Modeling and parallel simulation of high power semiconductor lasers Para 2008: Applications of Parallel Computations on Industry Engineering

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Abstract. Compact semiconductor lasers emitting single-frequency, diffraction limited beams at a continuous-wave (CW) optical power of several Watts are required for many applications including frequency conversion, free-space communications, and pumping of fibre lasers and fibre amplifiers. We discuss a mathematical model for the dynamics of such lasers. In order to simulate the long time dynamical behaviour a large system of several million variables has to be resolved for time steps of several orders of millions. Parallel simulation results and comparison with experimental data are given.

Key words: Laser Dynamics, Partial Differential Equations, Mathematical Modeling of semiconductor lasers

1 Extended Abstract

Compact semiconductor lasers emitting single-frequency, diffraction limited beams at a continuous-wave (CW) optical power of several Watts are required for many applications including frequency conversion, free-space communications, and pumping of fibre lasers and ampliers. Conventional narrow stripe or broad area semiconductor lasers do not meet these requirements, either due to the limited output power or the poor beam quality and wavelength stability.

Semiconductor lasers are characterized by a huge amount of structural and geometrical design parameters and they are subject to time-space instabilities like pulsations, self-focussing, filamentation, thermal lensing which yield restrictions to output power, beam quality and wavelength stability. In particular an increase of width, length and pumping leads to several instabilities which can be seen experimentally in kinks in the powercurrent characteristics [1], beam-steering [2] [5], and the appearance of higher order lateral modes in the lasing emission [3]. Possible reasons are carrierinduced index suppression, thermal lensing, and spatial hole burning [4].

In the past, numerous concepts to maintain a good beam quality and wavelength stability in the Watt range have been proposed by physicists and engineers, of which several have been successfully demonstrated. One of the most promising devices is the monolithically integrated master- oscillator power-amplier (MOPA), see figure 1, where either a distributed Bragg reflector (DBR) laser, or a distributed feedback (DFB) laser and a flared (or tapered) gain-region amplier are combined on a single chip. CW optical powers of $1.1W$ or $2W$ [6] [7] have been achieved. During the last years, no further improvement towards higher output power has been reported. Recently, an improved MOPA has been demonstrated in Berlin which emits a CW power of more than 10 W at 977 nm in a nearly diffraction limited beam and narrow spectral bandwidth of 40 pm.

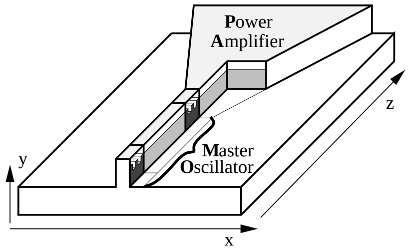

Fig. 1. layout of the MOPA device and system of coordinates used

For preparing technological processes to choose optimal parameters, to understand experimental data and for predicting new laser designs precise mathematical models for broad area semiconductor lasers are needed. As a next step suitable numerical algorithms have to be chosen and implemented. To adequately resolve the generation and propagation of photons for such laser devices one needs to use a spatial discretization which is of the order of the central wavelength of the laser (typically in the micrometer regime) - and use a time step of $\triangle t \sim c_0/(n_g \mu m) < 0.1ps$ (c_0 denotes speed of light and n_g group velocity in the semiconductor medium). Due to a considerable length of several millimeters and width of several hundrets of micrometers for high power semiconductor lasers we obtain a large scale system of several million spatial variables. Moreoever, the carrier dynamics is in the order of $\sim 1ns$ being much slower than the photon equation. This implies relaxation times of several ns which need to be simulated for different long time dynamical operating regimes of the laser. Moreover, for technological applications and corresponding design purposes one is interested in multimensional parameter studies, where different laser parameters like effective index steps, pumping levels, geometry of contacts or gratings are varied. For a reasonable resolution one dimensional parameter scan one needs to simulate dynamical regimes involving $>>$ 100 parameter steps. For a low resolution $2d$ parameter scan pairs of several 1000 different parameters have to be considered. Using a moderate simulation time of $2ns$ for each paramter a total simulation time of $2\mu s$ or much more is required. Using a time discretization of $0.06ps$ this means that about $>$ 30 million time iterations need to be performed. This can be achieved in acceptable time only by making use of parallel computation.

In this paper we present a model suitable for the dynamical simulation of broad area high power semiconductor lasers and show our parallel simulation results which we compare against experimental data. Using a slowly varying complex forward and backward traveling envelope $u^{\pm}$ (along the z axis in figure 1) of the electric field, the effective refractive index method with a vertical (along the y axis) single mode approximation, a paraxial approximation and a moving timeframe the $3d$ wave equation is reduzed to a $2d$ wave equation in the (x, z) plane [8], [9]. It consists of a hyperbolic system in the lateral z-dimension superposed with the Schroedinger evolution operator in the lateral x-dimension. The optics is nonlinear coupled to a parabolic diffusion equation for the carriers n. Moreover, a simple dielectric polarization model $p^{\pm}$ is added. The final system of equations has the following form:

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

with the reflecting boundary conditions

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

at the top ($z = l$) and bottom ($z = 0$) facet of the laser. Here $t \in \mathbb{R}$ denotes time, $z \in [0, l]$ longitudinal, $x \in \mathbb{R}$ lateral coordinate,

$$\beta = \delta_0(x,z) + \delta_n(x,z,N) + \delta_T(x,z,T) + i\frac{g(x,z,n,T) - \alpha(x,z)}{2}$$

is a propagation constant, $g(x,z,N,u,T) = g(x,z,T)\frac{\ln\frac{N(x,z,t)}{N_{tr}}}{1+\epsilon\|u\|^2}$ models gain and $\delta_n = -\sqrt{n'(x,z)N(x,z,t)}$ index dependence on the carrier density n. Spontaneous recombination is modeled using the standard ABC rule $R(n) = A(x,z)n + B(x,z)n^2 + C(x,z)n^3$. $I = I(t,z,x)$ denotes electrical injection or pumping.

Note that all coefficients with the exception of k_0 (wave number), v_g (group velocity), $\bar{n}$ (reference refractive index) are spatially, i.e. laterally and longitudinally in (z, x) plane, nonhomogeneous and discontinuous depending on the heterostructural lasergeometry. Well posedness (existence, unique, smooth dependence of solutions) of the model can be proved in a similar way as in [11] by using additional $L^{\infty} - L^{1}$ estimates for the Schroedinger semigroup.

We solve the evolution equation using a split step method: The Schroedinger and diffusion operators are split off and solved using fast Fouriertransform. Due to the splitting the remaining hyperbolic system decouples and can be solved for each x by differencing along characteristcs. For the fast disperive polarization $p^{\pm}$ ($p^{\pm}$ operates in fast fs regime) we use an exact exponentially weighted scheme using a forward estimate for $u^{\pm}$. We have implemented the following simple parallel algorithm: We decompose the grid along the z direction in uniform blocks which we distribute to seperate processes. Each process asynchronously transmits the boundary data at junctions points to its neighbouring processes using MPI. Each process executes the above split step method, where FFT is performed using the FFTW library in multithreading mode [10], the decoupled set of hyperbolic system is solved parallel on multiple cores using multithreading (POSIX), for thread synchronization mutexes are used. We have run simulations on a 32 node HP Blade server using the HPMPI library. Each node consists of two Intel Xeon Quad-Core (X5355). The nodes are connected via Infiniband 4xDDR (20 Gbit/s). For a grid size of 320 000, resulting in 2.88 million real spatial variables (corresponding to a $4mm$ long and $250\mu m$ wide MOPA device with discretization $\triangle z = 5\mu m$, $\triangle x = 0.625\mu m$), and a $2d$ parameter scan involving $10 \times 300ns$ simulation or 50 Million time iterations ($\triangle t = 0.061ps$) we report the following speedups:

- 1 node (8 cores): 833 hours, 34 days
- 4 nodes (32 cores): 288 hours, 9 days
- 9 nodes (72 cores): 114 hours, 4, 75 days
- 3 9 nodes (216 cores): 38 hours, < 2 days

Here we have used 4 processes on each node using 4 threads for each process (each node consists of 2 quad Xeons corresponding to 4 dual cores). We experimentally found 4 processes with 16 threads per node to be optimal. Although hyperthreading is not supported, we have observed a 10% performace boost using 16 instead of 8 threads per node.

For comparison, on a single dual core Xeon (X5160) processor total simulation time is about 2415 hours or 100 days.

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