gamma_a + i\gamma_p)A_\mp + \sqrt{\beta D_\pm}\,\xi_\pm(\vec{r}_\perp;t),$$

linear anisotropies

spontaneous emission

$$\hat{\mathcal{L}}E_\pm = \frac{c^2}{2\Omega n_e n_g}\left[\nabla_\perp^2 + \left(\frac{\Omega}{c}\right)^2 2n_e\Delta n(\vec{r}_\perp;\Omega)\right]E_\pm$$ ⇒ Lateral optical guiding

$$D_\pm = N_\pm / N_t$$

current profile

spontaneous recombination

spin flip for e^-

$$\partial_t D_\pm(\vec{r}_\perp;t) = \frac{\mu(t)}{2}C(\vec{r}_\perp) - AD_\pm - (BN_t)D_\pm^2 \mp \gamma_j(D_+ - D_-)$$
$$+\mathcal{D}\nabla_\perp^2 D_\pm + a\,\mathrm{Im}\chi_\pm\left(\Omega + i\frac{\partial_t A_\pm}{A_\pm}, D_+, D_-\right)|A_\pm|^2$$

carrier diffusion

stimulated recombination *(Spatial Hole Burning)*

$$\chi_\pm(\omega, D_+, D_-) = -\chi_0\left[\ln\left(1 - \frac{2D_\pm}{u+i}\right) + \ln\left(1 - \frac{D_+ + D_-}{u+i}\right) - \ln\left(1 - \frac{b}{u+i}\right)\right]$$

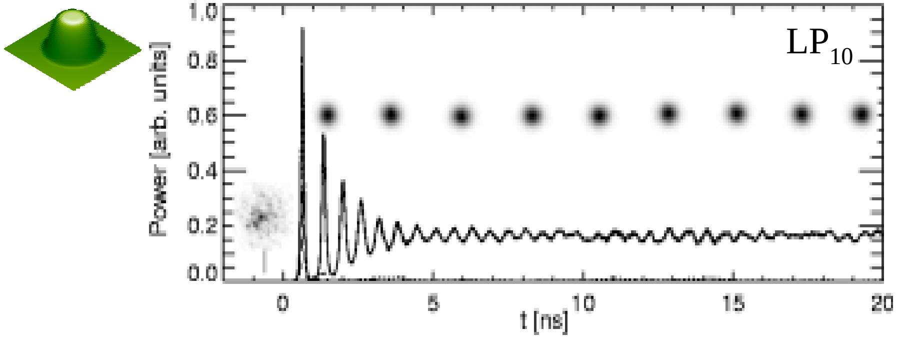
$$u_\pm = \Delta + \sigma(D_+ + D_-)^{1/3} + \omega_\pm/\gamma_\perp, \qquad \Delta = \frac{\Omega - \omega_t}{\gamma_\perp}, \qquad b = \frac{\hbar}{2m\gamma_\perp}k_m^2$$

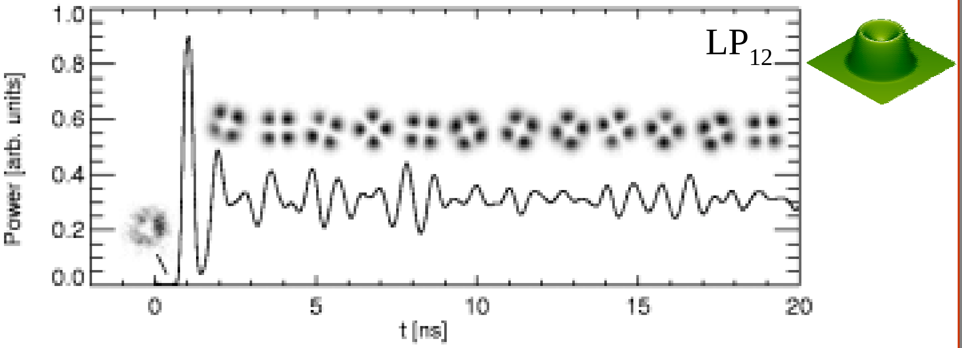
S. Balle. *Phys. Rev. A* **57**, 1304-1312, (1998)

Aspects of the Spatio-Temporal Dynamics

• Transverse mode selection close-to-threshold

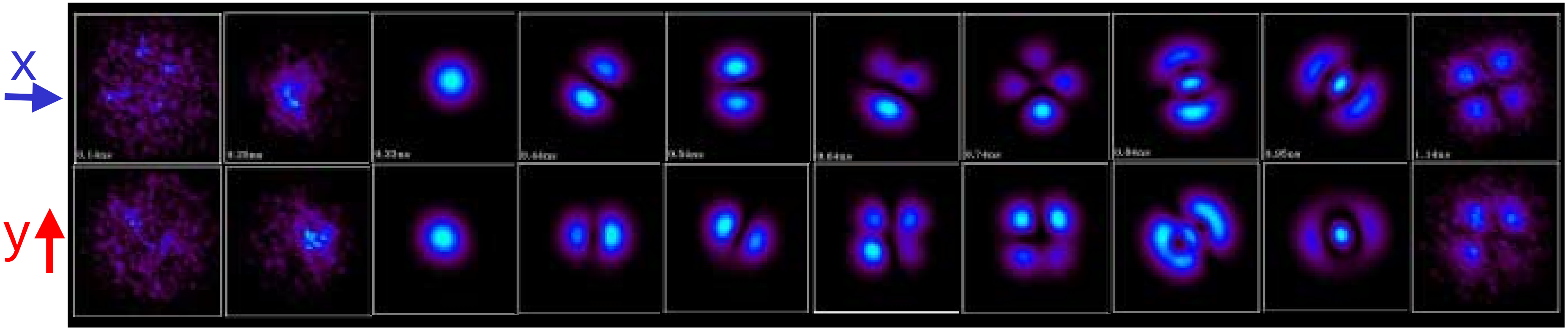
Associated with different device geometries





• Sub-nanosecond electrical excitation

ϕ =22µm, Gain-guided bottom-emitting VCSEL



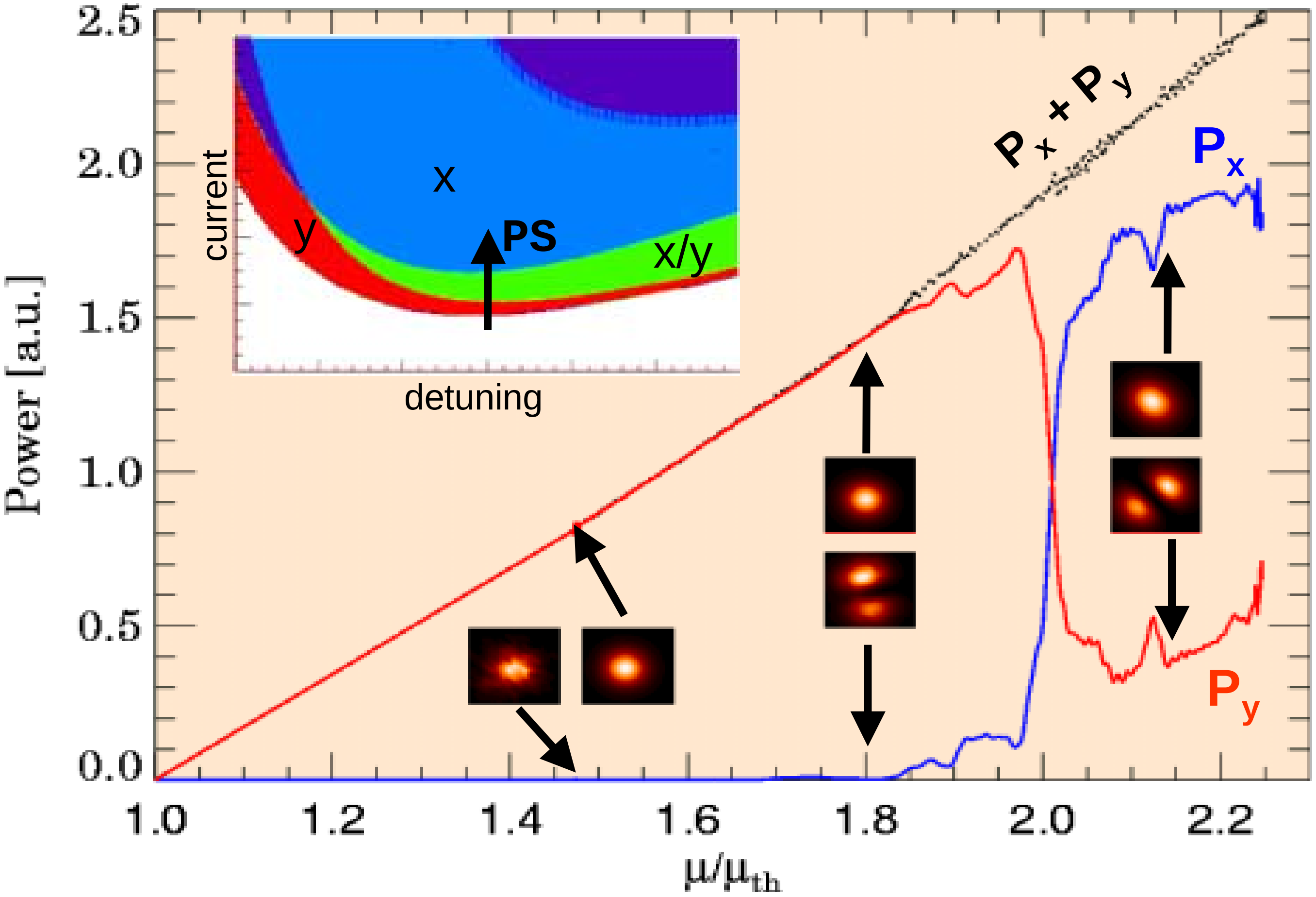
Time / 1 ns →

J. Mulet and S.Balle, *IEEE JQE* **38**, 291 (2002)

•Experiments: O. Buccafusca, et al. *IEEE JQE* **35**, 608 (1999).

NON-THERMAL POLARIZATION SWITCHING

- Gain guided VCSEL & Thermal lenses, ϕ_c=10 μm, ϕ_g=12.5 μm



Conclusions

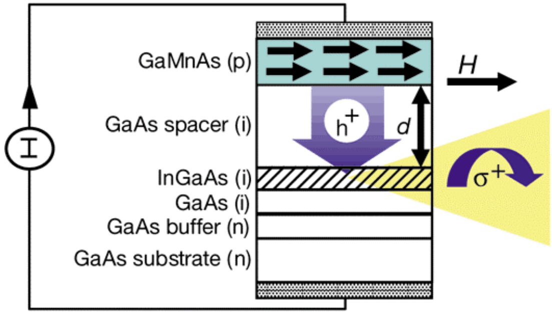
RELEVANCE OF THE SPIN-FLIP RATE DETERMINING THE POLARIZATION AND TRANSVERSE MODE PROPERTIES OF VCSELs

- Alternating polarization Larmor pulses of the stimulated emission
- Nonlinear anisotropies in the spectra of the polarization components
- Anticorrelated polarization fluctuations
- Polarization switching and optical bistability

Perspectives

ELECTRICAL SPIN INJECTION IN A VCSEL STRUCTURE

- Interesting method for preferentially exciting one spin channel
- No necessity of optical pumping
- Achieved in a ferromagnetic sc heterostructure



Y. Ohno, et al., *Nature* 402, 790 (1999).