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Rational Chebyshev spectral transform for the dynamics of broad-area laser diodes

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ABSTRACT

This manuscript details the use of the rational Chebyshev transform for describing the transverse dynamics of broad-area laser diodes and amplifiers. This spectral method can be used in combination with the delay algebraic equations approach developed in [1], which substantially reduces the computation time. The theory is presented in such a way that it encompasses the case of the Fourier spectral transform presented in [2] as a particular case. It is also extended to the consideration of index guiding with an arbitrary transverse profile. Because their domain of definition is infinite, the convergence properties of the Chebyshev rational functions allow handling the boundary conditions with higher accuracy than with the previously studied Fourier transform method. As practical examples, we solve the beam propagation problem with and without index guiding: we obtain excellent results and an improvement of the integration time between one and two orders of magnitude as compared with a fully distributed two dimensional model.

1. Introduction

An increasing demand for high-power and high-brightness laser diodes [3] stems from applications such as solid state and fiber laser pumping, telecommunications, remote sensing, medicine or material processing. Laser diodes offer high wall-plug efficiency, reliability, long lifetime, relatively low investment costs and a small footprint, but their output power is limited by catastrophic optical damage of the facets. The most direct path to increase the output power is to reduce the power density on the facets, which can be achieved by increasing the transverse size of the diode up to several hundreds of μm. These so-called broad-area laser diodes (BALDs) have obtained output powers of more than 10 W in continuous wave operation [4]. Yet this increase in power comes at the cost of a degraded beam quality in the transverse dimension due to thermal lensing and spatial hole burning in the carrier density. These phenomena result in high M^2 factors that limit the ability to focus the beam [5], and they might even lead to the chaotic filamentation [6,7] of the beam. In fact, when several high order modes are present, the emission profile is usually not stationary [8]. The complexity of these devices has stimulated the development of sophisticated models and simulation tools that can guide their design [9–11]. These models must include not only the structure of the passive cavity (through the spatial distribution of dielectric constants) but also the state of the active region through the material's response function that depends on the spatial distribution of carriers and temperature [12]. The three-dimensional nature of the problem is often reduced to only the transverse and

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longitudinal directions by invoking the effective index approximation in the dimension perpendicular to the active region plane. Time-independent models based on Helmholtz equation have been developed in order to determine the transverse mode structure of these devices [13–15]. Yet they cannot deal with dynamical phenomena, like beam filamentation, nor predict the onset of instabilities. For this reason, several time-dependent models have been developed and are mostly based upon the decomposition of the intra-cavity field into counter-propagating waves [16] in the slowly varying approach (SVA), differing mainly in the description of the optical response of the material, hence they are generically termed traveling-wave models (TWMs) [17–23].

The most popular method for solving the TWM equations in the presence of diffraction in the plane transverse to the propagation axis is arguably the Fourier transform (FT) whose main advantage is to diagonalize the transverse second order derivative operator describing diffraction. In addition, the calculation of the FT is achievable via an algorithm of low complexity ($N \log N$, where N is the number of points in the spatial grid [24]) and readily available as quality open source softwares, see e.g. [25]. Besides their conceptual beauty, spectral and pseudo-spectral algorithms are known to converge toward the exact solution much faster than finite difference algorithms, due to their so-called "infinite order" or "exponential" convergence [26]. In addition, the use of exponential differencing [27] in combination with the FT allows to treat exactly the effect of the spatial operators over propagation intervals that may not be infinitesimal. It has been recently shown [2] that such an exact treatment of diffraction over a large increment can work in synergy with the delay algebraic equation (DAE) mapping of TWMs developed in [1]. This mapping consists in folding in time delays the longitudinal dynamics [23] and typically allows for a reduction of the number of degrees of freedom—hence of the computation time—between one and two orders of magnitude, which alleviates the need of complex parallel codes for the simulation of BALDs [2].

However, the FT automatically imposes periodic boundary conditions in the transverse direction which is wrong for a single laser diode as the real physical boundary conditions for the field amplitude are of the radiative type. Hence, one is in general forced to consider a sufficiently large transverse domain in which the field is only concentrated in the central stripe and, as such, possesses enough space to decay "naturally" to zero and not feel the presence of the wrong boundary conditions. The inclusion of an absorbing perfectly matched layer (PML) close to the boundary may help to mitigate this problem; even so, an abrupt transverse variation of the losses would in principle give rise to a convolution product in the Fourier domain which may render the inclusion of such a PML if not difficult, at least costly from a numerical point of view. Another drawback of the FT is that its basis functions, the plane waves, are not the most adequate for describing the exponential decaying tails of the field outside of the central stripe, which may result in a sub-optimal convergence.

The aforementioned points suggest that a spectral method based upon a set of functions which decay, even weakly, in $x = \pm\infty$ should improve upon the convergence properties, as clearly indicated in the discussion at the end of [28]. In addition, a non-uniform discretization—with a high density of points in the central stripe where the nonlinear dynamics occurs, and a low density of points in the outer linear regions, where the field decays exponentially—would represent a clear improvement. These considerations hint toward the use of the rational Chebyshev transform (RCT). The RCT devised by Christov consists in a modification of the Chebyshev transform, defined on $x \in [-1, 1]$, onto $x \in [-\infty, \infty]$ by an arctan mapping [29]. The functional basis consists in a full set of rational fractions which tend to zero in $x = \pm\infty$ and that are represented over a non-uniform mesh whose density decreases with the distance from the origin. Such a method solves the aforementioned drawback of the FT while keeping essentially its good properties, i.e. a simple representation of the spatial derivative, even upon Exponential Differencing [27], and surprisingly enough, a fast $N \log N$ implementation based upon the Fourier transform.

In this work, we discuss how a method based upon the RCT can be implemented for a TWM at a *marginal* increase in complexity as compared to the FT method developed in our earlier work [2]. We use the TWM developed in previous works [23] generalized to the presence of transverse diffraction and both index and gain guiding. Propagation along the axis is solved in time-domain using the DAE formalism [1], which enables the use a coarse discretization along the optical axis. The numerical algorithm is formally equivalent for both the RCT and the FT approaches. As such, we present our theory in an unified way where only the precise form of the matrices corresponding to the second derivative and to the index guiding differ between the RCT and FT.

This manuscript is organized as follows. In Section 2, we recall the basis of our TWM [23] generalized to the presence of transverse diffraction and index guiding. We detail in Section 3 the basic properties of the RCT. In Section 4 the representation of the second order spatial derivatives and of the transverse index guiding is discussed for the RCT and the FT approaches. Section 5 is devoted to the implementation of the DAE transformation using Exponential Differencing [27] and discuss how one must treat the boundary conditions along the longitudinal direction. We detail in particular the many caveats present in the evaluation of the integration weights due to the stiffness incurred by the spectral transformation and how to avoid matrix inversions. We also show how the full two dimensional mesh profile can be reconstructed from the few actives "slices" that remain active with the DAE approach. In Section 6, we exemplify the validity of our approach by studying a variety of cases and comparing the FT and the RCT methods.

2. Model

Our model considers a single mode structure in the vertical direction (y), which is reduced via the effective index approximation. The optical field in the cavity is assumed to be almost TE polarized and it is decomposed into a forward and a backward wave of SVA $E_\pm(x, z, t)$. In addition, the carrier density $N(x, z, t)$ in the cavity is decomposed into a quasi-