

# Analytical propagation of traveling-waves in mode-locked Vertical-External-Cavity Surface-Emitting Diode Lasers ~ VECSEL ~

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# **Analytical propagation of traveling-waves in mode-locked Vertical-External-Cavity Surface-Emitting Diode Lasers ~ VECSEL ~**

1. Introduction
2. VECSEL setup
3. Reported experimental results
4. A model for the electrically-driven VECSEL
5. Numerical and analytical results
6. Conclusions

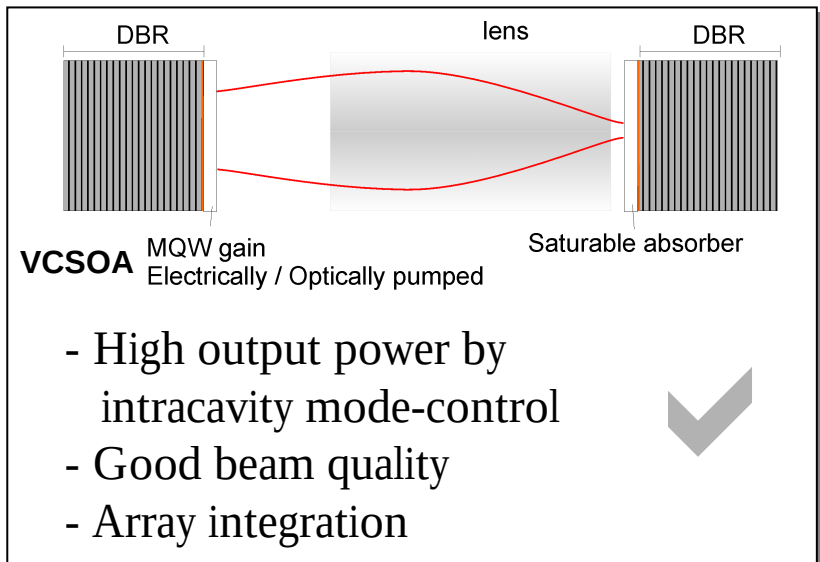
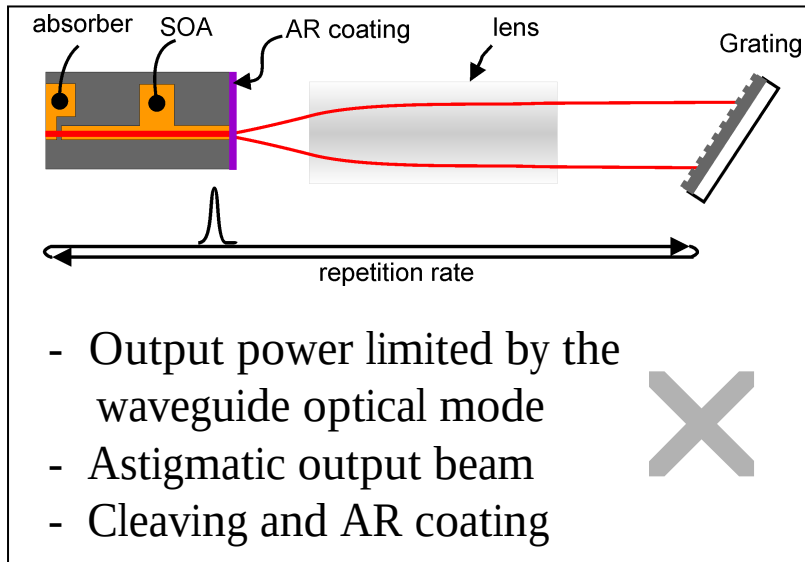
# 1. Introduction

## □ External-cavity lasers for mode-locking

### Edge-emitter

versus

### Vertical-cavity



## □ Mode-locking in VECSELs

### - Optically-pumped

- **Active** mode-locking by synchronous pumping (*Bowers, Ebeling*)
- High-power VECSELs **passively** modelocked by SESAM (*U. Keller*)

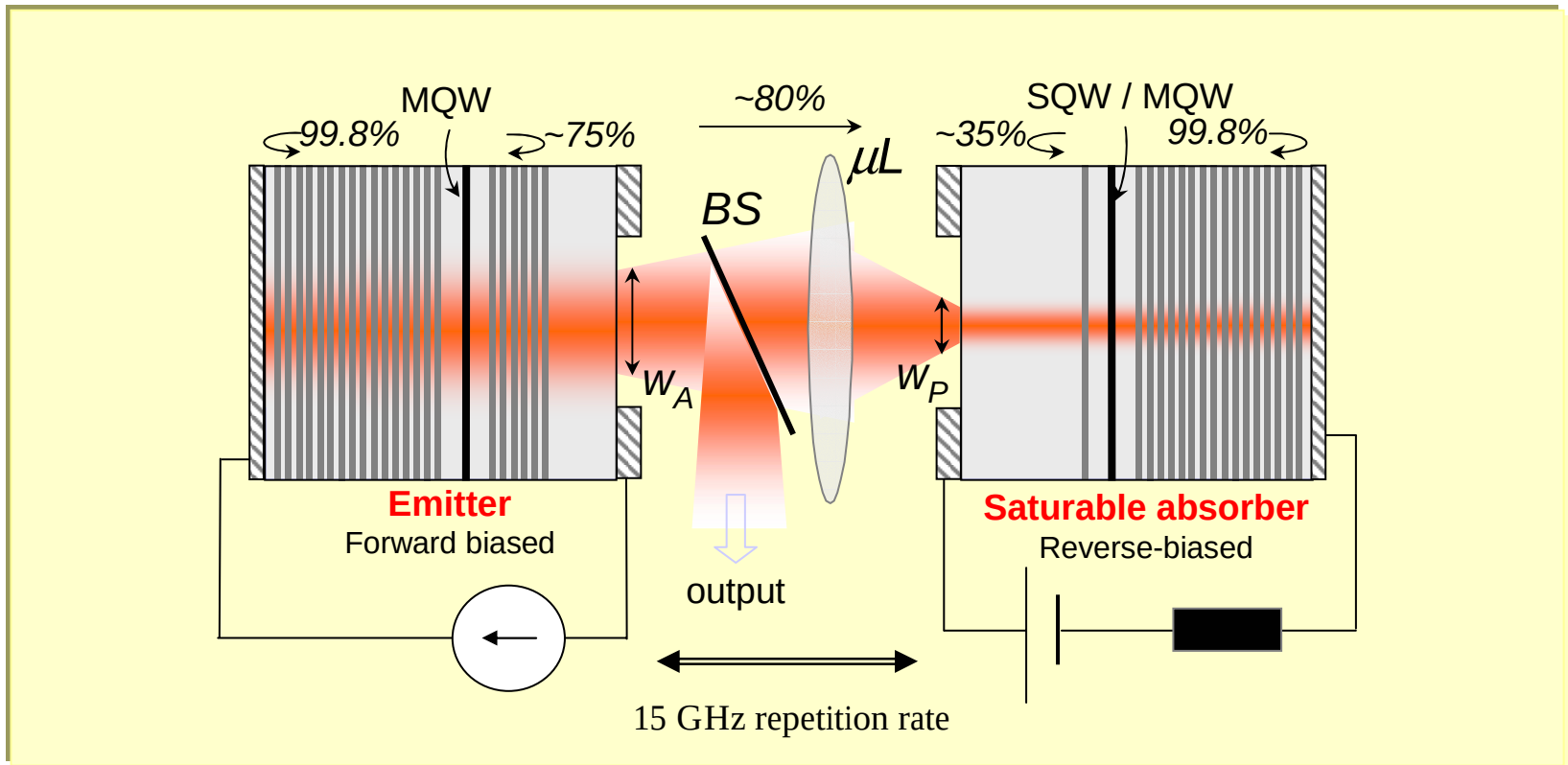
### - Electrically-driven

- **Passive** mode-locking with SESAM or MQW (*Brown + Novalux + MIT*)

## 2. VECSEL setup

### Linear resonator

~ K. Jasim et al., Electron. Lett. **40**, 34 (2004)



- The coupling strength can be controlled by varying the transmissivity of the beam splitter and the finesse of the vertical-cavities.
- The microlens defines the spatial mode size  $W_{A,P}$  on each vertical-cavity. Fundamental transverse mode operation is assumed.

# 3. Reported experimental results

## • Mode-locking with electrically-driven VECSELs

$\lambda \sim 980$  nm (So far)

| References                                      | Resonator           | Pulse-width (ps) | $f_{\text{Rep}}$ (GHz) | $\langle P_{\text{out}} \rangle$ (mW) |
|-------------------------------------------------|---------------------|------------------|------------------------|---------------------------------------|
| K. Jasim et al., Electron. Lett. 39, 373 (2003) | Z + SESAM           | 57               | 1.1                    | 40                                    |
| Q. Zhang et al., IEEE PTL 16, 885 (2004)        | Z, V + SESAM        | 48               | < 4                    | 30                                    |
| K. Jasim et al., Electron. Lett. 40, 34 (2004)  | Linear+MQW absorber | 15               | < 15                   | ~10                                   |

### Pulsewidth $\sim 15$ ps

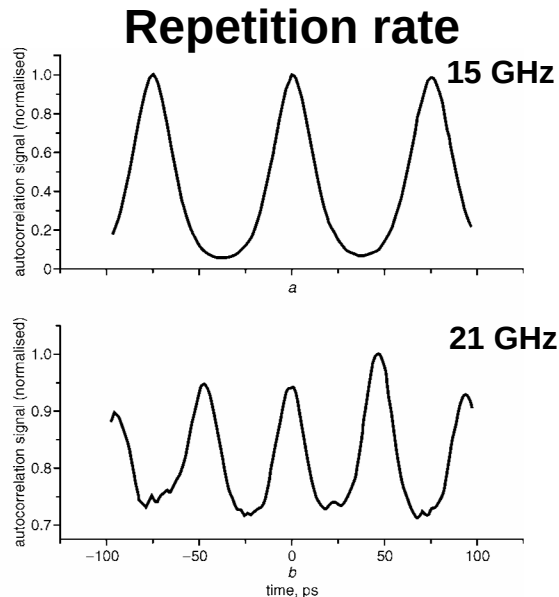
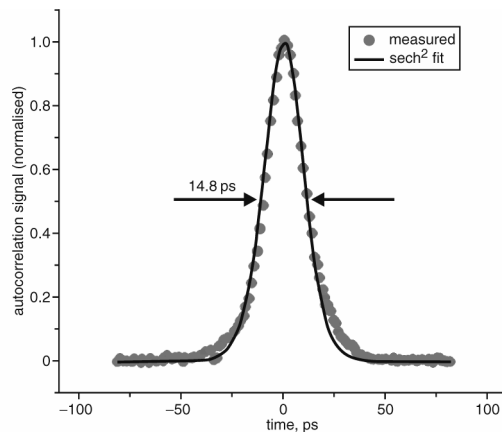


Fig. 3 Second-harmonic autocorrelation measurements

### Low timing jitter

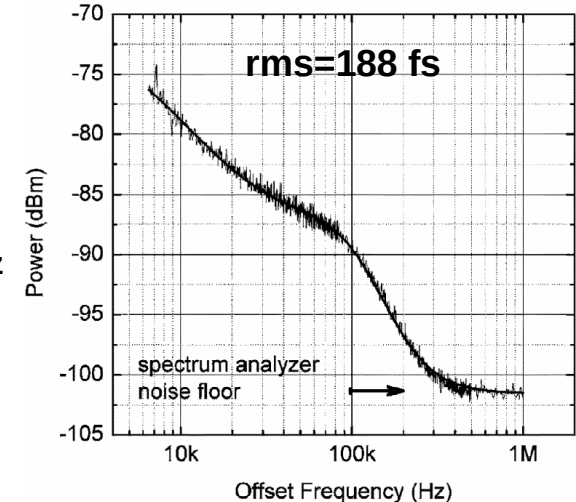


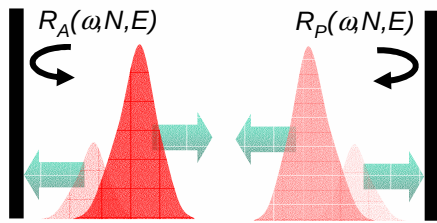
Fig. 2 Pulsewidth measurement by second-harmonic autocorrelation and corresponding hyperbolic secant fit

K. Jasim et al., Electron. Lett. **40**, 34 (2004)

Q. Zhang et al., IEEE PTL **17**, 525-527 (2005)

# 4. Pulse propagation models

## Pulse iterative models



-Effects of regeneration by the cavities are applied in succession

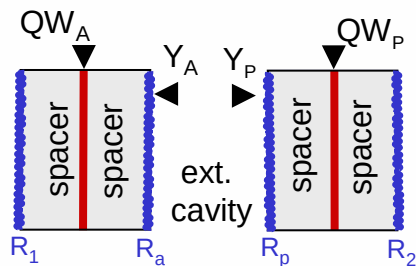
R. Paschotta et al., Appl. Phys. B **75**, 445 (2002)

O. E. Martínez et al., J. Opt. Soc. Am. B **2**, 753 (1985)

e.g.: H. Haus, J. Appl. Phys. **46**, 3049 (1975)

- The pulse is iterated over different roundtrips

## Analytical approach

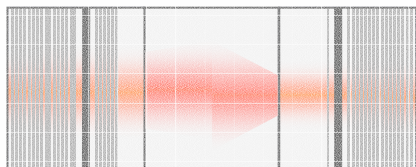


**Combines rigorousness and simplicity**

- Analytical solution to the bidirectional traveling wave equations in three coupled cavities

- Nonlinear interaction solely involves the QW layers

## Fully-distributed models

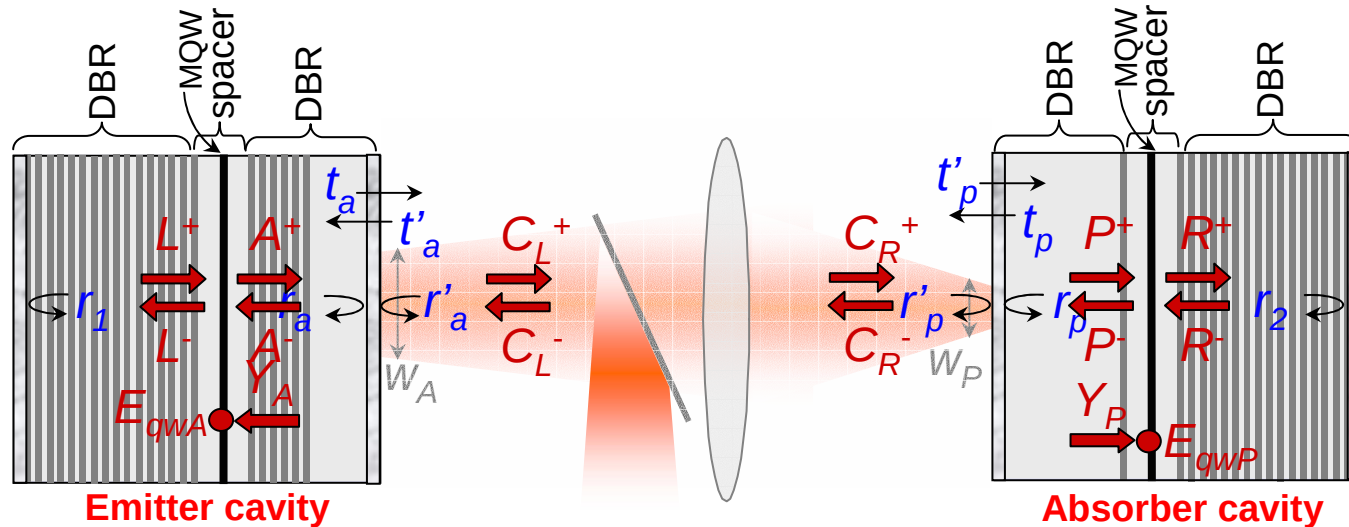


- Numerical solution of Maxwell's equations using a finite difference algorithm

M. Bahl et al., Opt. Lett. **29**, 1689 (2004)

- Detailed description of the intracavity optical fields
- Time consuming even without transverse dependence

# 4. Analytical propagation



## ▪ Hypotheses

1. Fundamental transverse mode.  
Homogeneous saturation in  $\pi W_{A,P}^2$
2. Linear response of DBRs
3. Thin QWs;  $W \ll \lambda$
4. Separation of time scales

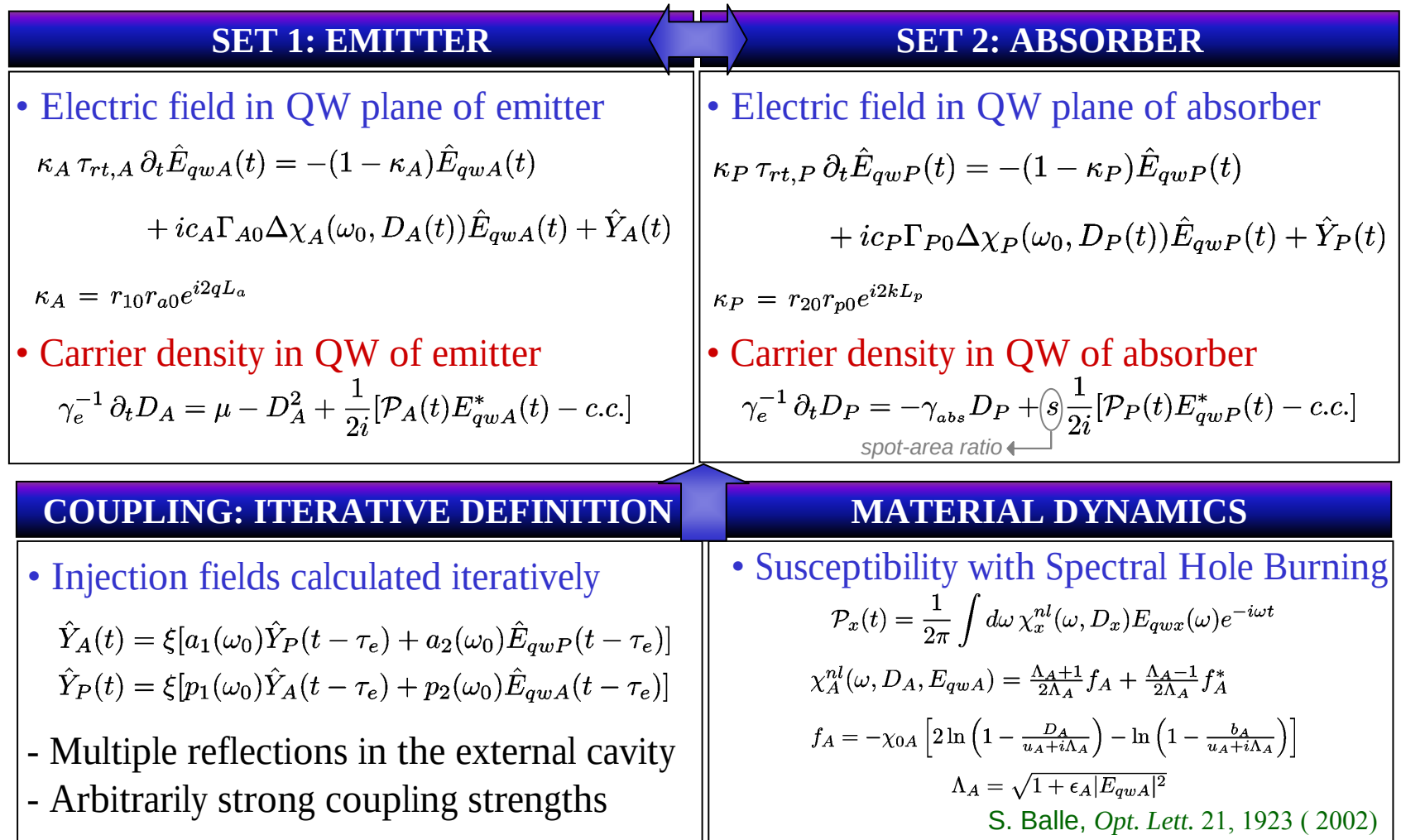
## ▪ Recipe

1. Effective-index approximation
2. Transfer matrix applied to DBRs
3. Apply boundary conditions
  - At mirrors and QWs
  - Express everything as function of QW and injection fields
4. SVA and inverse Fourier transform

J. Mulet and S. Balle, *IEEE JQE* **41**(9), 1148-1156 (2005)

# 4. A novel time-domain model

- Two sets of coupled laser equations with time-delay



J. Mulet and S. Balle, *IEEE JQE* 41(9), 1148-1156 (2005)

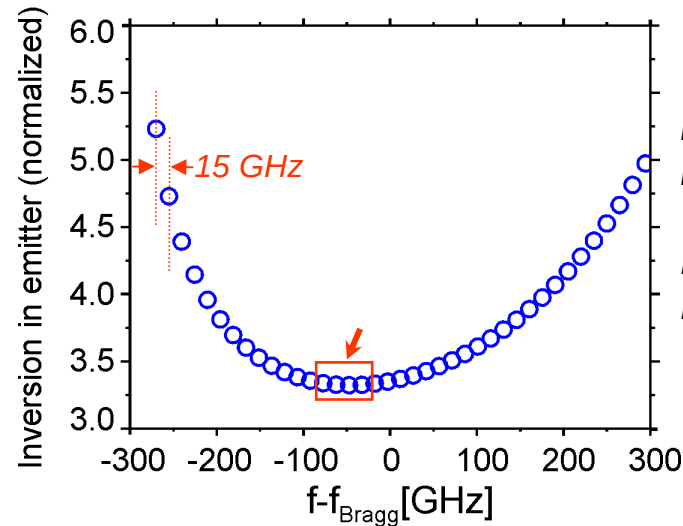
# 5. Compound-Cavity-Modes



→ Monochromatic solutions for  $E_{qwk}$  and steady state inversions  $D_k$

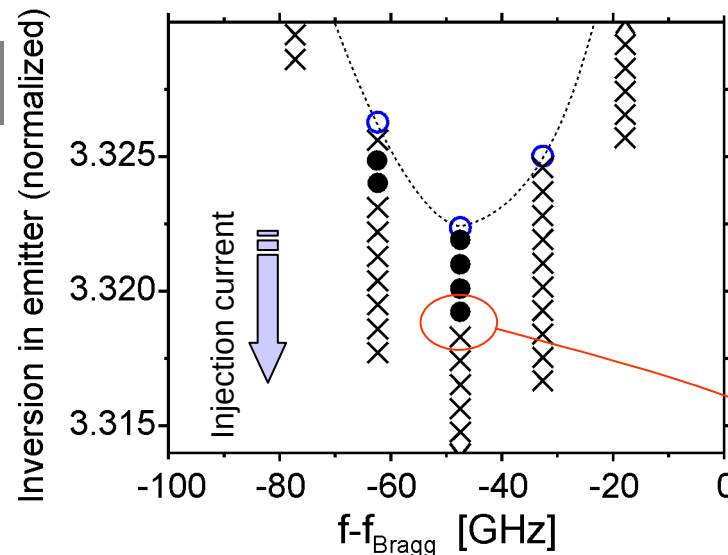
## OFF-state CCMs

*Absorber unbleached*



## ON-state CCMs

*Increasing current*  
 $1.02 - 1.38 I_{th}$   
 at  $0.04 I_{th}$  steps



## Linear Stability Analysis

○ = Off-CCM

● = Stable

✕ = Unstable

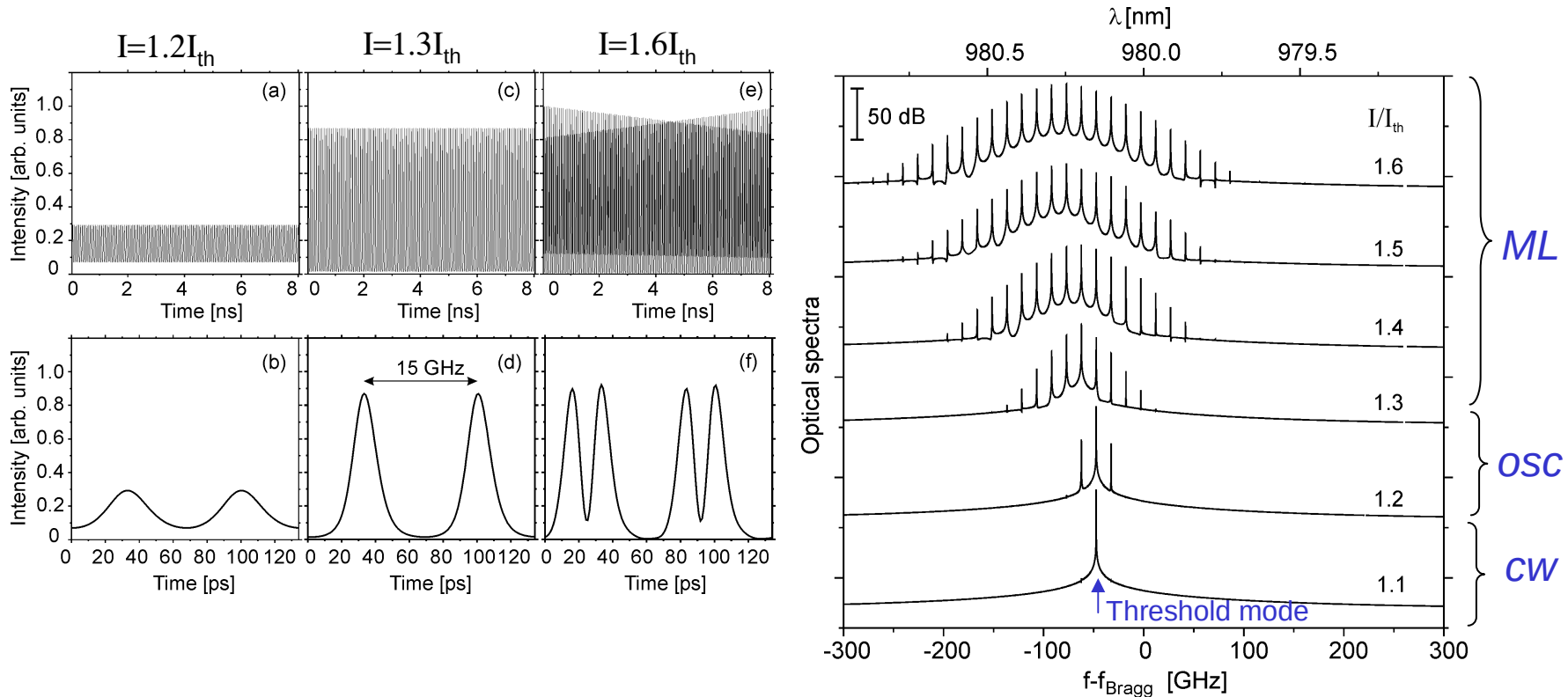
} On-CCM

→ Multimode Onset

# 5. Mode locking onset

- Scenario upon increasing the injection current in the emitter

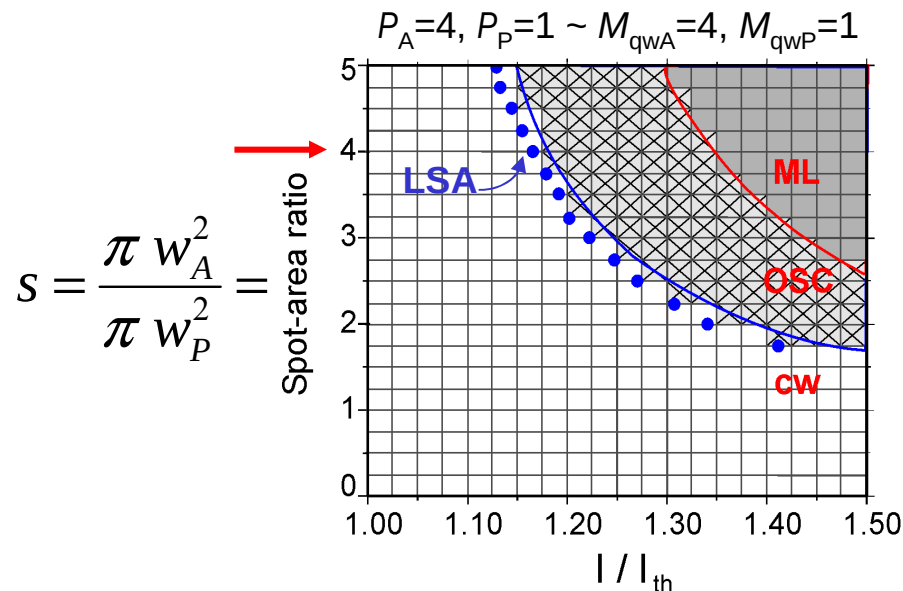
**CW → Oscillations → Mode locking → Incomplete mode locking**



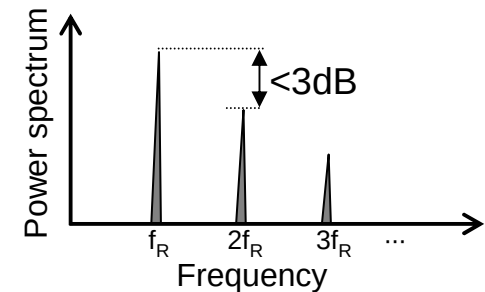
**Parameters:**  $\lambda = 980 \text{ nm}$ ,  $R_2 = R_l = 0.998$ ,  $R_a = 0.75$ ,  $R_p = 0.30$ ,  $W_a = W_p = 9 \text{ nm}$ ,  $M_{qwa} = 4$ ,  $M_{qp} = 1$ ,  
 $E_{gA} = 1.265 \text{ eV}$ ,  $E_{gP, \text{reff}} = 1.285 \text{ eV}$ ,  $V_{\text{abs}} = -3 \text{ V}$ ,  $B_{\text{rad}} = 1.5 \cdot 10^{-16} \text{ m}^3/\text{s}$ ,  $N_{tA} = 1.5 \cdot 10^{24} \text{ m}^{-3}$ ,  
 $N_{ip} = 0.75 \cdot 10^{24} \text{ m}^{-3}$ ,  $A_{\perp} = \pi 75^2 \mu\text{m}^2$ ,  $w_a/w_p \sim 2$ ,  $f_{\text{REP}} = 15 \text{ GHz}$ ,  $t_{bs} = 0.90$

## 5. Resonator design: Spot-area ratio

- **Spot area** of the spatial-mode on each vertical-cavity
- **Finesse** of the vertical-cavities



**CW** : continuous wave  
**OSC** : oscillations  
**ML** : developed mode locking



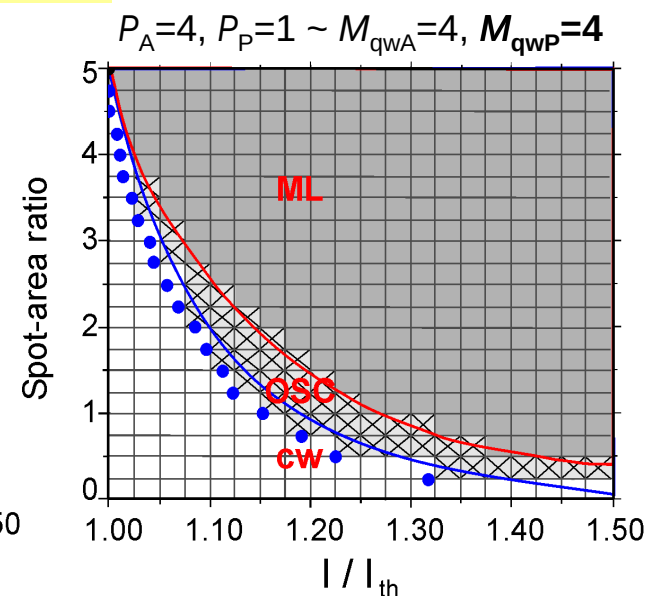
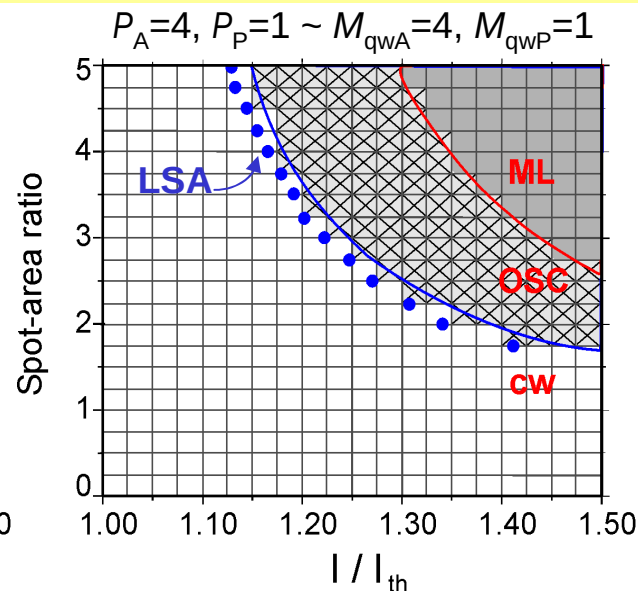
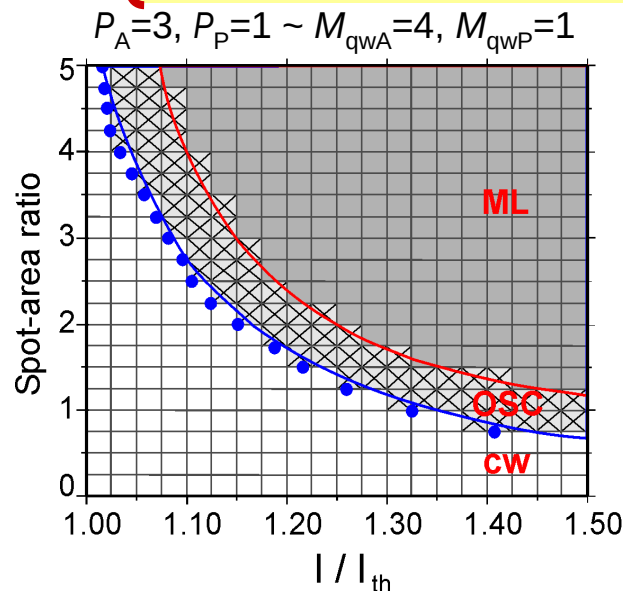
➡ **The onset of fully-developed mode locking can be favored by**

- More tightly focusing the spatial mode on the absorber facet
- There exists a critical value of  $s$  to obtain mode locking

# 5. Resonator design: Finesse

- Spot area of the spatial-mode on each vertical-cavity

- Finesse of the vertical-cavities

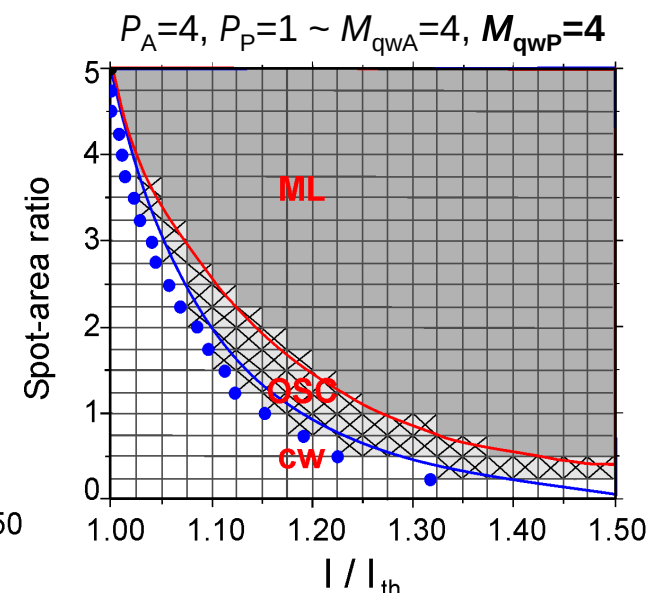
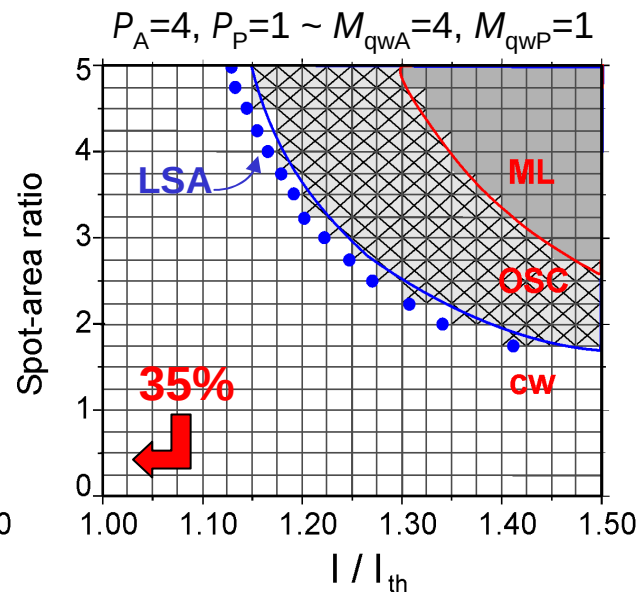
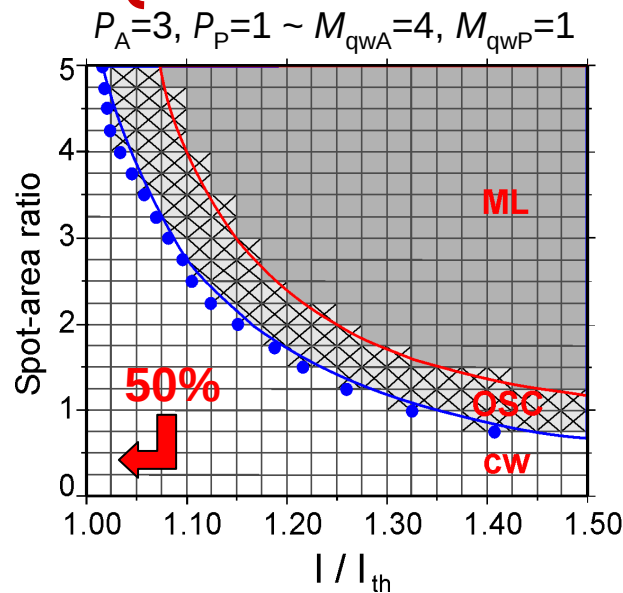


➡ The onset of fully-developed mode locking can be favored by

- Moderate/Low finesse of the emitter cavity
- MQW saturable absorber

# 5. Resonator design: Analysis

- **Spot area** of the spatial-mode on each vertical-cavity
- **Finesse** of the vertical-cavities



## Ratio of saturation energies

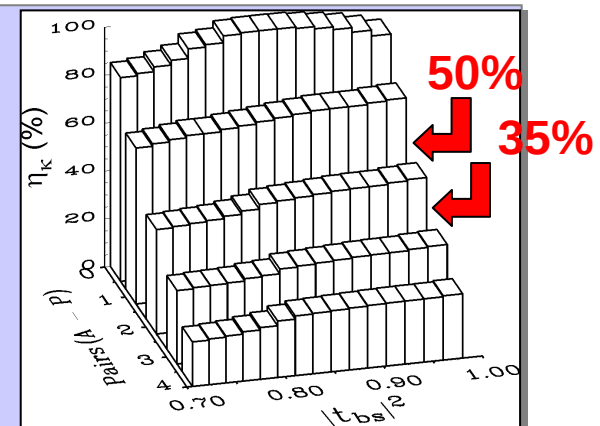
Important parameter for mode locking

$$\sigma \propto \left( \frac{F_{sat,A}}{F_{sat,P}} \right) \frac{\pi w_A^2}{\pi w_P^2} \times \eta_\kappa$$

(coupling efficiency)

Standing wave effects  $\eta_\kappa = \left| \frac{E_{qw,A}}{E_{qw,P}} \right|^2$

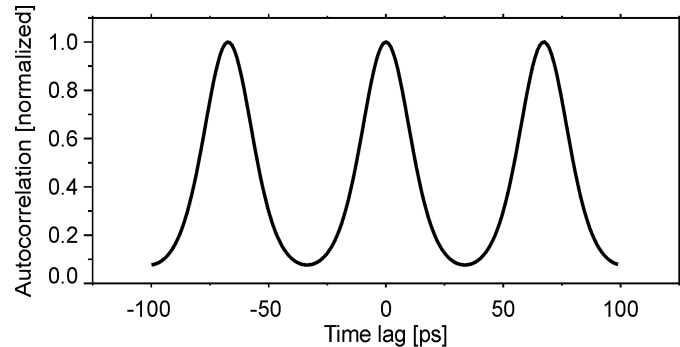
↑ Saturation fluences      ↑ Spatial-mode areas



# 5. Pulsewidth

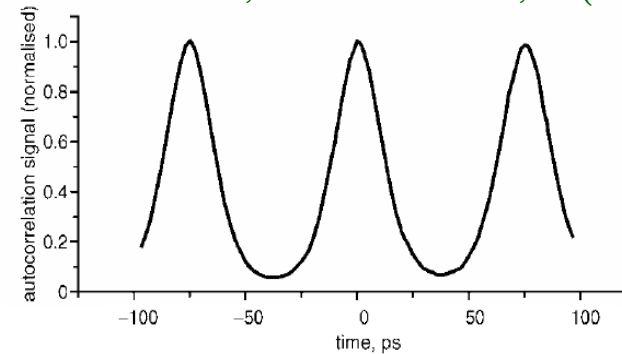
## - Autocorrelation function at 15 GHz

**Simulations**  $I = 1.3I_{th}$

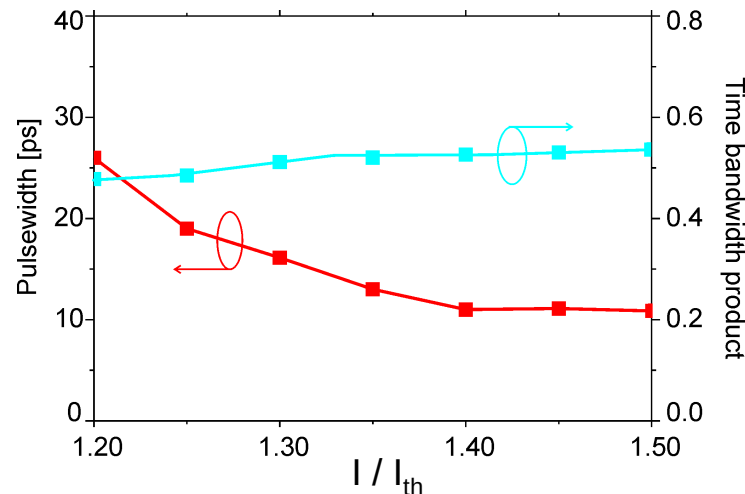


**Experiments**

K. Jasim et al., Electron. Lett. **40**, 34 (2004)



## - Pulsewidth *versus* injection level in the emitter



- Stable pulses of few tens of picoseconds at  $\sim 15$  GHz repetition rate
- Further optimization required for  $\sim 1$  ps

## 6. Summary and conclusions

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### Conclusions

- A novel time-domain model for mode-locking dynamics in VECSELs
- Stable multi-GHz rate picosecond pulse generation from a VECSEL:  
~15 ps pulses at 15 GHz repetition rate in agreement with reported experimental results
- Effects of the resonator design on the mode-locking onset:
  - Spot-area ratio and finesse of the cavities  $\sim LSA / Simulation$
  - Strong mode coupling between both cavities is recommended

### Generalizations

- Spatial-hole burning effects on transverse mode characteristics
- Including thermo-electro-optical simulation
- Noise characteristics: Phase noise and timing jitter