Delay algebraic equations for broad area lasers

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***Abstract*—We discuss an efficient modeling approach for the simulation of broad area laser diodes. Our method is based on folding the longitudinal propagation dimension into time delays. We compare the results of the dynamics obtained with our improved model with the results of a standard traveling wave description in the cases of straight current stripes and tapered anti-reflection coated devices. We obtain an excellent agreement and an improvement of the integration time between one and two orders of magnitudes.**

***Index Terms*—Semiconductor laser, broad area lasers.**

I. Introduction

The optical power that can be extracted from a semiconductor laser is limited due to catastrophic optical damage and one path to circumvent this limit is to increase the volume of the lasing mode which in the simplest case is achieved by increasing the lateral dimension. However, the emission profile of Broad-Area Laser Diodes (BALDs) usually presents a low quality, with M^2 factors substantially larger than unity [1], which prevents their application in fields where a close to diffraction limited beam is required. The large BALDs lateral dimension allows for many lateral modes that are nearly degenerated in gain which leads to multi-peaked near-fields, but more importantly, the spatial profile usually depends on the current value due to carrier-induced self-focusing, which might even lead to chaotic filamentation of the beam [2]. The origin of this phenomenon is the so-called Spatial Hole Burning (SHB) which leads here to transverse multi-mode operation. Several strategies have been proposed to improve beam quality in BALDs, mostly based on spatial filtering aimed at suppressing higher order lateral modes, e.g. using Bragg gratings [3]. However, filamentation due to SHB depends on the bias point and its analysis requires models and simulation tools that consider the whole state of the system.

Different physical models have been proposed in order to understand the behavior and the modal properties of BALDs. Some aim at finding the stationary electro-thermo-optical solutions [4], [5] but time-dependent approaches have been successfully applied to amplifiers and tapered lasers in order to assess multi-mode behavior and filamentation effects. From the numerical point of view, the two-dimensional character of the field and of the carrier distributions combined with the large spectral width of the semiconductor gain curve result in models that are characterized by a huge number of degrees of freedom (DOF). Such large numbers of DOF demand an exceedingly large computing power for performing exhaustive simulations in the asymptotic regimes using standard Finite-Differences Time-Domain (FDTD) approaches [6]. In addition, all the spatially resolved and time dependent approaches are hindered by the stiffness of laser dynamics: to properly account for the broad gain spectrum one must use an appropriately small time step δt, while the CFL numerical stability condition imposes an accordingly fine spatial step δz.

Recently, it was shown by some of us [7] that a one dimensional traveling Wave model (TWM) can be recast into an ensemble of a few coupled Delayed Algebraic Equations (DAE)s. It was shown in [7] that such a description for a bi-directionaly emitting laser cavity containing an extended medium permits to drastically reduce the computation time as compared to a TWM while accurately preserving the dynamics even in the non linear regimes. The large reduction in complexity allowed for a direct linear stability analysis and numerical bifurcation diagram reconstruction using a similar method as the one detailed in [8]. However the method discussed in [7] could be applied *per se* to the case of a multi-dimensional laser due to the presence of diffraction in the transverse plane that must be properly accounted for. In this paper we present an efficient model for the simulation of BALDs [9] that is based on a combination of a Fourier method and of the Delay Algebraic Equations (DAE)s method previously developed for the simulation of narrow-stripe devices.

II. Results

The original model for the gain-guided BALD considers a single polarization mode in the transverse direction that we decompose into a forward and a backward wave, $E_\pm(x,z,t)$, whose instantaneous distributions in the lateral (x) and longitudinal (z) direction are described in the paraxial approximation by a TWM [10] extended to include diffraction in the transverse dimension. In addition, the carrier density $N(x,z,t)$ in the cavity is decomposed into a quasi-homogeneous term $N_0(x,z,t)$ and a grating term at half the optical wavelength, $N_{\pm 2}(x,z,t)$. After a proper scaling our model reads

$$\begin{aligned}
\left(\partial_t \pm \partial_z\right) E_\pm &= i\Delta\partial_x^2 E - \alpha_i E_\pm + iP_\pm \,, && (1)\\
\partial_t N_0 &= J\left(x,z\right) - R\left(N_0\right) + \mathcal{D}\partial_x^2 N_0 \\
&- i\left(P_+ E_+^\star + P_- E_-^\star - c.c.\right), && (2)\\
\partial_t N_{\pm 2} &= -\left(R'\left(N_0\right) + 4\mathcal{D}q_0^2\right) N_{\pm 2} \\
&- i\left(P_\pm E_\mp^\star - E_\pm P_\mp^\star\right), && (3)
\end{aligned}$$

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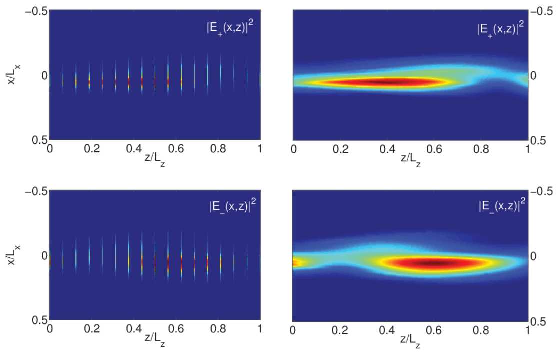

Fig. 1. Mesh reconstruction from the past values in the case of a $100\,\mu$m device. The model contains only 17 mesh lines. The current is $J = 3J_{th}$.

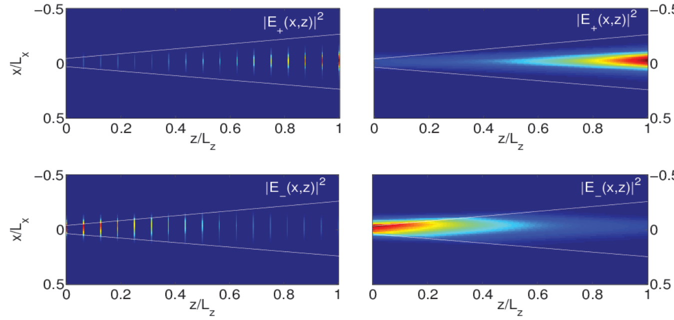

Fig. 2. Mesh reconstruction from the past values in the case of a tapered device. The model contains only 17 mesh lines. The current is $J = 1.4J_{th}$.

where α_i takes into account for the internal losses, $J(x,z)$ is the spatially dependent pump current profile, $\mathcal{D}$ and Δ are the scaled diffusion and diffraction lengths, respectively and $R(N) = AN + BN^2 + CN^3$ the non linear recombination. The boundary conditions at the left and right facets read in the simplest case of a Fabry-Perot cavity

$$E_+(x,0,t) = r_l E_-(x,0,t),\, E_-(x,1,t) = r_r E_+(x,1,t) \quad (4)$$

The field amplitudes and the carrier density components are coupled through the polarizations of the active medium, $P_\pm(x,z,t)$, which describe in time-domain the carrier-induced gain and refractive index experienced by the forward and backward fields by a convolution kernel that reproduces the full gain curve of the semiconductor material hence permitting to describe both gain and absorbing sections simultaneously. By solving analytically the wave equations in Fourier space we obtain

$$E_\pm(q,z,t) = \left[E_\pm(q,z\mp h,t-h) + i\mathcal{S}_\pm\right] e^{-\left(i\Delta q^2+\alpha_i\right)h} \quad (5)$$

$$\mathcal{S}_\pm = \int_0^h ds P_\pm(q,z\mp s,t-s)\, e^{\left(i\Delta q^2+\alpha_i\right)s} \quad (6)$$

where q is the lateral wavevector associated with Fourier transformation along x. By approximating the source term $\mathcal{S}_\pm$ up to second order we obtain a set of DAEs which can be solved numerically more easily than the original TWM model.

Still, all the complexity of the dynamics remains intact and is hidden in the past values of the field kept at each mesh point. For instance, it is still possible to reconstruct the full two dimensional profile by using the past values of the fields. Such a reconstruction at a point z_i is done from a past value t_p of the closest point on the left z_l (resp. right z_r) for the forward (resp. backward) propagating wave and reads

$$\begin{aligned}\tilde{E}(x,z_i,t) &= \mathcal{F}\{[E_\pm(q,z_{l,r},t_p) \\ &+ t_p P_\pm(q,z_{l,r},t_p)]\, e^{-\left(i\Delta q^2+\alpha_i\right)t_p}\}\end{aligned} \quad (7)$$

with $t_p = |z_i - z_{l,r}|$. This spatial reconstruction of the longitudinal profiles of the fields achieved in eq. (7) is simply an Euler prediction from the past values to recover the corresponding mesh points. The result of such a reconstruction is exemplified in Fig. 1 in the case of a straight, $100\,\mu$m wide BALD operated in a chaotic regime and where the dynamics is multimode in both the longitudinal and transverse dimensions. The smoothness of the reconstructed profiles indicates *a posteriori* that no significant information was lost. The same succesful reconstruction in showed in Fig. 2 in the case of tapered gain section linearly increasing from $l_1 = 10\,\mu$m to $l_2 = 100\,\mu$m which represents an opening angle $\theta = 2.5^o$ over 1 mm.

The estimation of the computational time here comes at no surprise: the CPU time is simply divided by the number of slice folded into time delays, what we define as the decimation factor. The typical reduction of *at least* one order of magnitude observed renders BALDs simulations doable on a single computer and thus avoid all the implementation difficulties associated with truly parallel MPI codes. Another important improvement of the method discussed would consider the inclusion of the thermal and electro-thermal effects due to current injection and field two photon absorption which are known to play a dominant role in the dynamics of BALDs.

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