Hybrid electromagnetic modelling of coherent radiation in electrically-pumped semiconductor lasers.

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***Abstract*—In this paper method for linking device simulation (drift diffusion model) and electromagnetic simulation is presented. For full wave simulation Finite Difference Time Domain method with auxiliary differential equation has been used. Lasing model has been characterized by four-level two-electron atomic system with Pauli Exclusion Principle (PEP) and with electric pumping ratio extension.**

***Index Terms*—device, FDTD, ADE, drift diffusion, full wave, nonlinear optics, lasers, laser optics**

I. Introduction

Nowadays laser action can be simulated using various methods, as Finite Difference Time Domain (FDTD) metod with auxiliary differential equation (ADE) which reprezents classical dispersive Lorentzian gain [1] or with FDTD with rate equations ADE [3]. AnotherADE-FDTD technique presented in [4] and extended in [2], uses the density-matrix method for solving Maxwell-Bloch equation.

In this paper ADE-FDTD method for electrically-pumped lasers is reported. Initial point base on device simulation, computed using drift diffusion method [5] and recalculated in co-processing.

II. Drift-Difussion simulation

First step in the proposed method is the computation of a drift-diffusion model of a device [5], which consists of the Poisson's equation and continuity equations. As a result of this calculation spatial distribution of electron and hole density is obtained, which will be used, subsequently, in electrodynamic simulations presented in the next Section.

III. Electromagnetic simulation

In the next step, electrodynamic simulation will be undertaken with the aid of a finite-difference time-domain (FDTD) method with auxiliary differential equation (ADE) hRate equations are coupled with Ampre's circuital law (with Maxwell's addition) as density of electric polarization:

$$\frac{\partial^2 P_i}{\partial t^2} + \gamma_i \frac{\partial P_i}{\partial t} + \omega_i^2 P_i = \kappa_i \Delta N_i E \tag{1}$$

where i indicates a or b, $P_a(P_b)$ stands for the density of electric polarization between 0-3 (1-2) levels of a four-level atomic model, γ are linewidths, and ω are resonant frequencies, $\Delta N_{a(b)}$ is diference between population densities at 0-3 (1-2 levels) and κ is model parameter.

In addition to a typical form of rate equations [2] [3], electrical pumping rate, P_R, has been added:

$$\frac{\partial N_3}{\partial t} = -\frac{N_3(1-N_2)}{\tau_{32}} - \frac{N_3(1-N_0)}{\tau_{30}} + \frac{1}{\hbar\omega_a} E \frac{\partial P_a}{\partial t} + P_R \tag{2}$$

$$\frac{\partial N_2}{\partial t} = \frac{N_3(1-N_2)}{\tau_{32}} - \frac{N_2(1-N_1)}{\tau_{21}} + \frac{1}{\hbar\omega_b} E \frac{\partial P_b}{\partial t} \tag{3}$$

$$\frac{\partial N_1}{\partial t} = \frac{N_2(1-N_1)}{\tau_{21}} - \frac{N_1(1-N_0)}{\tau_{10}} - \frac{1}{\hbar\omega_b} E \frac{\partial P_b}{\partial t} \tag{4}$$

$$\frac{\partial N_0}{\partial t} = \frac{N_3(1-N_0)}{\tau_{30}} + \frac{N_1(1-N_0)}{\tau_{10}} - \frac{1}{\hbar\omega_a} E \frac{\partial P_a}{\partial t} - P_R \tag{5}$$

where N_i is population density at level $i \in \{0,1,2,3\}$, τ_{ij} is the decay time constant between i and j levels and $\hbar$ is reduced Planck constant

Due to chosen model, wide spectrum of results can be obtain, for example spectral characteristic of generated radiation.

IV. Linking electromagnetic and Drift-Diffusion simulations

Electromagnetic simulation of a semiconductor laser with Eq. (2)-(5) requires knowledge on material parameters, which can be determined with the aid of DD. All calculations presented in this section are preformed for one selected voltage.

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For both type of computing processes the same mesh grid have to be used. In this paper, the study is limited to a 1D structure.

Once DD is computed, gain characteristic is calculated in each cell [6]:

$$
\begin{aligned}
g(z) = {} & \frac{\nu}{4\pi^2\hbar\gamma\varepsilon_0 nc}\left(\frac{2m_r}{\hbar^2}\right)^{\frac{3}{2}}\cdots \\
& \int_0^\infty d\epsilon|\mu_k|^2\left[f_e(t)+f_h(t)-1\right]\cdots \\
& L(\omega_k-\nu)\left(1-j\frac{\omega_k-\nu}{\gamma}\right)
\end{aligned}
\tag{6}
$$

where ν is angular frequency, $\hbar$ is reduced Planck constant, γ is homogeneous linewidth factor, ε_w is vacuum permittivity, m_r is reduced mass given by equation $m_r^{-1} = m_e^{-1}+m_h^{-1}$, $d\epsilon$ is part of energy used for integral calculations, $|\mu_k|$ is dipole moment, $L(\omega_k-\nu)$ is Lorentzian lineshape function, ω_k is angular plasma frequency of lorentz model, and f_e, f_h are Fermi-Dirac distributions for electron and holes respectively given by equation:

$$
f_\alpha(\varepsilon) = \frac{1}{\exp\left[\beta\left(\varepsilon\frac{m_r}{m_\alpha}-\mu_\alpha\right)\right]+1}
\tag{7}
$$

where α stands as $e(h)$ for electron (hole) distribution, β is equal to $\frac{1}{k_BT}$ where T is temperature and k_B is Boltzmann coefficient, and μ is quasi-chemical potential.

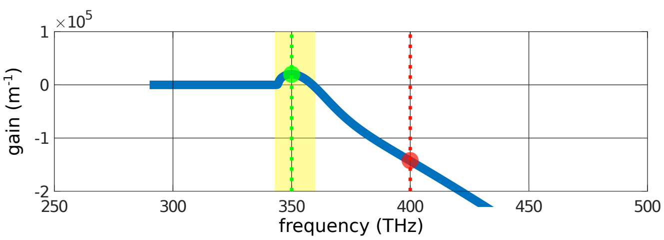

Fig. 1. An example of gain curve computed using equation (6).

As an example of those calculation gain curve is presented on figure 1. If gain is negative in a given cell, it is assumed to be lossy, which is represented with electric conductivity:

$$
\sigma = \omega\varepsilon_0\chi''
\tag{8}
$$

where χ'' is imaginary part of electrical susceptibility and can be easy obtained using equation

$$
\chi'' = -2\frac{g}{nK_0}
\tag{9}
$$

where K_0 is the wavenumber in vacuum and n is refractive index.

On the contrary, when gain charracteristic is positive at the frequency of interest, pumping rate, PR, is calculated using spatial distribution of current density, DN, by integrating density of states between 0-3 energy levels.

V. Numerical results

As an example PN junction [7] (see fig. **??**) has been used. It consist of $0.5\mu m$ n-type $Al_{0.25}Ga_{0.75}As$ and $0.5\mu m$ p-type $GaAs$ blocks. After DD simulation for chosen voltage (1.4 V) parameters for novel model have been computed. As an example of results evolution of population densities between populations densities at levels 2 and 1 (see fig. 2) and value of E-field (see fig. 3) have been presented.

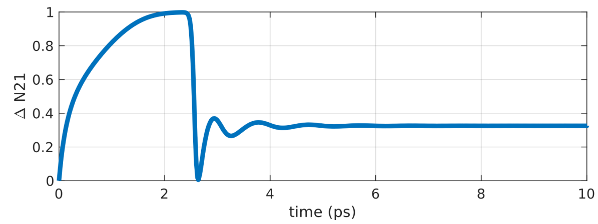

Fig. 2. Time evolution of difference between population densities at levels N_2 and N_1.

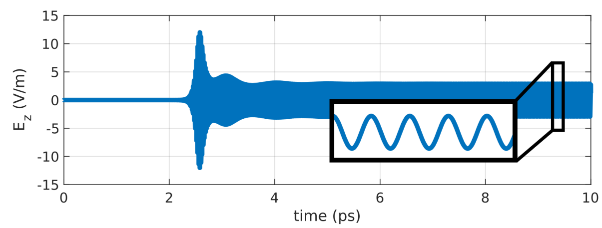

Fig. 3. E-field evolution in time generated in active area of analized structure.

VI. Conclusions

Using novel method presented in this paper it is possible to calculate insensitivity of generated electromagnetic field and threshold current. Presented methodology will be extended for two dimensional simulations.

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