Weierstrass Institute for
Applied Analysis and Stochastics

Leibniz Association

Forschungsverbund
Berlin e.V.

Modeling, simulations, and analysis of nonlinear dynamics in edge-emitting semiconductor lasers

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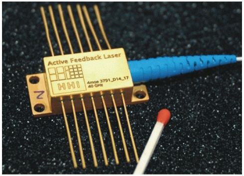
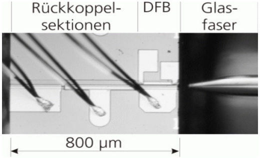
R. Čiegis (VGTU, Vilnius)
V. Tronciu (TU Moldova)
U. Troppenz, ... (HHI, Berlin)
...

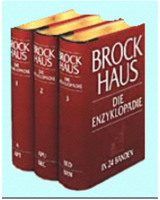
- Motivation;
- Mathematical model of narrow- and broad-area edge-emitting semiconductor amplifiers and lasers;
- Simulation and analysis of nonlinear dynamics in semiconductor lasers with the WIAS software packages LDSL-tool and BALaser (examples);
- Publications / cooperations / projects.





made in HHI, Berlin

Example: encyclopaedia



24 volumes
~1000 pages each
~ 9000 letters each
8 bits for each letter

$\sim 2 * 10^9$ bits

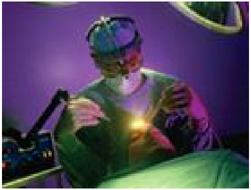
Transmission of encyclopaedia with 40 Gbit/s in 0.05 seconds

Example: pulsating lasers at ~40 GHz with

- tunable frequencies;
- unique stable pulsating state;
- large pulsation amplitude;
- fast attraction after perturbation;
- pulsation frequency entrainment by external modulated signal.

Compact semiconductor lasers emitting single-frequency, diffraction limited beams at a continuous-wave optical power of several Watts are required for:

- cosmetology
- free-space communications,
- image recording,
- materials processing,
- medical therapy,
- military,
- spectroscopy,
- telecommunications,
- etc.



Modeling, analysis, and simulation

of nonlinear dynamics in edge-emitting semiconductor lasers

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Tasks:

- efficient modeling of complex laser structures;
- development of software including numerical bifurcation analysis;
- analysis of resulting nonlinear dynamical systems.

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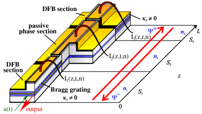
Goals:

- support the experimental development by numerical simulations;
- optimize performance of existing devices;
- create design rules for new dynamical effects.



We use (1+1)-dimensional traveling wave models for studying nonlinear dynamics in multisection edge-emitting semiconductor lasers.

Traveling wave equations for slowly varying counter-propagating optical fields:

$$\frac{n_g}{c}\partial_t\Psi^\pm \pm \partial_z\Psi^\pm = \left(\frac{G(N,|\Psi|^2)-\alpha}{2} + i\tilde{n}(N) - \mathcal{D}\right)\Psi^\pm + i\kappa\Psi^\mp + \mathcal{F}^\pm_{sp},$$

$$\Psi^+|_{z=0} = r_0\Psi^-|_{z=0} + a_0(\;t), \qquad \Psi^-|_{z=L} = r_L\Psi^+|_{z=L} + a_L(\;t).$$

An example of carrier-dependent gain and index change functions:

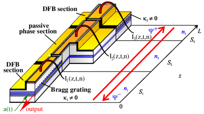
$$G(N,|\Psi|^2) = \frac{g' N_{\mathrm{tr}} \ln(N/N_{\mathrm{tr}})}{1+\varepsilon|\Psi|^2}, \qquad \tilde{n}(N) = \delta_0 + \sqrt{\sigma N}.$$

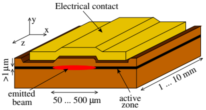
Carrier rate equations:

$$\partial_t N = \frac{J}{qd} - \left(AN + BN^2 + CN^3\right) - \frac{c}{n_g}\Re\sum_{\nu=\pm} E^{\nu *}\left[G(N,|\Psi|^2) - 2\mathcal{D}\right]\Psi^\nu.$$

Bandelow et al., IEEE JQE 37, 183 (2001), Wünsche et al., IEEE JSTQE 9, 857 (2003), LDSL-tool: www.wias-berlin.de/software/ldsl

In the case of $a \equiv 0$, this is a slow-fast system with rotational invariance, $\Psi \mapsto \Psi e^{i\varphi}$.
Can be used for simulations of multisection, ring, or coupled laser systems.





We use (1+1)- and (1+2)- dimensional traveling wave models for studying nonlinear dynamics in multisection edge-emitting semiconductor lasers.

Traveling wave equations for slowly varying counter-propagating optical fields:

$$\frac{n_g}{c}\partial_t\Psi^{\pm} \pm \partial_z\Psi^{\pm} = \frac{-i}{2k_0\bar{n}}\partial_{xx}\Psi^{\pm} + \left(\frac{G(N,|\Psi|^2)-\alpha}{2} + i\tilde{n}(N) - \mathcal{D}\right)\Psi^{\pm} + i\kappa\Psi^{\mp} + \mathcal{F}^{\pm}_{sp},$$

$$\Psi^{+}|_{z=0} = r_0\Psi^{-}|_{z=0} + a_0\left(x,t\right), \qquad \Psi^{-}|_{z=L} = r_L\Psi^{+}|_{z=L} + a_L\left(x,t\right).$$

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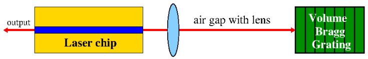
Spreemann et al., IEEE JQE 45, 609 (2009), Radziunas, Ciegis, in Springer LNCS series 8385, 332 (2014), BALaser: www.wias-berlin.de/software/balaser

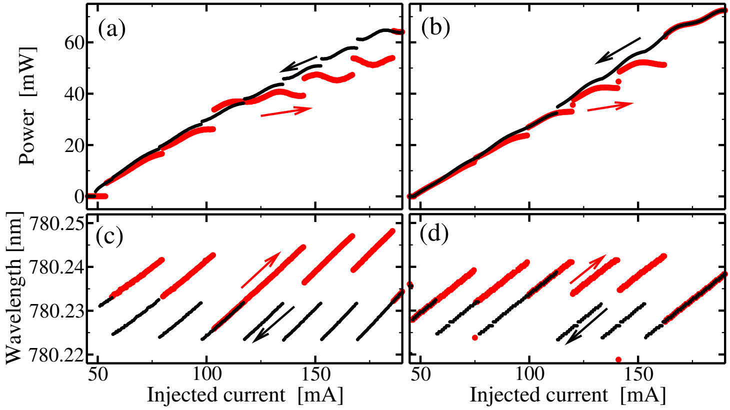
In the case of $a \equiv 0$, this is a slow-fast system with rotational invariance, $\Psi \mapsto \Psi e^{i\varphi}$.
Can be used for simulations of multisection, ring, or coupled laser systems.
For broad area devices the numerical integration is done using parallel computing.

In WIAS created program packages LDSL-tool and BALaser allows us to perform

- numerical integration of model equations [both (1+1)-D and (1+2)-D models], i.e.,
  - numerical simulation of laser devices for given set of parameters,
  - performing simulations while scanning one or more laser parameters,
  - characterising and representing the simulated dynamical states;
- mode analysis [(1+1)-D model], i.e.,
  - finding of instantaneous longitudinal optical modes,
  - expanding of the simulated optical field into modal components,
  - following changes of optical modes with the change of time or parameters;
- location, continuation and stability analysis of regular states [certain versions of (1+1)-D case], i.e.,
  - finding all relevant stable and unstable steady states,
  - constructing related mode approximation [low dimensional ODE] systems,
  - analyzing these systems with the numerical continuation and bif. analysis tool AUTO.

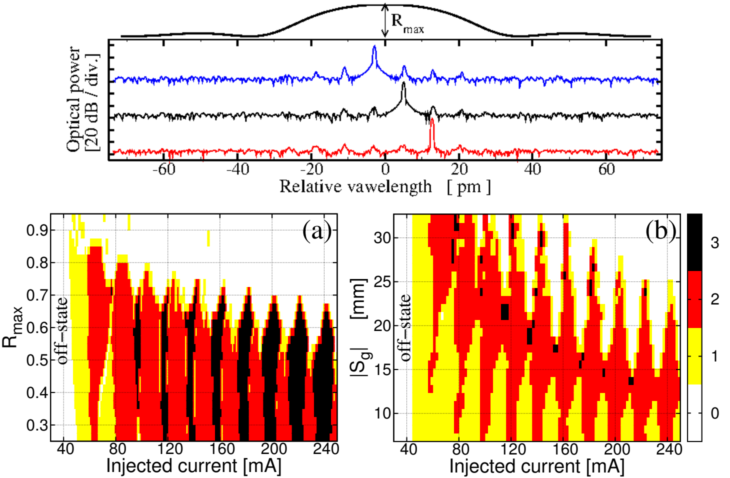


Experiments: FBH Berlin
Simulations and mode analysis: LDSL-tool
(www.wias-berlin.de/software/ldsl) at WIAS Berlin



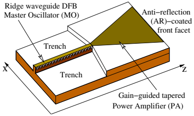
Emission power (top) and wavelengths (bottom) in experiments (left) and simulations (right).

Project MANUMIEL (2013-2015) in the frame of BMBF program "Förderung der Wissenschaftlich-Technologischen Zusammenarbeit (WTZ) mit der Republik Moldau", FKZ 01DK13020B. German side partners - FBH and WIAS. Radziunas et al., IEEE JQE 51, 2000408 (2015), Tronciu et al., OQE 47, 1459 (2015).



Number of coexisting stable steady states can be controlled by laser design parameters.

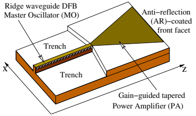
Project MANUMIEL (2013-2015) in the frame of BMBF program "Förderung der Wissenschaftlich-Technologischen Zusammenarbeit (WTZ) mit der Republik Moldau", FKZ 01DK13020B. German side partners - FBH and WIAS. Radziunas et al., IEEE JQE 51, 2000408 (2015).



Narrow Master-Oscillator generates light on a single lateral mode

Tapered Power-Amplifier amplifies a propagating beam

Optical field back-reflections from the power amplifier facet can destabilize the emitted field.



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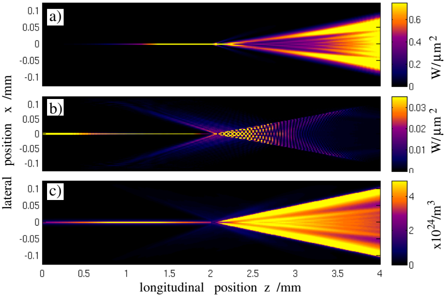
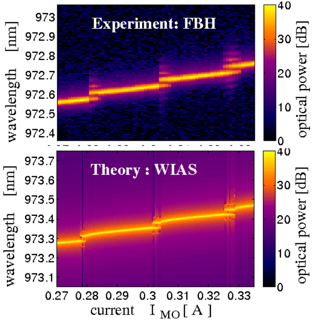


Simulated distributions of the field intensities and carrier density: BALaser (www.wias-berlin.de/software/balaser) at WIAS

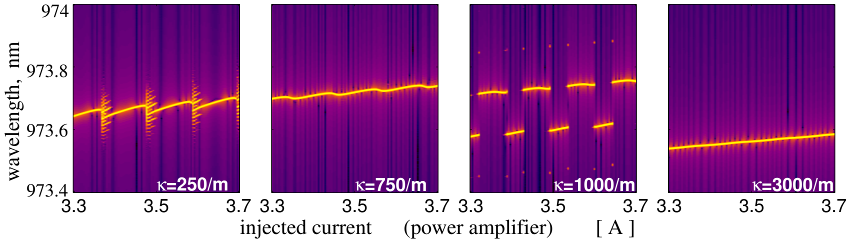


Measured (FBH) and simulated (WIAS) optical spectra as functions of bias current.

Optical field back-reflections from the power amplifier facet can destabilize the emitted field.

Subcontract by FBH in the frame of the IBB Programme PROFIT for performing research on wavelength stabilization of semiconductor lasers (2006-2007).

M. Radziunas et al., OQE, **40**, 1103-1109, 2008. V.Z. Tronciu et al., OQE**41**,531-537, 2009. M. Spreemann et al., IEEE JQE, **45**, 609-616, 2009.



Simulations of DFB MOPA devices with uniform Bragg gratings for different values of κ

An appropriate choice of the Bragg grating coupling (parameter κ) allows achieving stabilization of the emitted field for large range of injected currents.

Subcontract by FBH in the frame of the IBB Programme PROFIT for performing research on wavelength stabilization of semiconductor lasers (2006-2007).

V.Z. Tronciu et al., OQE**41**,531-537, 2009.

- Publications:
  - ~20 articles in peer-reviewed journals with application of LDSL-tool,
  - ~10 articles in peer-reviewed journals with application of BALaser;
- Cooperation projects and grants
  - Subcontract by FBH in the frame of "BMBF-Fördermaßnahme EFFILAS" (2016-2019) (pending).
  - Cooperation in the frame of BMBF program "Förderung der Wissenschaftlich-Technologischen Zusammenarbeit mit der Republik Moldau" [German side partners - WIAS and FBH] (2013-2015).
  - Subcontract by FBH in the frame of the "BMBF-Fördermaßnahme INLAS" (2009-2010).
  - Subcontract by FBH to perform some study of wavelength stabilization in Fabry-Perot lasers by external Bragg reflector (2008).
  - Subcontract by FBH in the frame of the IBB Programme PROFIT (2006-2007)
  - Subcontract by FhG/HHI in the frame of the IBB Programme PROFIT (2004-2005)
  - MATHEON Project D8 (2002-2014)
  - SFB 787 Project B5 (2008-2019)

Thank You for Your attention!