Weierstraß-Institut für Angewandte Analysis und Stochastik

Dynamic Simulation of High Brightness Semiconductor Lasers

M. Lichtner, M. Radziunas, U. Bandelow,
M. Spreemann and H. Wenzel

Leibniz Gemeinschaft

Ferdinand-Braun-Institut für Höchstfrequenztechnik

Outline

- Modelling
- Numerical Solution
- Results
- Summary

Mathematical Modelling and Numerical Simulation

•Semiconductor lasers are characterized by a huge amount of physical and geometrical parameters

•Time-space instabilities like
- •Pulsations
- •Self-focusing
- •Filamentation
- •Thermal Lensing

⇒ Restrictions to beam quality and wavelength stability.

•Mathematical modeling and computer simulations are needed for
- –preparing technological processes to choose optimal parameters
- –understanding experimental data
- –predicting new laser designs.

2d Optical Amplitude Equations

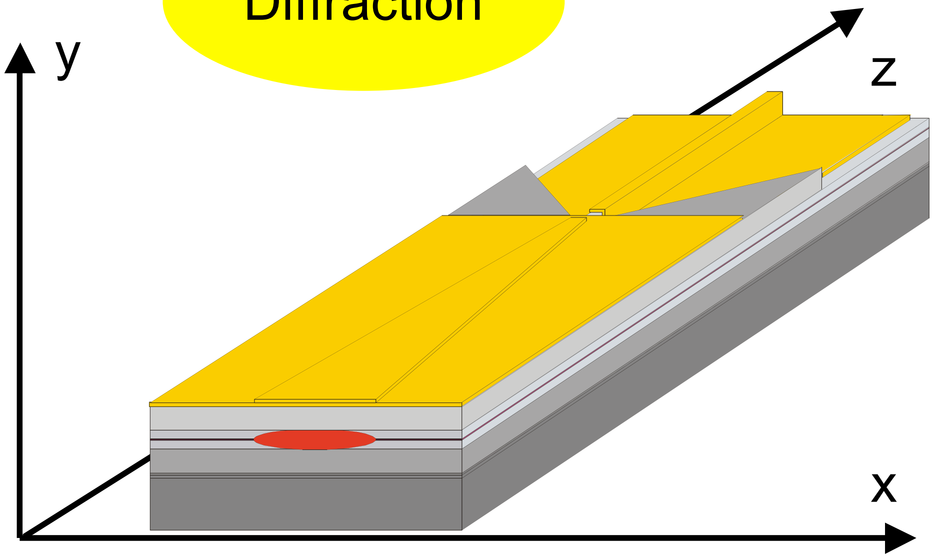
Propagation

$$\frac{1}{v_g}\partial_t u^{\pm}(x,z,t) = \mp\partial_z u^{\pm}(x,z,t) - i\beta(x,z)u^{\pm}(x,z,t) - \frac{1}{2\bar{n}k_0} i\partial_{xx}u^{\pm}(x,z,t)$$

Diffraction

with

$$\beta(x,z) := k_0 \frac{n_{eff}^2(x,z) - \bar{n}^2}{2\bar{n}}$$



Model for β

Effective refractive index depends on carrier density N and temperature. We use the following model for β:

$$\beta = \delta_0(x,z) + \delta_\Sigma(x,z,N,J) + i\frac{g(x,z,N,u)-\alpha(x,z)}{2},$$

$$\delta_\Sigma(x,z,N,J) = \delta_n(x,z,N) + \delta_T(x,z,J),$$

where

- δ_0 index variation in space,
- $\delta_n = -\sqrt{n'N}$ dependence of effective index on the carrier density,
- δ_T temperature dependence of effective index,
- $g(x,z,N,u) = g'(x,z)\frac{\ln\frac{N(x,z,t)}{N_{tr}}}{1+\epsilon\|u\|^2}$ optical gain,
- $\alpha = \alpha(x,z)$ optical losses.
- Model parameters determined at FBH and HU Berlin experimentally.

Model Equations

$$\begin{aligned}
\frac{1}{v_g}\partial_t u^{\pm} &= \frac{-i}{2k_0\bar{n}}\partial_{xx}u^{\pm} + \left(\mp\partial_z - i\beta\right)u^{\pm} - i\kappa u^{\mp} - \frac{\overline{g}}{2}\left(u^{\pm} - p^{\pm}\right) \\
\partial_t p^{\pm} &= \overline{\gamma}\left(u^{\pm} - p^{\pm}\right) + i\overline{\omega}p^{\pm} \\
\partial_t n &= d_n\partial_{xx}n + \frac{J}{qd} - R(n) - v_g \mathfrak{Re}\langle u, g(n,u)u - \overline{g}(u-p)\rangle_{\mathbb{C}^2}
\end{aligned}$$

$$u^{+}(t,0,x) = r_0(x)u^{-}(t,0,x) + \alpha(t,x), \;\; u^{-}(t,l,x) = r_l(x)u^{+}(t,l,x).$$

- Spont. Recombination $R(n) = A(x,z)n + B(x,z)n^2 + C(x,z)n^3$
- Electrical injection $J = J(t,z,x)$, optical injection $\alpha(t,x)$
- Reflection coefficients $r_0(x),\; r_l(x)$
- All coefficients with the exception of $k_0,\; v_g,\; \bar{n}$ are spatially, i.e. laterally and longitudinally in (z, x) plane, nonhomogeneous and discontinuous (depending on the heterostructural lasergeometry)

Heating

Considered parametrically via Injection $J(t,z,x)$:

$$I_{MO} = \int_{MO} J(x,z)dxdz, \;\; I_{PA} = \int_{PA} J(x,z)dxdz.$$

Nonlocal dependence via:

$$\delta_T(x,z) \;\; = \;\; \frac{k_0 n_g}{\lambda_0} \int c_T(x,z,\tilde{x},\tilde{z}) J(\tilde{x},\tilde{z}) d\tilde{x} d\tilde{z},$$

Shift of gain peak:

$$\overline{\lambda}(x,z) = \overline{\lambda}_0(x,z) + \int \nu_T(x,z,\tilde{x},\tilde{z}) J(\tilde{x},\tilde{z}) d\tilde{x} d\tilde{z}.$$

Spectral method

$$\frac{1}{v_g}\partial_t E^{\pm} = \frac{1}{2K} i\partial_{xx}E^{\pm} + (\mp\partial_z - i\beta(n))\,E^{\pm} - i\kappa E^{\mp} - \frac{\overline{g}}{2}\left(E^{\pm} - P^{\pm}\right)$$

$$\partial_t P^{\pm} = \overline{\gamma}\left(E^{\pm} - P^{\pm}\right) + i\overline{\omega}P^{\pm}$$

$$\partial_t n = d_n\partial_{xx}n + I(t) - R(n) - v_g\mathfrak{Re}\langle E, g(n)E - \overline{g}(E-P)\rangle_{\mathbb{C}^2}$$

•Step 1: Solve diffraction und diffusion (red coloring) with fast Fourier transform

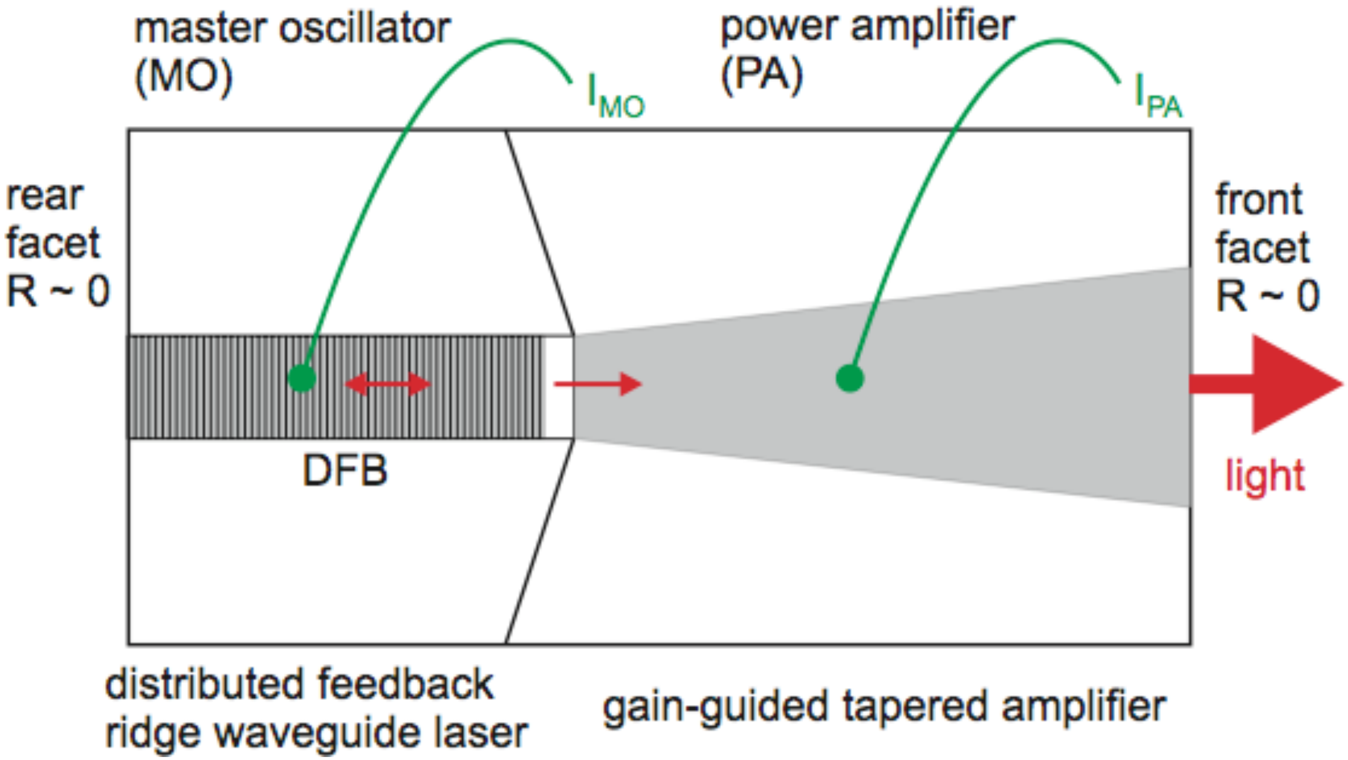
•Step 2: Solve remaining 1d hyperbolic system for each lateral x coordinate via integration along characteristics for fields

- •Solve fast P equation using exact solution formula with forward value for fields

•For spectral split method good L^2 convergence has been proven for smooth scalar nonlinear Schrödinger equation

•Use predictor / corrector method for optical nonlinearities

MOPA



master oscillator
(MO)
I_{MO}
power amplifier
(PA)
I_{PA}
rear
facet
R ~ 0
front
facet
R ~ 0
DFB
light
distributed feedback
ridge waveguide laser
gain-guided tapered amplifier

Large Scale Problem

- Longitudinal discretization 5μm for 973nm laser
- Time step 0.061ps
- Lateral discretization 0.625μm
- Resulting # of spatial variables:
    - 2.88 million (4mm long MOPA)
    - 8 − 16mm laser: 5.76 − 11.52 million variables
- 1d parameter scan of different dynamical regimes requires ≈300ns
- 2d scans 10−100 times more expensive

⇨ Parallel computing required!

Remark:
In comparison with previous 1d TWE model (*LDSL-tool*) calculation for HHI lasers our problem is 6400 times more complex!

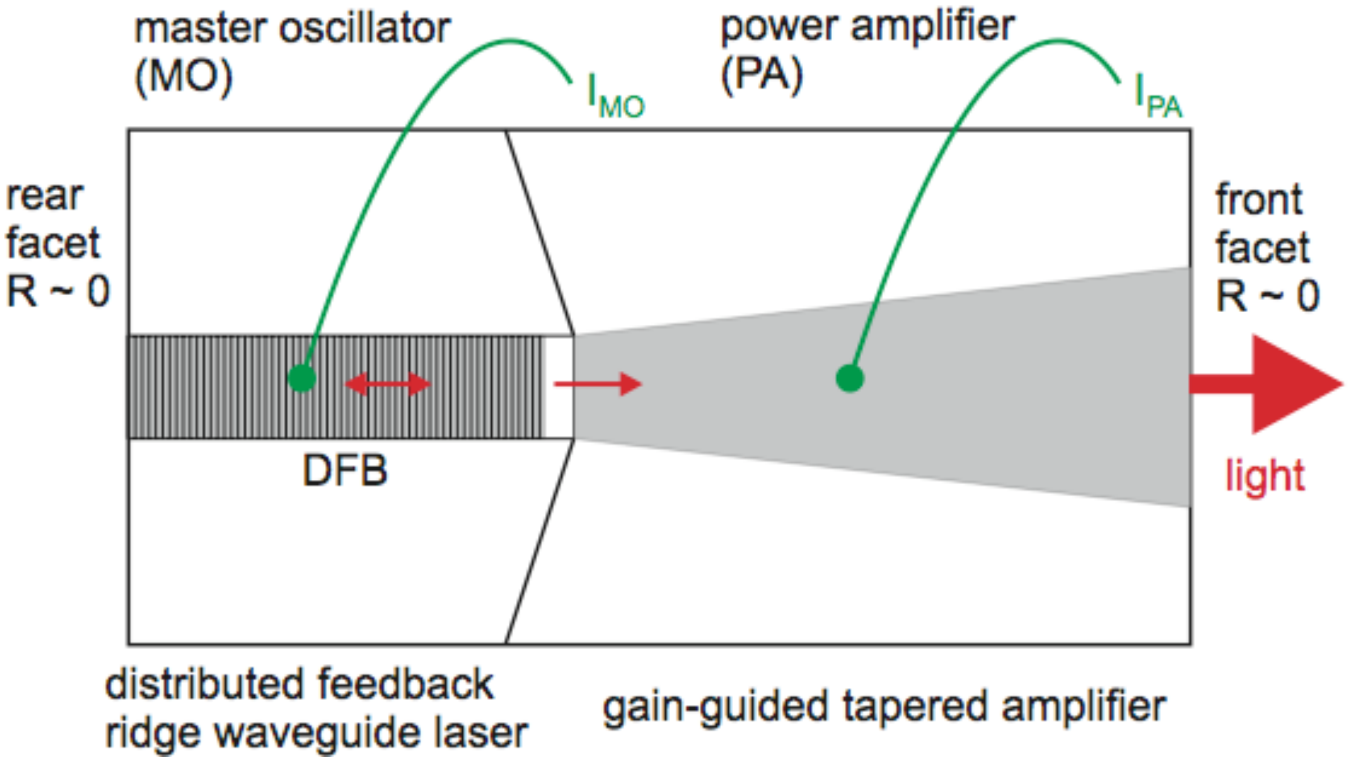
High performance parallel computation on WIAS cluster Euler

10 × 300ns 2d parameter simulation on Euler cluster using multilayer parallel computing with MPI via Infiniband and POSIX Multithreading:

- Single PC: 2415 hours, 100 days
- Euler 1 node (2 quad Xeons, 8 cores): 833 hours, 34 days
- Euler 4 nodes (32 cores): 288 hours, 9 days
- Euler 9 nodes (72 cores): 114 hours, 4.75 days
- Euler 3×9 nodes (216 cores): 38 hours, < 2 days
- total number of available nodes on Euler: 32 (256 cores)

- A single low resolution 2d parameter scan of dynamical regimes requires about 1 day on whole cluster.

Results


master oscillator
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rear
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light
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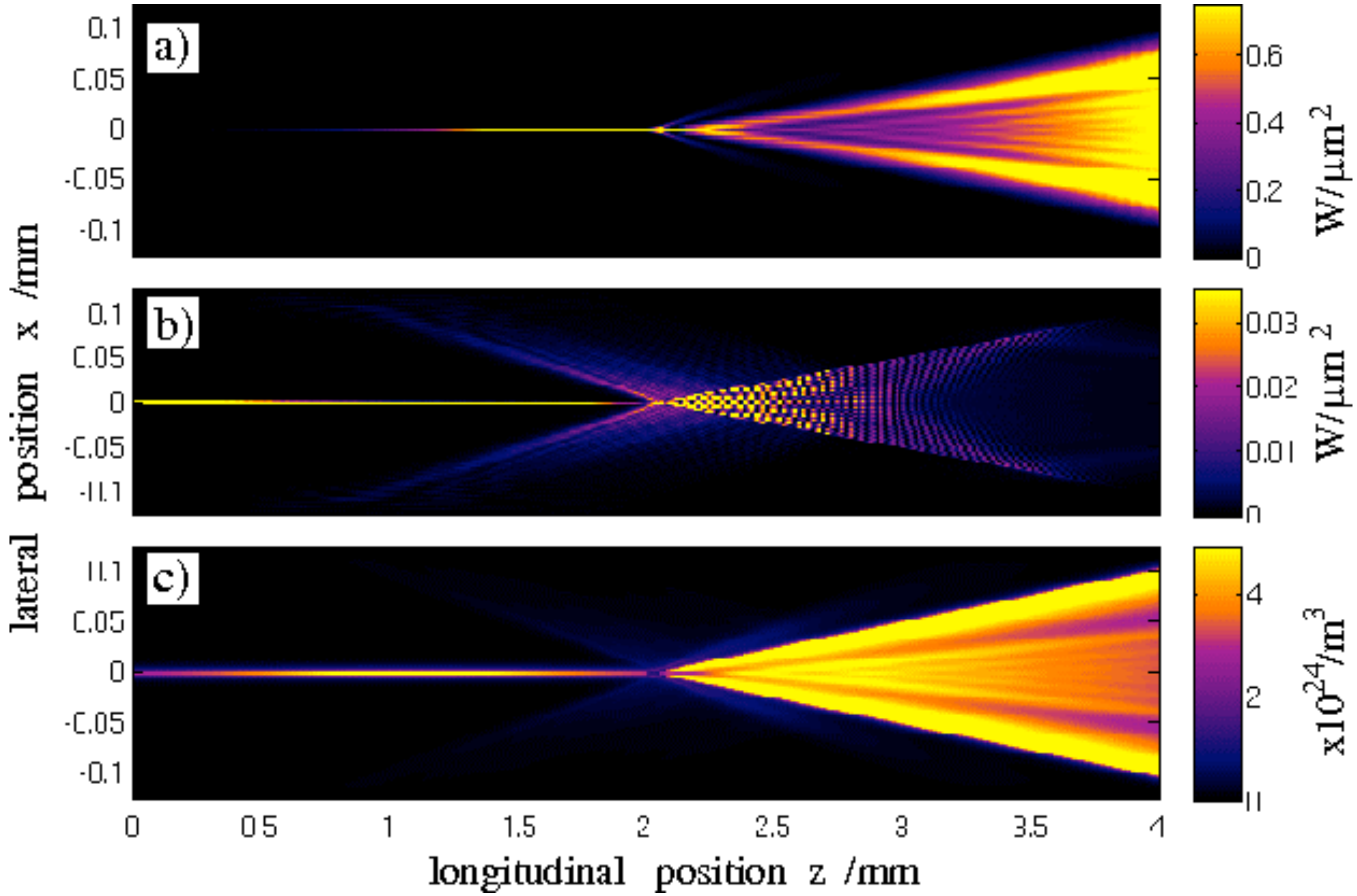
ridge waveguide laser
gain-guided tapered amplifier

Intensity and Carrier Distributions

forward field:

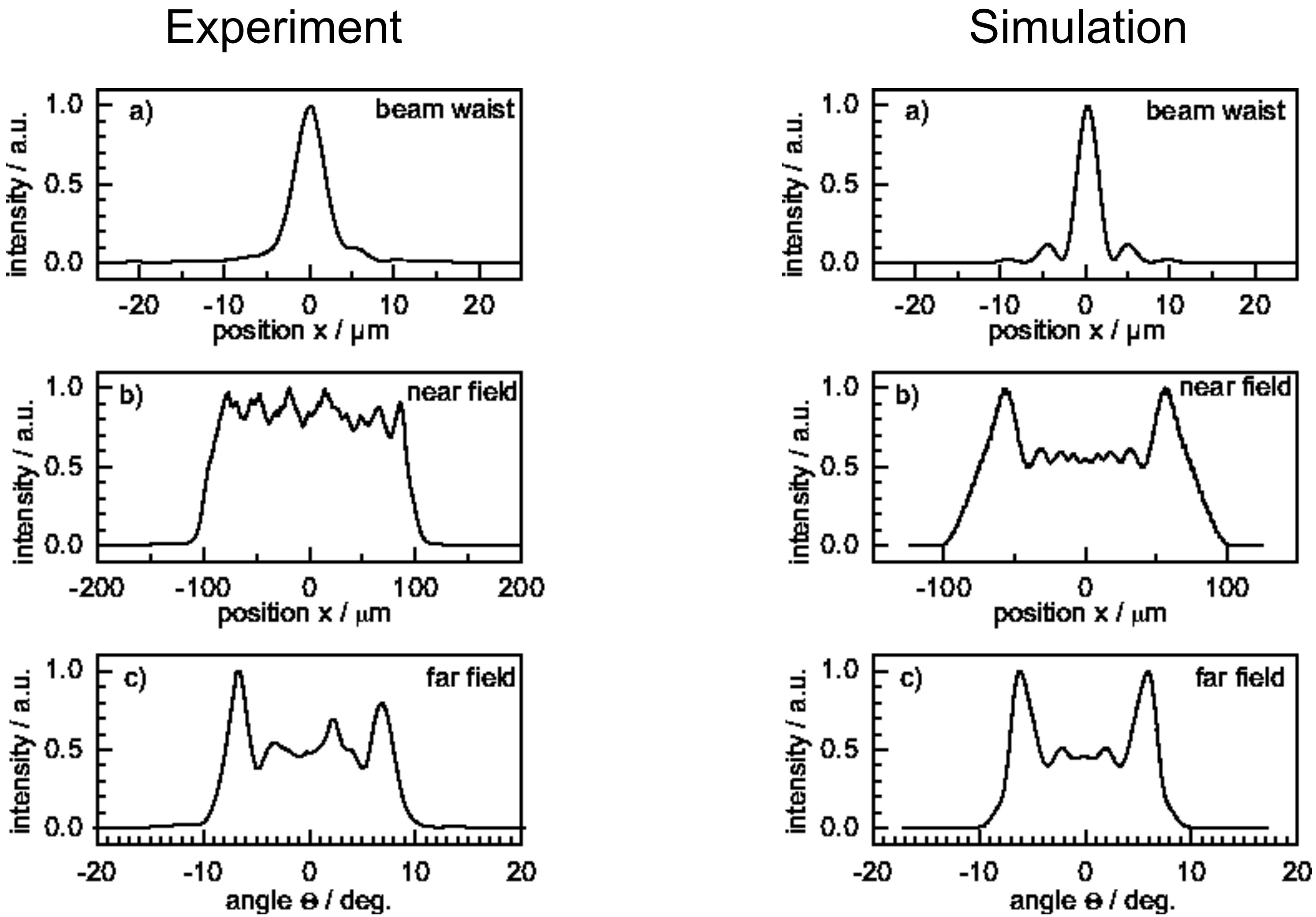
backward field:

carrier density:



I_{MO}=400mA, I_{PA}=4 A

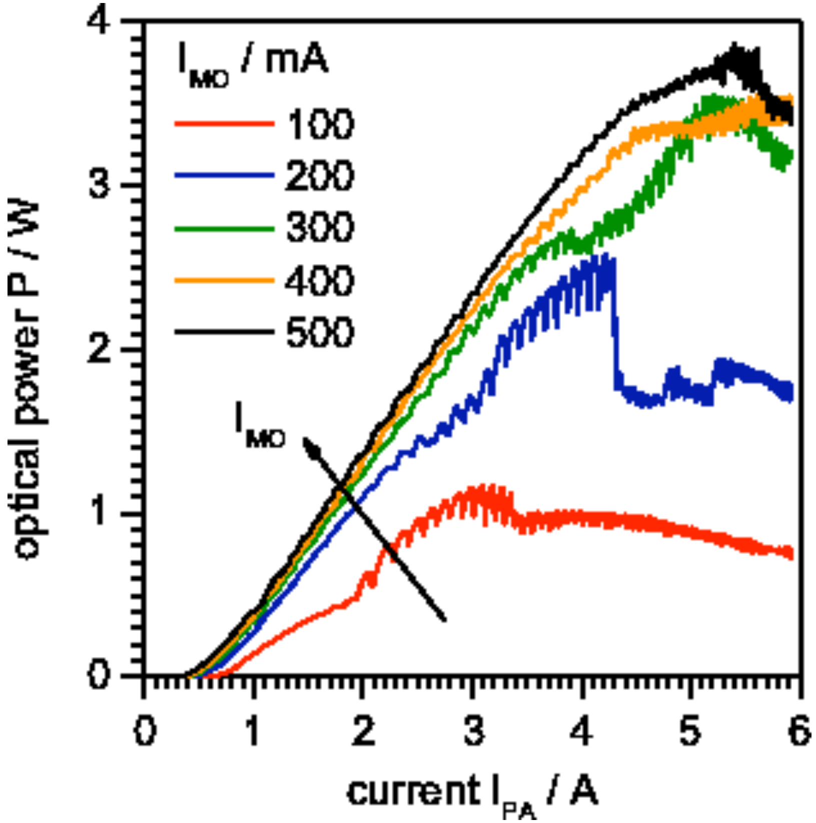
Lateral Intensity Profiles



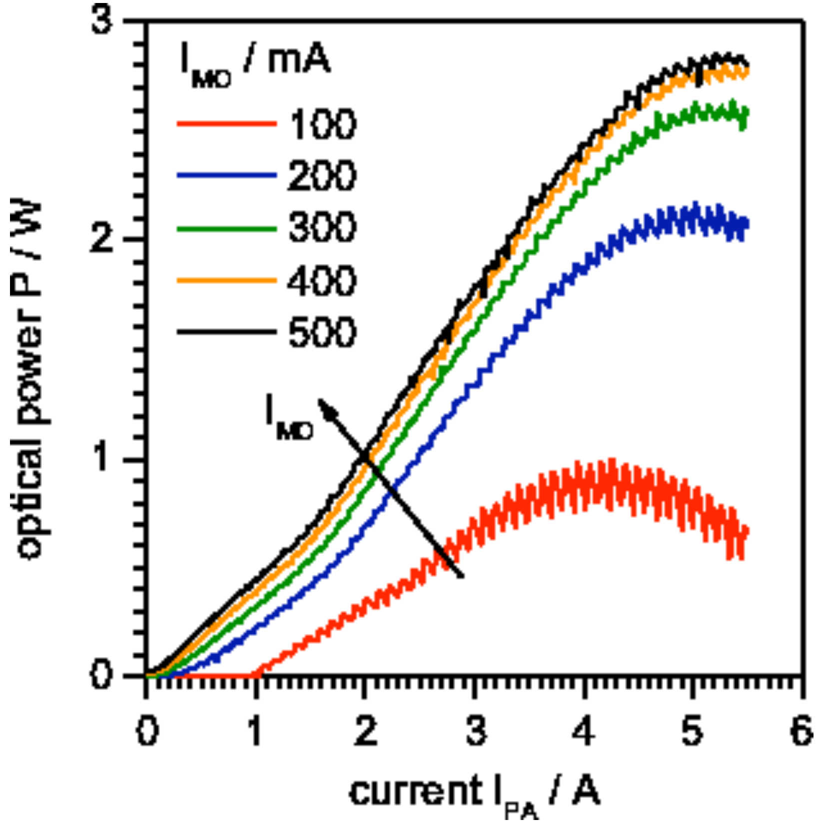
I_{MO}=400mA, I_{PA}=4 A

P-I Characteristics

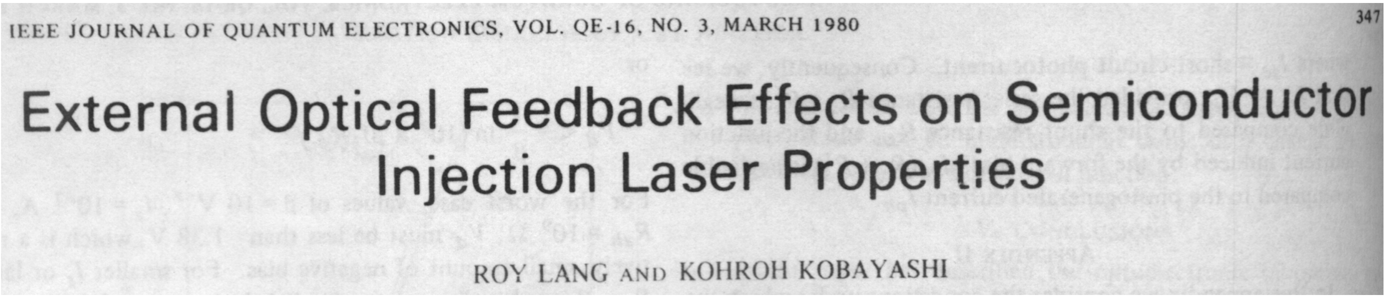
Experiment:



Theory:

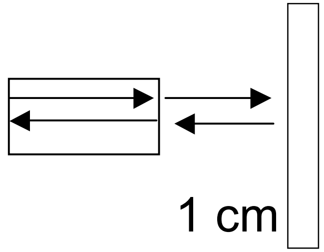


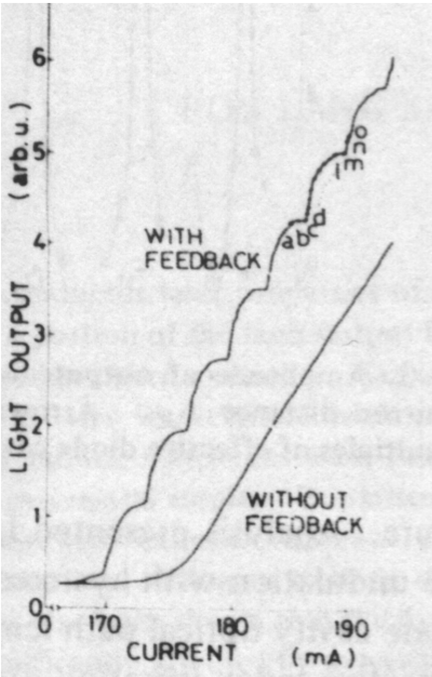
Comparison with feedback experiments


IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. QE-16, NO. 3, MARCH 1980 347

External Optical Feedback Effects on Semiconductor Injection Laser Properties

ROY LANG AND KOHROH KOBAYASHI





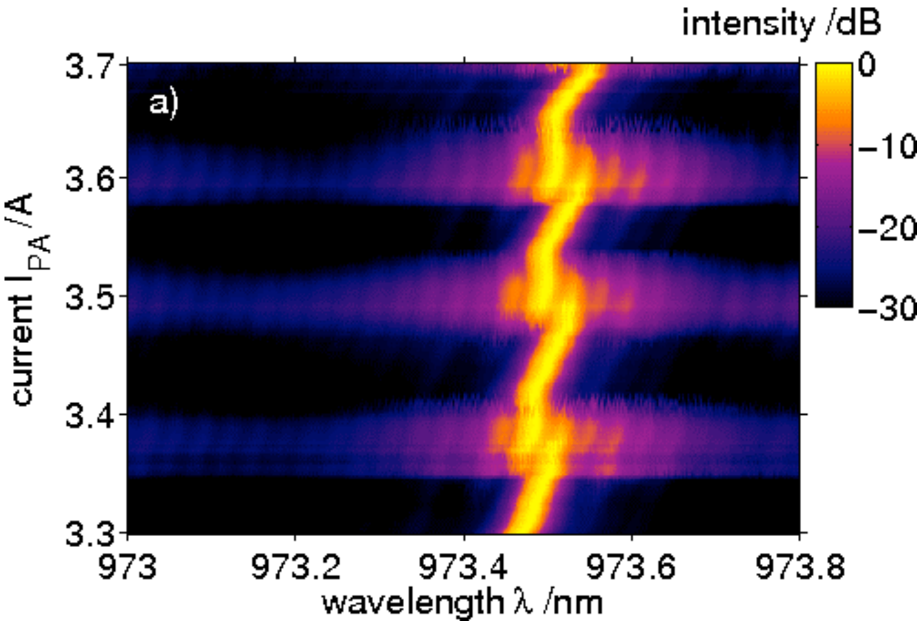
- laser + external mirror form compound cavity laser
- coherent interference effects between reflected light and field inside the laser diode
- $I^{\uparrow} \Rightarrow \lambda^{\uparrow} \Rightarrow$ feedback phase changes
  $\Rightarrow$ intensity undulations

→ Feedback from taper into DFB-laser !

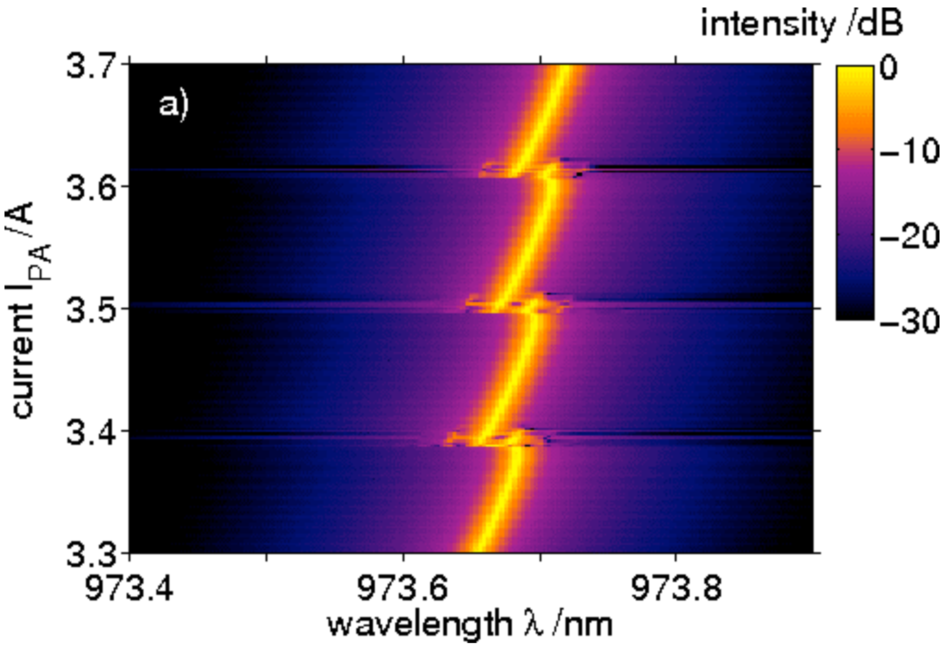
More recent for AFL: *S. Bauer et al., Phys. Rev. E 69 (2004) 016206*
O.Ushakov et al., Phys. Rev. Lett. 95 (2005) 123903

Optical Spectra vs I_{PA}:

Experiment:



Simulation:

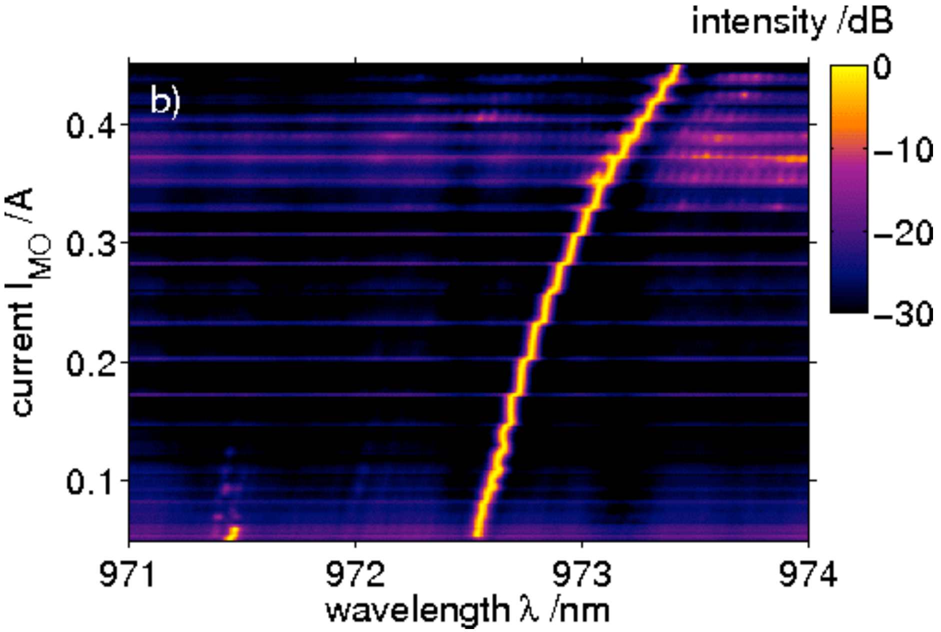


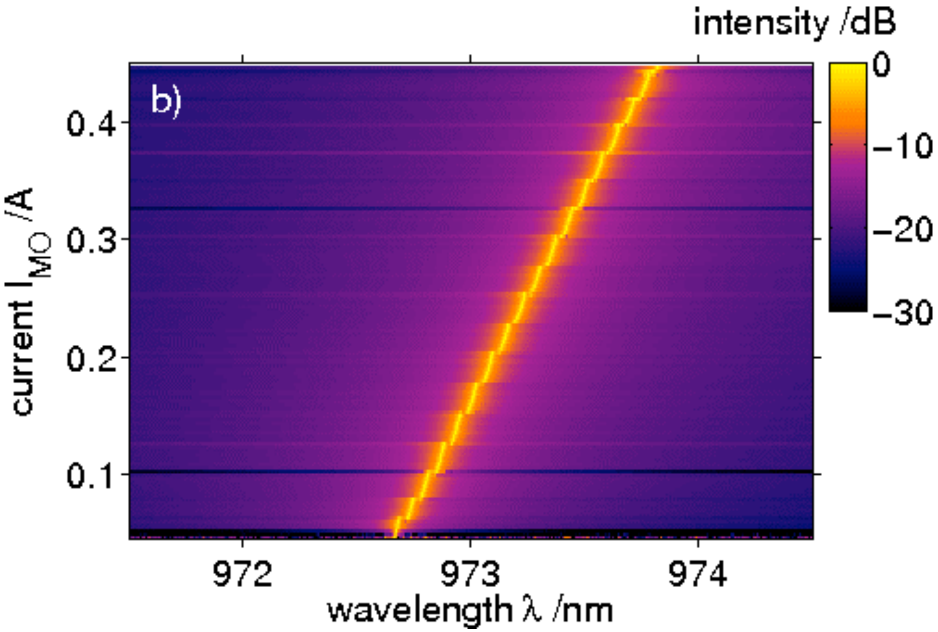
I_{MO}=350mA

Optical Spectra vs I_{MO}:

Experiment:

Simulation:

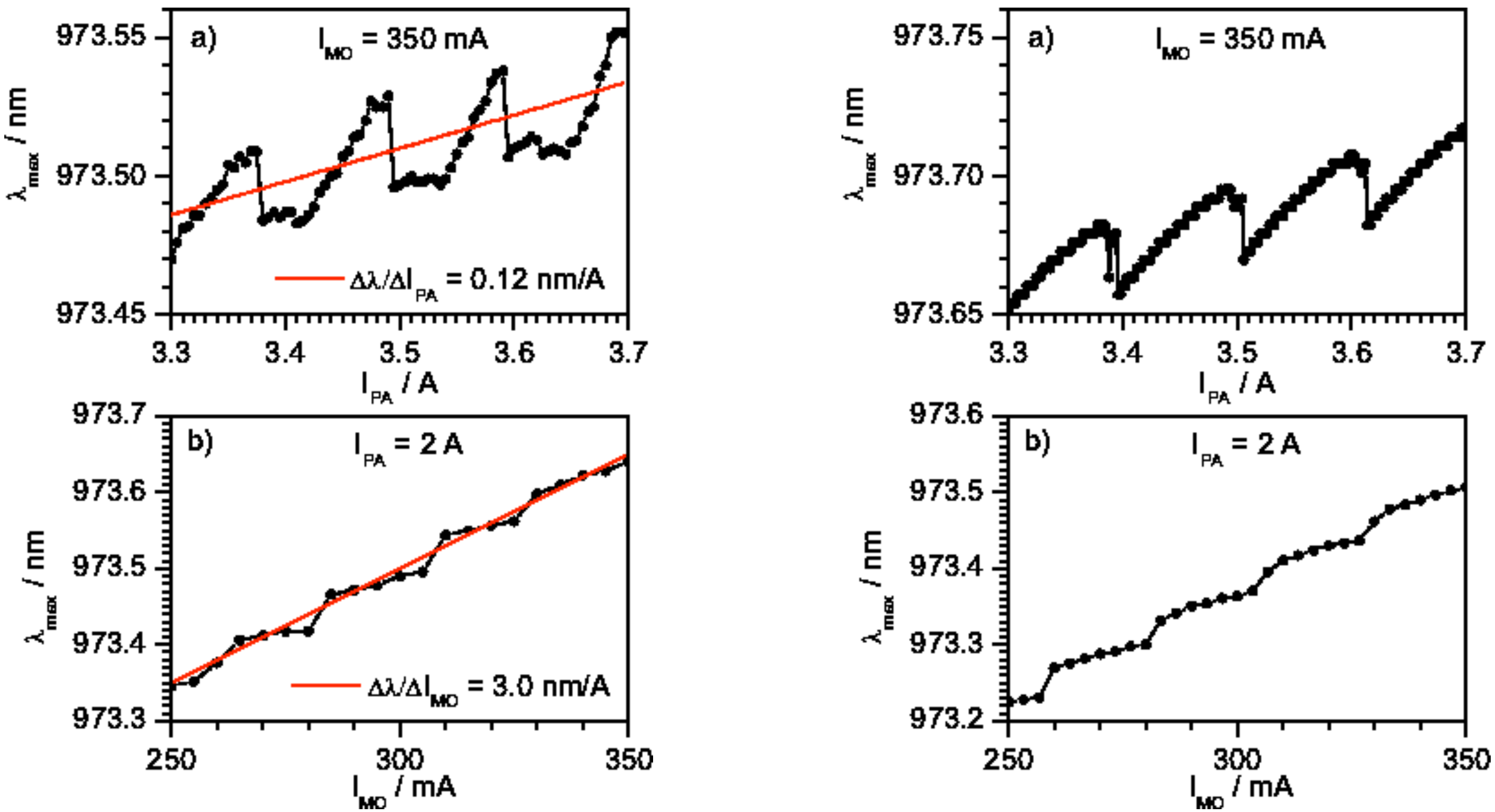




I_{PA}=2 A

Wavelength Shift

Experiment | Simulation



Summary

- Effective mathematical Model for MOPA‘s
- Heating effects parametrically included
- Detailed Comparison Experiment - Simulation
- Qualitative (longitudinal) understanding

Thank you for your Attention!