Dynamic simulation of high brightness semiconductor lasers

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***Abstract*—High-power tapered 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-focusing, filamentation and thermal lensing which yield restrictions to output power, beam quality and wavelength stability. Numerical simulations are an important tool to find optimal design parameters, to understand the complicated dynamical behavior and to predict new laser designs. We present a fast dynamic high performance parallel simulation tool suitable for model calibration and parameter scanning of the long time dynamics in reasonable time. The model is based on traveling wave equations and simulation results are found to be in satisfactory agreement with experimental data.**

I. Introduction

Compact semiconductor lasers emitting single-frequency, diffraction limited continuous-wave (CW) beams at a optical power of several Watts are required for many applications including frequency conversion, free-space communications, and pumping of fiber lasers and amplifiers. Conventional narrow stripe or broad area semiconductor lasers do not meet these requirements, either due to limited output power or poor beam quality and wavelength stability. Such lasers are characterized by $\sim 10^2$ structural and geometrical design parameters, and they are subject to time-space instabilities like pulsations, self-focusing, filamentation and thermal lensing which yield restrictions to output power, beam quality and wavelength stability.

In the past numerous concepts to maintain a good beam quality and wavelength stability in the Watt range have been proposed. One of the most promising devices, which will be simulated in this paper, is the monolithically integrated master-oscillator power-amplifier (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 amplifier are combined on a single chip. A CW optical power of 2 W [1] has been achieved in the past. During the last years no further improvement towards higher output power has been reported. Only recently, an improved MOPA, 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, has been demonstrated [2].

For preparing technological processes, to choose optimal parameters, for understanding experimental data and for predicting new laser designs precise and mathematical well posed models [3] are needed. As a next step suitable numerical algorithms have to be chosen and implemented. To adequately resolve the dynamics of optical fields one needs a spatial discretization which is of the order of the central wavelength $\lambda \sim 1$ μm of the laser - and a time step in the range of $\triangle t \sim v_g/\lambda < 0.1$ ps (v_g denotes group velocity). Due to a considerable length of several millimeters and width of several hundred micrometers for high power semiconductor lasers we obtain a large scale system of several million real spatial variables. Moreover, the carrier dynamics is in the order of ~ 1 ns being much slower than the field equations. This implies relaxation times of several ns which need to be simulated for different dynamical operating regimes. For model calibration and technological applications one has to perform multidimensional parameter studies and a bifurcation analysis [4], which characterize dynamic operations of the device within different parameter ranges (e.g. effective index steps, pumping levels, phase tunings, geometries of contacts or gratings). For a reasonable resolution $1d$ parameter scan one needs to simulate regimes involving more than 100 parameter steps. For a low resolution $2d$ parameter study several 1000 parameter pairs have to be scanned. Considering a moderate simulation time of a few nanoseconds for each set of parameters, time ranges of several thousand ns need to be simulated. Using a reasonable time discretization of 0.06 ps for lasers with a central frequency close to 1 μm this means that $\sim 10^8$ time iterations need to be performed. This can only be achieved in acceptable time by making use of high performance parallel computation.

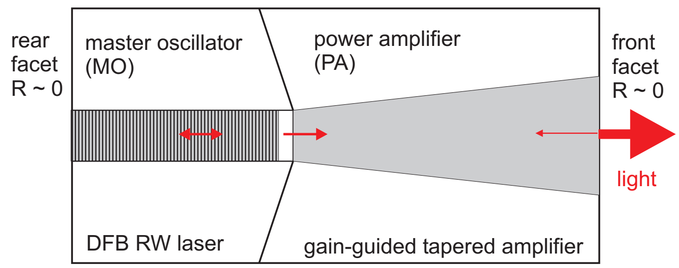

Fig. 1. Top view of a MOPA device consisting of a DFB Master Oscillator (MO) and a tapered Power Amplifier (PA).

We use the following traveling wave equation model (1) coupled to an ordinary differential equation (2) for gain dispersion and a parabolic diffusion equation (3) for the carrier inversion [5]:

$$\begin{aligned}
\frac{1}{v_g}\partial_t u^{\pm} &= \frac{-i}{2k_0\bar{n}}\partial_{xx}u^{\pm} + (\mp\partial_z - i\beta)\,u^{\pm} - i\kappa u^{\mp} \\
&\quad -\frac{\overline{g}}{2}\left(u^{\pm} - p^{\pm}\right) \qquad (1)\\
\partial_t p^{\pm} &= \overline{\gamma}\left(u^{\pm} - p^{\pm}\right) + i\overline{\omega}p^{\pm} \qquad (2)\\
\partial_t N &= D_N\partial_{xx}N + I - R(N) \\
&\quad -v_g\mathfrak{Re}\langle u, g(N,u)u - \overline{g}(u-p)\rangle_{\mathbb{C}^2} \qquad (3)
\end{aligned}$$

with reflecting boundary conditions at both facets of the laser at $z = 0$ and $z = l$

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

Equation (1) can be derived from the scalar wave equation by using a slowly varying forward and backward rotating wave Ansatz, a paraxial approximation and the effective index method [6]. Equation (2) is a time domain description of a Lorentzian gain dispersion profile [7] and (3) follows from a standard carrier transport equation. More precisely, $u^{\pm}$ are complex slowly varying amplitudes for the forward and backward traveling optical fields, $t \in \mathbb{R}$ denotes time, $z \in [0,l]$ corresponds to longitudinal propagation direction, $x \in \mathbb{R}$ lateral space dimension (see figure 1), β is a complex dielectric function modelled via

$$\begin{aligned}
\beta &= \delta_0(x,z) + \delta_n(x,z,N) + \delta_T(x,z,T) \\
&\quad + i\frac{g(x,z,N,u) - \alpha(x,z)}{2},
\end{aligned}$$

where g denotes peak gain, depending on the carrier inversion $N = N(t,x,z)$ within the active zone (averaged along the transversal y direction perpendicular to the layers), $\delta_0(x,z)$ is a built-in variation of the dielectric function independent of N and the temperature T, δ_n and δ_T denote dependence of the effective refractive index on N and T, respectively. We use the following models for g, δ_n and δ_T:

$$\begin{aligned}
g = g(x,z,N,u) &= g'(x,z)\frac{\ln\frac{N(t,x,z)}{N_{\mathrm{tr}}}}{1+\epsilon\|u\|^2}, \\
\delta_n(x,z,N) &= -\sqrt{n'(x,z)N(t,x,z)}, \\
\delta_T(x,z,T) &= I(x,z)\cdot n'_T(x,z).
\end{aligned}$$

The introduction of δ_T has an important impact on the qualitative dynamic behavior of our simulated MOPA device. In particular, changes of $n'_T(x,z)$ directly influence the dynamic instabilities (the mode jump behavior) of the device. Here $I = I(x,z)$ denotes inhomogeneous electrical injection rate. Non-radiative and spontaneous radiative recombination is given by

$$R(N) = A(x,z)N + B(x,z)N^2 + C(x,z)N^3$$

and the last expression in (3) is due to stimulated recombination.

All coefficients with the exception of k_0, v_g and $\bar{n}$ are spatially nonhomogeneous and discontinuous depending on the heterostructural lasergeometry. Unique existence and smooth dependence of solutions on the data for our model can be proven in a similar way as in [3] by using additional $L^\infty - L^1$ estimates for the Schrödinger semigroup along x. Equations (1)-(3) are solved numerically using a splitting scheme, where lateral diffraction and diffusion along x are resolved with FFT and the remaining coupled hyperbolic system in (1) is integrated along characteristics using finite differences. For numerical stability it is crucial to precisely resolve the stiff equation (2). For this we use an exponentially weighted scheme with forward values for $u^{\pm}$, which ensures that in the limit for $\overline{\gamma} \to \infty$ the discretized solutions for p converge to u. We have used a uniform grid of size $\Delta z = 5\ \mu$m and $\Delta x = 0.625\ \mu$m yielding a time step of 0.061 ps. In figure 2 the simulated photon density distribution of the forward $|u^+|^2$ and backward field $|u^+|^2$ is shown for a stationary CW state. The resulting large scale system of equations is solved using multilevel parallel distributed computing (MPI+Multithreading) which allows us to run long-time dynamic simulations corresponding to simulation times of several thousands of ns over large parameter sets on a blade cluster of 64 quad core Intel $Xeon5430$ processors interconnected via infiniband in only one day. Our fast simulations enable us to calibrate model parameters and to find satisfactory agreement of simulated optical spectra, output power characteristics and beam profiles with measurements.

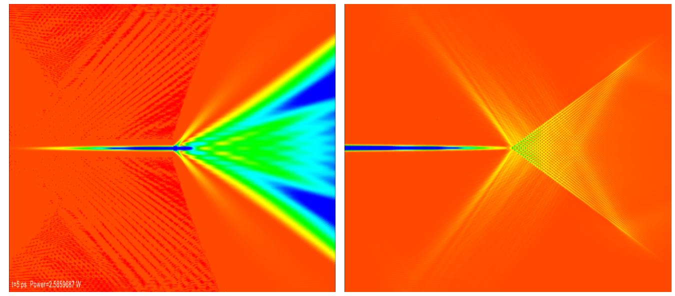

Fig. 2. CW state: Photon density of forward (left) and backward field (right)

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