Dynamic Simulation of High Brightness Semiconductor Lasers

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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

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

with

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

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

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

where

- $\delta_0$ index variation in space,
- $\delta_n = -\sqrt{n'N}$ dependence of effective index on the carrier density,
- $\delta_T$ temperature dependence of effective index,
- $g(x, z, N, u) = g'(x, z) \ln \frac{N(x,z,t)}{N_{tr}} \frac{1}{1+\epsilon||u||^2}$ optical gain,
- $\alpha = \alpha(x, z)$ optical losses.

Model parameters determined at FBH and HU Berlin experimentally.
Model Equations

\[
\begin{align*}
\frac{1}{v_g} \partial_t u^\pm &= \frac{-i}{2k_0 \bar{n}} \partial_{xx} u^\pm + (\mp \partial_z - i \beta) u^\pm - i \kappa u^\mp - \frac{\bar{g}}{2} (u^\pm - p^\pm) \\
\partial_t p^\pm &= \bar{\gamma} (u^\pm - p^\pm) + i \bar{\omega} p^\pm \\
\partial_t n &= d_n \partial_{xx} n + \frac{J}{q d} - R(n) - v_g \Re \langle u, g(n, u) u - \bar{g}(u - p) \rangle_{C^2}
\end{align*}
\]

\[u^+(t, 0, x) = r_0(x) u^-(t, 0, x) + \alpha(t, x), \quad u^-(t, l, x) = r_l(x) u^+(t, l, x).\]

- 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 $J(t, z, x)$:

$$I_{MO} = \int_{MO} J(x, z) dx dz, \quad I_{PA} = \int_{PA} J(x, z) dx dz.$$ 

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:

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

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

\[
\partial_t P^\pm = \gamma \left( E^\pm - P^\pm \right) + i \omega P^\pm
\]

\[
\partial_t n = d_n \partial_{xx} n + I(t) - R(n) - v_g \Re \langle E, g(n) E - \bar{g}(E - P) \rangle_C^2
\]

• 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
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
Intensity and Carrier Distributions

forward field:

backward field:

carrier density:

$I_{MO} = 400\text{mA}, \ I_{PA} = 4\ A$
Lateral Intensity Profiles

**Experiment**

- **a)** beam waist
  - Intensity / a.u.
  - Position x / μm

- **b)** near field
  - Intensity / a.u.
  - Position x / μm

- **c)** far field
  - Intensity / a.u.
  - Angle θ / deg.

**Simulation**

- **a)** beam waist
  - Intensity / a.u.
  - Position x / μm

- **b)** near field
  - Intensity / a.u.
  - Position x / μm

- **c)** far field
  - Intensity / a.u.
  - Angle θ / deg.

\[ I_{MO} = 400\text{mA}, \ I_{PA} = 4\ \text{A} \]
P-I Characteristics

Experiment:

Theory:
Comparison with feedback experiments

- laser + external mirror form compound cavity laser
- coherent interference effects between reflected light and field inside the laser diode
- $I \leftrightarrow \lambda \leftrightarrow$ feedback phase changes
  $\Rightarrow$ intensity undulations
  $\Rightarrow$ Feedback from taper into DFB-laser!

Optical Spectra vs $I_{PA}$:

Experiment:

Simulation:

$I_{MO} = 350mA$
Optical Spectra vs $I_{MO}$:

Experiment:

Simulation:

$I_{PA} = 2 \, \text{A}$
Wavelength Shift

Experiment

Simulation

\( \lambda_{\text{max}} \) / nm

\( I_{\text{MO}} = 350 \) mA

\( \Delta \lambda / \Delta I_{\text{PA}} = 0.12 \) nm/A

\( I_{\text{PA}} / \) A

\( I_{\text{MO}} = 350 \) mA

\( \lambda_{\text{max}} / \) nm

\( I_{\text{PA}} / 2 \) A

\( \Delta \lambda / \Delta I_{\text{MO}} = 3.0 \) nm/A

\( I_{\text{MO}} / \) mA

\( I_{\text{PA}} / 2 \) A
Summary

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

Thank you for your Attention!