Two-dimensional time-dynamic simulations of DFB lasers and MOPAs

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***Abstract*—Due to the lateral structure of Distributed Feedback lasers (DFB) and Master Oscillator Power Amplifiers (MOPAs), the one-dimensional classical Transfer Matrix Method (TMM) as well as similar one-dimensional methods do not lead to satisfactory simulation results. Therefore, we present a two-dimensional simulation technique based on Trigonometric Finite Wave Elements (TFWE) - a generalization of the TMM in two or three dimensions - that solves the time-dependent wave equation. By coupling the wave equation with a temperature and a drift-diffusion model, we can simulate the time-dynamic behavior of DFB lasers and MOPAs. Furthermore, by Fourier transformation, we can investigate which modes and which frequencies appear. In this way, the influence of the injected current and of the stripe width on the resulting modes and on the output power can be analyzed in detail.**

I. Introduction

Master Oscillator Power Amplifiers (MOPAs) and Distributed Feedback lasers (DFB) are difficult to simulate. Firstly, they have a small-scale grating structure in propagation direction that has to be resolved and further leads to internal reflections. Secondly, the lateral structure of the device (gain- or index-guiding) has a strong influence on the resulting modes and the output power such that a one-dimensional simulation technique as the Transfer Matrix Method (TMM) does not lead to satisfactory results for a large range of applications.

Therefore, we developed special finite elements - the so-called Trigonometric Finite Wave Elements (TFWE) - that can be applied to two- and three-dimensional problems (see [1]). They are based on the TMM and are widely applicable. For example, they can be used for varying wave number in propagation and lateral direction (see [1], [2]). Furthermore, they are particularly suitable for three section lasers or MOPAs, as in regions without grating one can increase the mesh size significantly. But also in case of DFB lasers, one has the great advantage that only a few grid points in regions out of the active stripe width are needed. In comparison with other multi-dimensional simulation techniques as for example the beam propagation method, the TFWE method solves the full time-dynamic wave equation including current spreading and temperature dependence. Furthermore, without loss of performance, we can investigate the wavelength spectrum of the optical wave by means of Fourier transformation (FFT).

In the following, we introduce our model and the TFWEs. Afterwards, simulation results including output power and wavelength spectra for DFB lasers and MOPAs are presented.

II. Model and Trigonometric Finite Wave Elements

Derived from the Maxwell equations, the two-dimensional optical wave equation can be expressed as (see [1], [3])

$$-2\mathrm{i}k_0 \frac{\bar{n}}{v_g}\frac{\partial u}{\partial t} = -\triangle u - k_0^2 \tilde{n}^2 u \qquad (1)$$

where u denotes the complex amplitude of the electric field and $\tilde{n} = n' + \mathrm{i}n''$ is the complex refractive index. Since $E(x,t) := \exp(\mathrm{i}\omega t)u(x,t)$ is the electrical field of the optical wave, we obtain the following identity for the photon density n_{dens}:

$$n_{\mathrm{dens}} = \frac{\epsilon_0 n' n_g}{2\hbar\omega}|E|^2 = \frac{\epsilon_0 n' n_g}{2\hbar\omega}|u|^2.$$

The wave equation (1) is coupled with the following drift diffusion equation:

$$\frac{\partial n_A}{\partial t} = \nabla\cdot(D_A \nabla n_A) + \eta_{i,leck}\frac{j_{inj}}{q d_A} - r_{rec,A}. \qquad (2)$$

Herein, $r_{\mathrm{rec},A}$ denotes the recombination density (see [3]). The injected current density j_{inj} including current spreading is described as follows:

$$j_{\mathrm{inj}} = \begin{cases} \frac{I}{SL} & \text{if } |y| \le \frac{S}{2} \\ \frac{I}{SL}/(1+\frac{|y|-\frac{S}{2}}{l_0})^2 & \text{if } |y| > \frac{S}{2} \end{cases},$$

where y denotes the direction perpendicular to the propagation direction.

To compute the real part of the complex refractive index, we have to solve a third partial differential equation describing the temperature distribution

$$-\nabla\cdot(\kappa\nabla T) + \gamma T = p, \qquad (3)$$

where T is the temperature rise with respect to the ambient temperature, κ is the effective thermal conductivity, and p is the dissipated power density which is assumed to be of constant value p_0 inside the active stripe width and to be zero outside. γ depends on the injected current density and models the heat sink. Then, the real part of the complex refractive index can be written in the following way: $n' := n_{\mathrm{bi}} + \delta_{n_A}(n_A) + \delta_T(T)$. Herein, n_{bi} is the built-in variation of the refractive index independent of n_A and the temperature T, $\delta_{n_A} := -\sqrt{n_{n_A} n_A}$ denotes the dependence of the index on the carrier density n_A, and $\delta_T := n_T T$ denotes dependence of the index on the temperature T.

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For solving (1), we constructed new finite element basis functions by multiplying the standard linear nodal basis functions with trigonometric cosine and sine functions, which approximate the behavior of an oscillating and internally reflected wave (see [1]). Due to this construction, the TFWE method can be applied to general wave numbers k in two and more dimensions (see [1]–[3]) in contrast to the TMM.

To analyze the wavelength spectrum of the simulated optical wave, we apply a FFT (see [3]). Thus, we get information about the lateral shape of the mode for a specific wavelength.

III. Application and Simulation Results

In the following, we present simulation results for DFB lasers and MOPAs obtained by the TFWE method.

Firstly, we numerically solved the three coupled partial differential equations (1), (2), and (3) for a DFB laser resonator of size $20\mu m \times 500\mu m$ with varying stripe width S emitting at wavelength $973nm$. In Figure 1, the wavelength spectrum for a small stripe ($2.5\mu m$) is depicted. Due to the small stripe width, different ground order modes occur and the output power oscillates. Figure 2 shows the wavelength spectrum for a larger stripe width ($5\mu m$). Because of the larger stripe width, ground order modes compete with higher order modes. The shape of the modes corresponding to the two peaks in Figure 2 is depicted in Figure 3.

Secondly, we simulated a MOPA of size $35\mu m \times 500\mu m$ emitting at wavelength $973nm$. We varied the injected current in the power amplifier from $3.5A$ to $4A$. For $3.5A$, the MOPA becomes stationary after some relaxation oscillations and the wavelength spectrum depicts only one ground order mode. Whereas for $4A$, the wavelength spectrum shows two competing modes (see Fig. 5) where one is of higher order and one is a ground order mode (see Fig. 6). Therefore, the MOPA does not reach a stationary state (see Fig. 4).

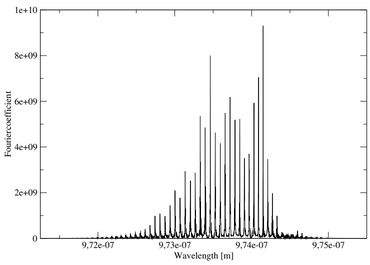

Fig. 1. Wavelength spectrum for $S = 2.5\mu m$

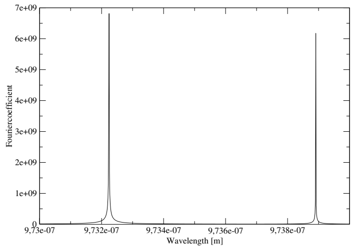

Fig. 2. Wavelength spectrum for $S = 5\mu m$

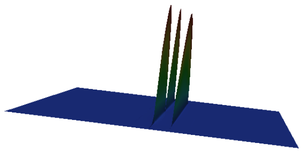

Fig. 3. Competing modes of low and higher order

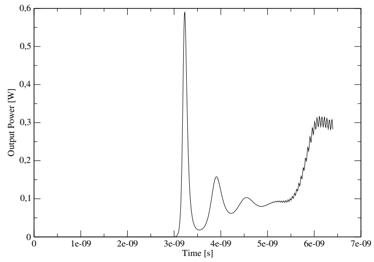

Fig. 4. MOPA output power for $I_{MO} = 4A$

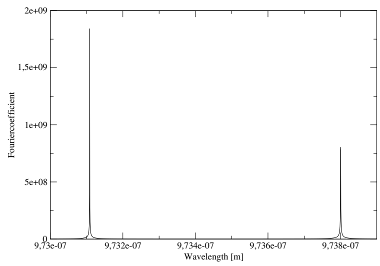

Fig. 5. MOPA wavelength spectrum for $I_{MO} = 4A$

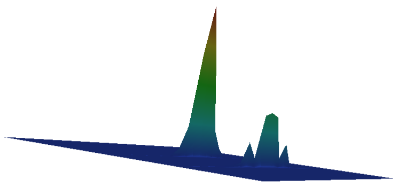

Fig. 6. Competing modes of low and higher order

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