# Two-mode dynamics in different semiconductor laser structures

I·M·E·D·E·A
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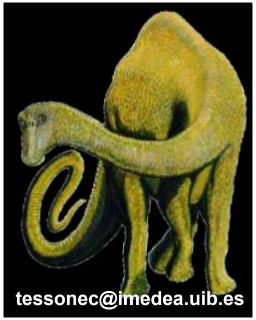
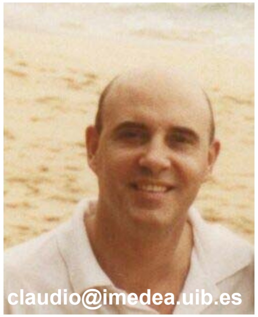
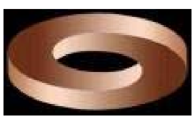






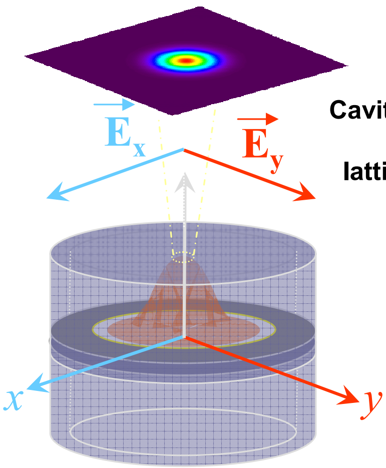

- **Vertical Cavity Surface Emitting Lasers**

- **Twin Stripes Semiconductor lasers**



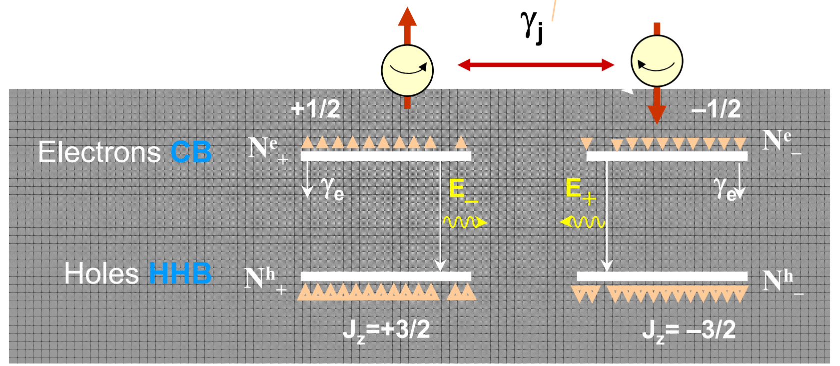
- **Semiconductor Ring-lasers**

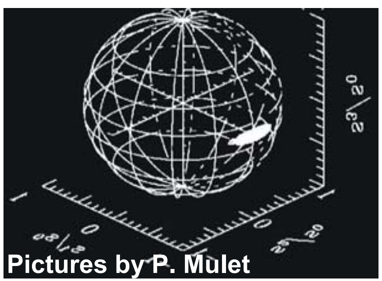
# VCSELs – two-polarization modes

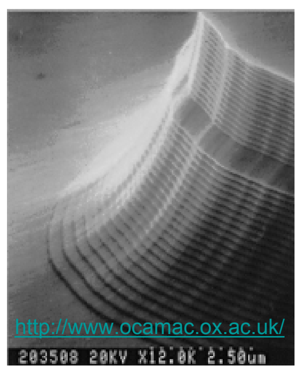



**Cavity constraints**
**+**
**lattice symmetry**

**Light/matter interaction selection rules …**




Polarization switching

# Polarization switching

| | | Thermal (lattice) | Non-thermal |
|---|---|---|---|
| Intensity instab. | Material gain | - gain shift<br>- gain/loss shifts<br>- Strain (thermo-elastic) | - Carrier heating<br>- type I PS in SFM |
| | Modal gain | - Thermal lensing | - Spatial hole burning |
| Phase instab. | No gain mech. | | Spin Flip + $\alpha$-factor<br>(Pol./Phase/Ampl-coupling)<br>Type II PS |

**G.Verschaffelt, et al.**

**≠ types of PS in ≠ types of VCSELs.** VISTA RTN

# VCSELs: Proposed theoretical descriptions

*Spin-Flip Model*

## 1. Processes and features

- **SVA.Polarization d. of f.**
  - **Intensity-Phase-polarization interaction (cavity-anisotropies & alpha-factor)**
  - **Polarization resolved Light/matter int.selection rules**

## 2. Achievements

- **Good description of *some* PS processes (non-thermal PS, phase instabilities)**
- **Good description of intensity/phase/polarization non-linear dynamics**

## Extensions:

- **multi-transverse mode dynamics (mesoscopic susceptibility beyond the two-level approach)**
- **External cavity, phase conjugated feedback, ext. Injection, sat.absorber.**
- *Two mode rate equations:*

  **Explain jitter (variances)**

  **Investigate the switching time statistics**

  **frequency-limit current-induced PS**

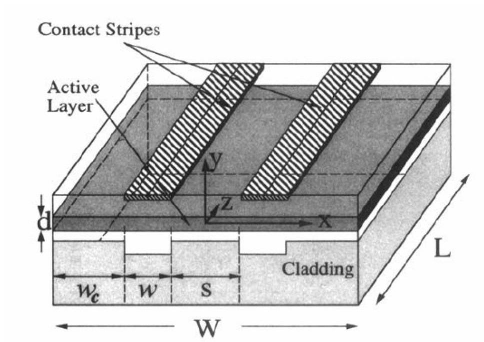
  **Origin of PS in VCSELs**

Relationship SFM-TMRE
Van der Sande et al, PRA 2003.

- **Twin Stripe lasers: two-spatial modes**

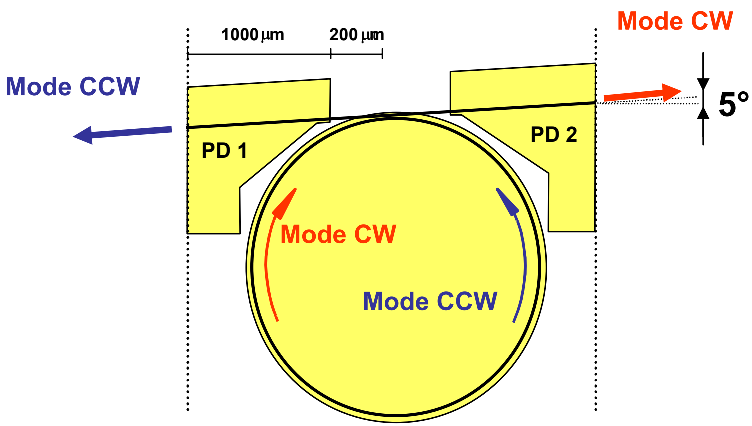
- Fast two-mode dynamics (e.g. anti-phase current driving)
- Bistability

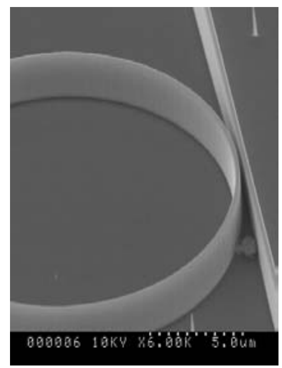
- FALCON-TMR




*[O.Hess, E.Scholl, PRA 50, 787 1994]*
*[I.Paiss, A.Hardy, IEEE JQE 25, 1609 1989]*

- **Semiconductor Ring-lasers: two-counterpropagating-modes**
- Bistability
- Inertial Rotation Sensors




*[M.Sorel et al. Opt.Lett. 27 1992 (2002)]*
*[…Nature…]*

# Theoretical framework

## Maxwell – Bloch Eqs.

Two-levels $\chi$ + $\alpha$-factor
+ phen. Dissipation
$\delta_t P=0$

Single mode operation
SVEA
Mean field

**VCSEL**

Spin-Flip model
Four levels + spinflip
div(E)=0
Linear anisotropy

Rate Eqs.
$\gamma_s=\infty$

$\gamma<1$
[M. San Miguel
PRL 75, 425 (1995)]

**Twin Stripes**

Twin-Stripe.TwoModeSVA
Coupled-Mode theory

**Sem. Ring Laser**

Ring.TwoModeSVA
Perturbative symmetry br.

$\gamma=2$ (!)...

VC Ginzburg-Landau Eq
[I.R.Aranson Rev.Mod.Phys. 74 99 (2002)]
*Time scales < $f_{rel.ox.}$ $\delta_t N=0$*

$\gamma<<1$

**VCGLE**

$$\dot{E}_{1,2} = (\mu + i\omega)E_{1,2} + (b+i\theta)\left(|E_{1,2}|^2 + \gamma|E_{2,1}|^2\right)E_{1,2} - (k_d + ik_c)E_{2,1}$$

Cross-saturation
Linear-field-coupling

[1997 - Polarization Properties of Vertical-Cavity Surface-Emitting Lasers.
*J.Martin-Regalado*,Ph.D. www.imedea.uib.es

# Gain Cross-saturation in SRL

Given form of $\delta\hat{N}(z)$ can pick out any synchronous terms besides the unsaturated gain:

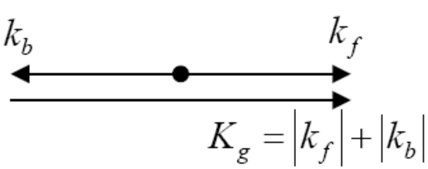
#12.5:
$$\delta\hat{N}(z) = \frac{I_f + I_b}{I_{sat}} + \frac{\sqrt{I_f I_b}}{I_{sat}}\left(e^{-i2kz} + e^{i2kz}\right)$$

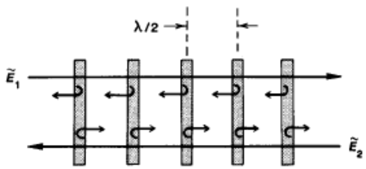
Besides usual uniform self- and cross-saturation terms, circled terms also synchronous

$$\frac{dI_f}{dz} = g_0[1 - \frac{I_f}{I_{sat}} - \frac{2I_b}{I_{sat}}]I_f$$

Leads to cross-saturation *twice* as strong as self-saturation: major impact on stability analysis

Result of coherent scattering off the Bragg-matched grating
Similar phenomena appear in many contexts: photorefractives, FWM, …




www.stanford.edu

## Gain Cross-saturation in VCSEL

•Cross-sat is dynamically included through spin-deviation var. *d(t) in SFM model*
Spin deviations affects polarization, coupled to phase ( $\gamma_p$) and to amplitude ($\alpha$).

•In two mode rate equations cross sat. Coef. are euristically included or derived from SFM …

$$\varepsilon_{xy} = \frac{2\kappa\gamma_s}{\gamma_s^2 + 4\gamma_p^2}\left(1 - 2\alpha\frac{\gamma_p}{\gamma_s}\right)$$

$$\varepsilon_{yx} = \frac{2\kappa\gamma_s}{\gamma_s^2 + 4\gamma_p^2}\left(1 + 2\alpha\frac{\gamma_p}{\gamma_s}\right)$$

Van Exter et al, JOB 1999.
Van der Sande et al, PRA 2003.

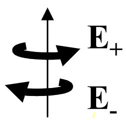
## Gain Cross-saturation in TSs

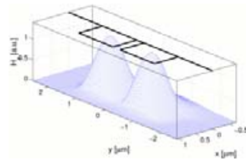
•Often neglected ($\gamma$=0)

•Incoherent coupling due to Cross-carrier diffusion

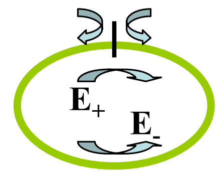
# Complex linear fields coupling

| **VCSEL** | **Twin Stripes** | **Sem. Ring Laser** |
|---|---|---|
| Spin-Flip. RE model<br>Circular pol. basis | Twin-Stripe.TwoModeSVA<br>Local fields | Ring.TwoModeSVA<br>Travelling waves |



$E_+$ $E_-$

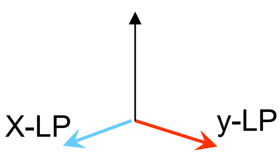



- Cavity anisotropy
- Diffraction - Evanescent wave
- localized reflection

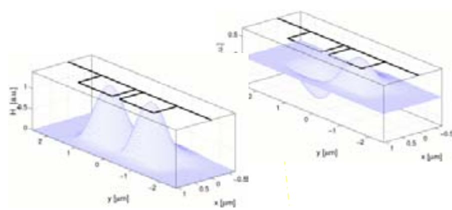
**VCGLE: O(2) group symmetry breaking**

*[E.J. D'Angelo et al PRL 68 3702, 1992]*

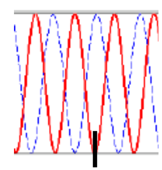
| Linear pol. basis | Supermodes | Standing waves |
|---|---|---|
| **0** *or* π *phase diff* | **0** *or* π *phase diff* | **0** *or* π *phase diff* |

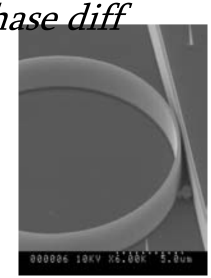



VISTA



*O. Hess et al. Phys. Rev. A 50, 787 (1994)*

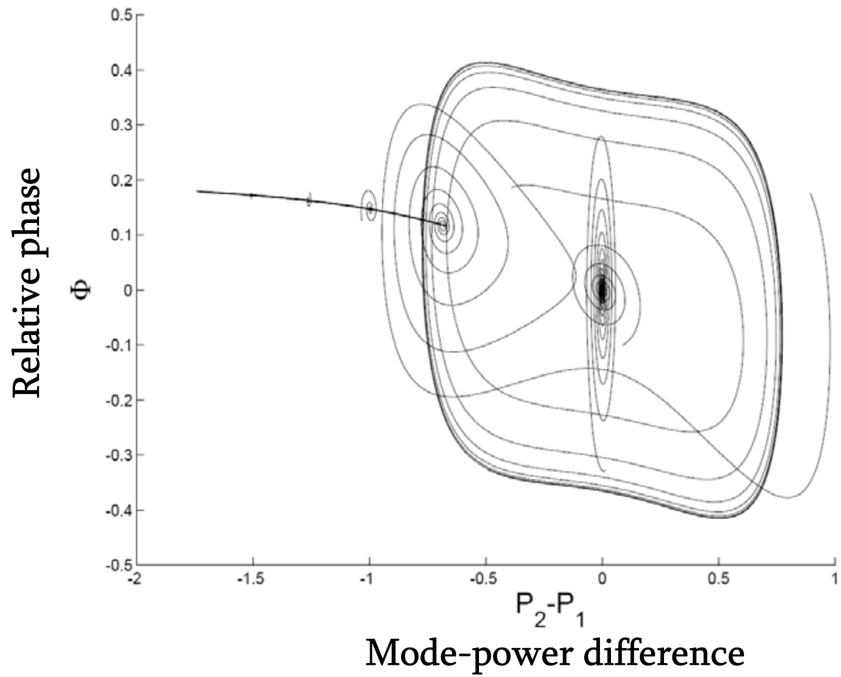




*R.J.C. Spreew et al. PRA 45 1213 (1992)*

Different effective ref. index: Different Frequency and losses

**VCGLE**. Bifurcations. $\gamma$ =2. $k_d$, $k_c$ ~ $10^{-3}$,$10^{-4}$

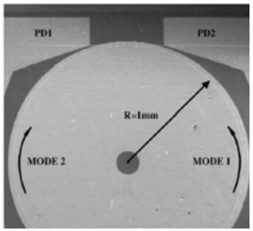



VCGLS ≡ experiments on AlGaAlAs 1mm radius Ring Laser

Why?

• $f_{Hopf}$ ~ 10-100 MHz << $f_{Rel.Ox.}$

# Experimental Results.SRL modeled by TwoMode. SVA Eqs.




**2mm∅ , DQW GaAs-AlGaAs**

<u>Three regimes</u>

**A: bi-CW**

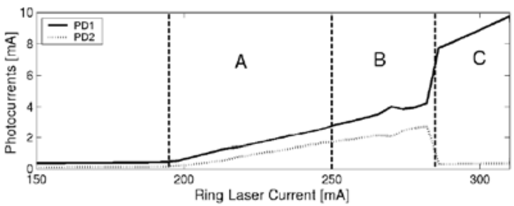
*Symmetric fixed point*

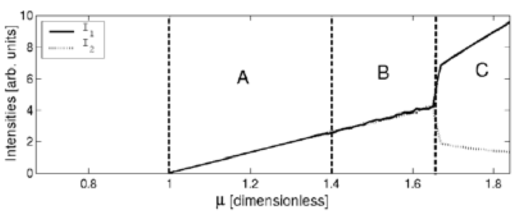
**B: bi-AO** →

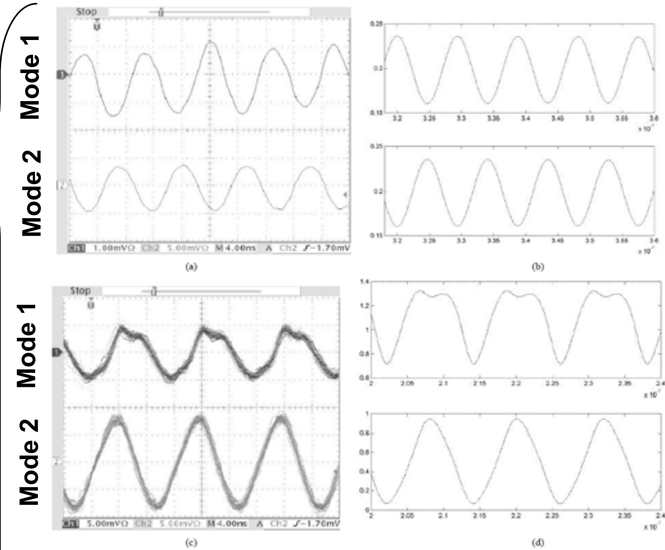
*Hopf induced limit cycle*

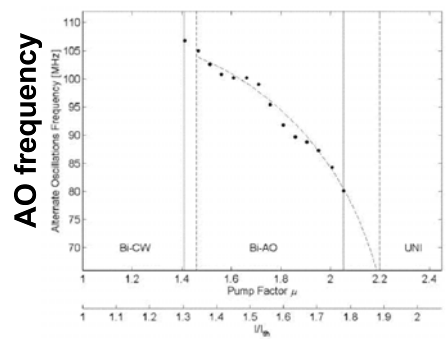
**C: UNI**

*Pitchfork induced bistability*




Sorel et al, IEEE JQE, <u>10</u> 1187 (2003), *Opt.Lett.* <u>27</u> 1992 (2002)

# Switching in bistable SRL

## Two-mode SVA model results

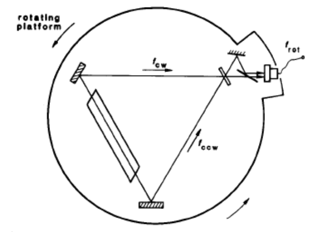
- **Single mode SRL with perturbative backscattering is intrinsically bistable**
- Structural constraints to achieve bistability
- Some insight on the switching process: energy redistribution between CW and CCW
- Switching time *10-30 ps*. Switching energy *few fJoules*

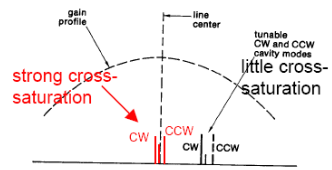
*….. But …..*

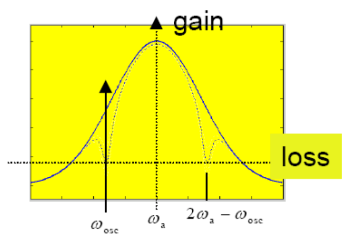
☹ Model not suitable @*ps* timescale
☹ Model not suitable for microRings
➔ TW approach ( local SHB due to pulse propagation)

## He-Ne Ring-Laser-Gyro

- Ring lasers used as rotation sensors
  - CCW and CW mode frequencies split
    $\omega_{CCW} - \omega_{CW} \propto \text{rotation rate}$
  - beat note measures rotation
- Obviously need both modes oscillating simultaneously
  - usually OK as gain medium (He-Ne) is inhomogeneously broadened
  - spectral holes usually don't overlap
  - cross-saturation weak: $C < 1$



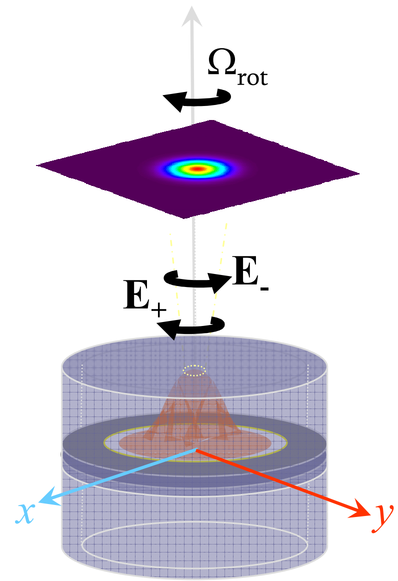

Phase-locking (Adler eq.) $d\Delta\phi/dt = \Delta\omega + k_d \sin(\Delta\phi)$

General coupled oscillators behavior $\Delta\phi = \arcsin(\Delta\omega/k_d)$

Fokker-Plank description of phase noise (NER)

[W.W.Chow et al. Reviews of Modern Physics 57 61, 1985.]

## Spinning-VCSEL




## Inertial rotation induces circular anisotropy In VCSELs

### Theoretical approach

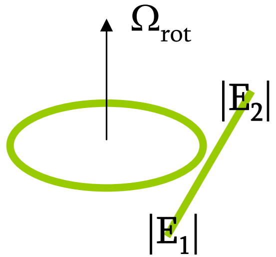
• Maxwell Eqs in rotating framework (*Lorentz tr.*)
+ Bloch Eqs. (medium at rest) see discussion
[Phys. Rev. 1966-1969]

Modified Spin-Flip model + circular birefringence $\gamma_c \sim \Omega_{rot}$
• Indirect effect on polarization through $\gamma_p$:

<u>phase-ellipticity coupling</u>

$$\tan(2\chi) = -\frac{\gamma_c}{\gamma_p}\left(1 + \frac{\alpha k(\mu - 1)\gamma}{\gamma_s \gamma_p}\right)$$

# Rotating SRL




$$\Delta = \frac{2\pi R\tau_p}{\lambda}\Omega_{rot} \,,$$

Inertial rotation term
In two-mode SVA eq

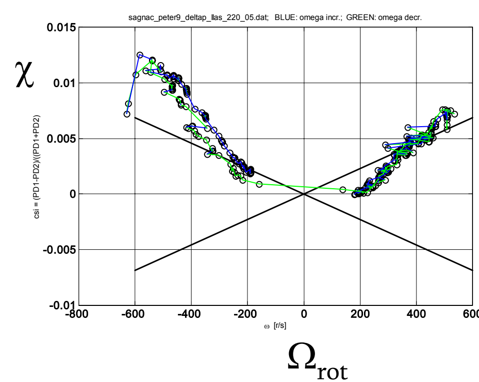
$$\dot{E}_{1,2} = \pm i\Delta E_{1,2} + \ldots - (k_d + ik_c)E_{2,1}$$

$$E_{1,2} = Q(1\pm\delta)\exp(i\omega + i\phi_{1,2}) \qquad \chi = \frac{|E_1|^2 - |E_2|^2}{|E_1|^2 + |E_2|^2} \approx 2\delta \qquad \phi = \phi_2 - \phi_1$$

$$\dot{\delta} = (\eta Q^2 N_0 - k_d)\delta - k_c\phi + \sqrt{\beta_{sp}\tau_p N_0}W_\delta$$

$$\dot{\phi} = (\alpha\eta Q^2 N_0 - k_c)\delta + k_d\phi + \Delta + \frac{\sqrt{\beta_{sp}\tau_p N_0}}{Q}W_\phi$$

$$\delta = \frac{-k_c}{[(k_d + \alpha k_c)2\eta Q^2 N_0 - k_d^2 - k_c^2]} \times \Delta\,.$$



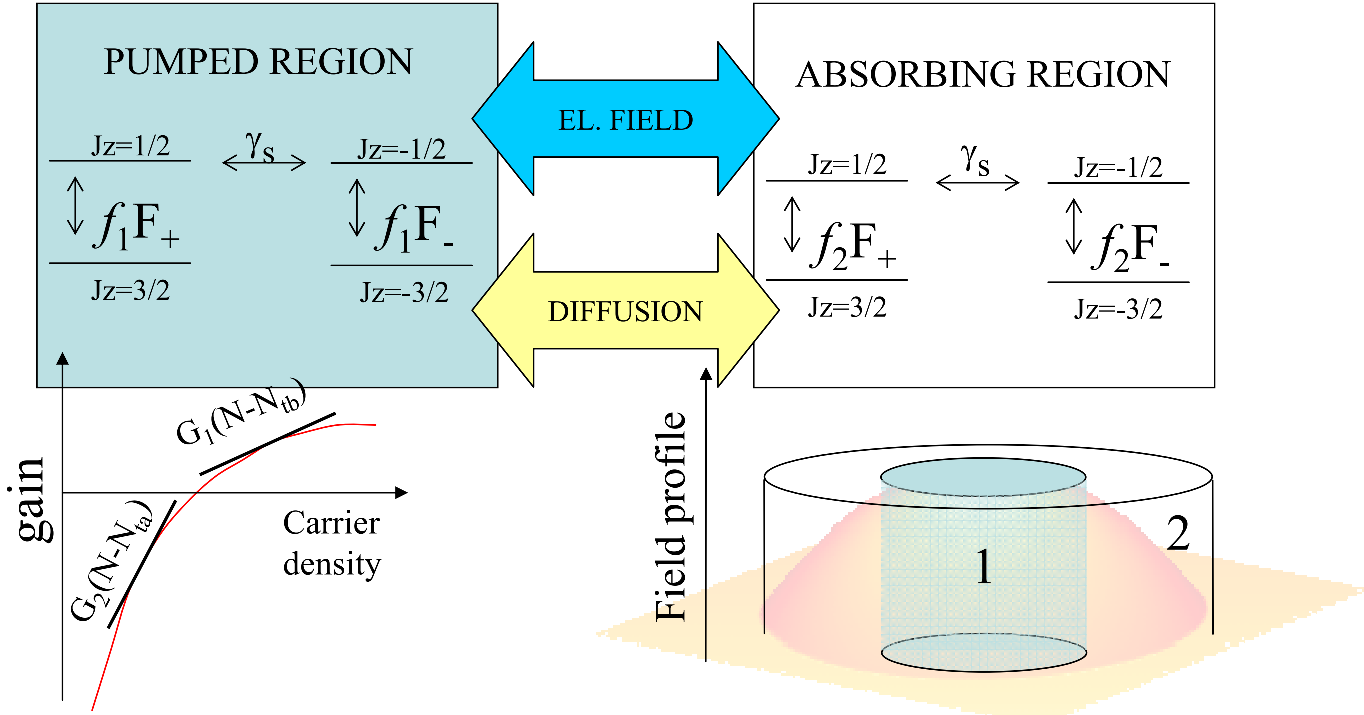

CW measure of inertial rotation

**Exp. by G.Giuliani, Università di Pavia**
**GaAs-AlGaAs SRL**

## Two.mode models + saturable absorber: small radius VCSEL

Spin-Flip + Yamada Model *[M.Yamada IEEE JQE 29 1330 1993 ]*

- Self-pulsations with polarization d. of f. *[Scirè et al. Opt. Lett. 27 391, 2002]*
- Polarization chaos: application to encoded communications *[Scirè et al. PRL 90, 113901, 2003]*
- Vectorial excitability (?)




Different gain slope

Different field fraction

# Two.mode models + saturable absorber

## Twin-Stripes

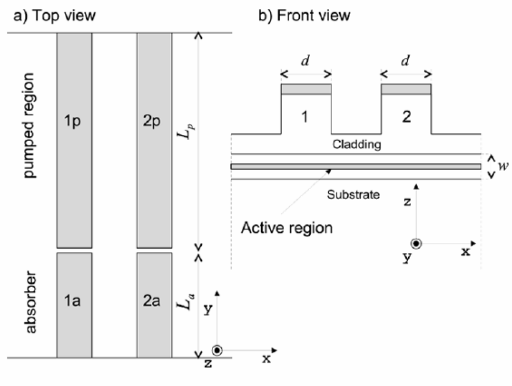
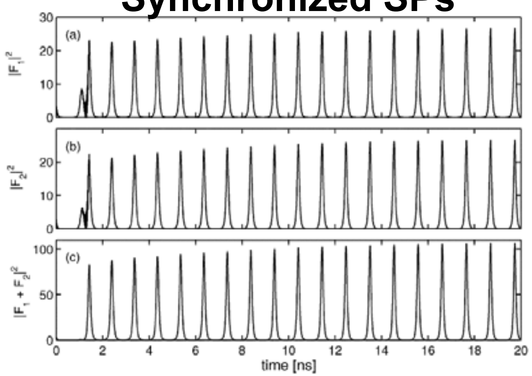



Fig. 1. Schematic picture of the device.

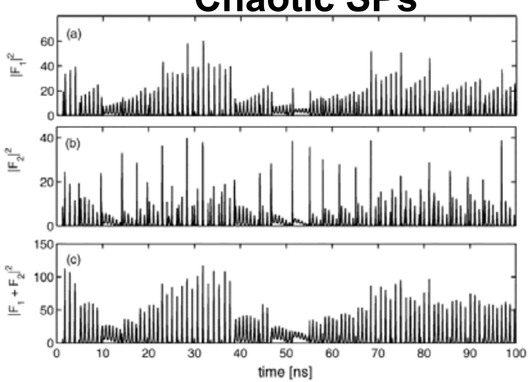
Two.modeSVA + Yamada Model

- Synchronization of SP *[Scirè et al. JQE 41 272, 2005]* in TS+sat.abs.
- View of synchronizing a many element SP_EELs array
- **View of Synchronized array of mode-locked EELs**

**Synchronized SPs**




**Chaotic SPs**




☹ Linearized gain Vs large carrier escursions ☹ Fast dynamics

- **Arrays**

Early works on arrays as a phase-oscillators-synchronization problem
*[H.G.Winful, ch.5 Diode Laser Arrays,* Cambridge 1994*]*

**Theory:**

- Rate equations with first neighbour coupling

Perfect synchronization – Kuramoto Model

- From network theory

All-to-all coupling, **kc = 1/**$\sigma$, av. path length $\ell$ **=1**

Given topology, **kc =** $f(\ell)/\sigma$ . E.g. linear chain of osc. $\ell = \ln(N)$

Coupled – mode theory is perturbative

e.g. *[ O.Hess PRA 50, 787 1994] – three regimes dep. on interelement spacing*

**Array synchronization is a size dependent problem**

Small arrays: coupled mode theory.

Big arrays: Bloch functions [D.Botez Diode laser arrays, Cambridge 1994].

Int. Case: device oriented modeling [P.Debernardi]

**Peculiarities in synchronizing pulsating lasers**

- **Conclusions**

?

- **Acknoledgments**


- **Salvador Balle, Guido Giuliani, Jan Danckaert, Siyuan Yu, Sandor Fuster, Pep Mulet** *and his nice figures*, **Francesco Marino, Francesco d'Ovidio, Iacyel Gomez da Silva, Victor M. Eguiluz, and many others….**