Simulation of the mode dynamics in broad ridge laser diodes

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***Abstract*—Broad-ridge laser diodes exhibit rich lateral mode dynamics in addition to longitudinal mode dynamics observed in narrow-ridge laser diodes. To simulate mode dynamics in these diodes, an effective mode interaction term is derived from the bandstructure and carrier scattering in the quantum well. The spatial dependency of pump current densities plays a crucial role in lateral mode dynamics, and thus, a Drift-Diffusion model is employed to calculate the current densities with an additional capturing term.**

***Index Terms*—Laser diodes, Mode competition**

Fabry-Pérot type laser diodes show mode-competition phenomena such as mode hopping, where the level of activity of different longitudinal modes changes over time due to an antisymmetric interaction of the modes. This effect can be observed experimentally using a streak camera for narrow ridge laser diodes [1, 2] and more recently in broad ridge laser diodes [3]. While a rate equation model exists in literature for the simulation of the longitudinal mode dynamics in narrow ridge laser diodes with a single lateral mode [4, 5], we present a model that can be used for broad ridge laser diodes.

The ridge width of the laser diode is assumed to be small compared to the resonator length in order to be able to separate the longitudinal and transverse contributions of the mode functions $\mathbf{u}_{mp}(\mathbf{r}_{\|}, z)$:

$$\mathbf{u}_{mp}(\mathbf{r}) = \mathbf{t}_m(x,z) g_p(y),$$

where the index p is used for the longitudinal modes $g_p(y)$ and m is used for the transverse modes $\mathbf{t}_m(x,z)$. In the following the coordinate x denotes the lateral direction, y the longitudinal direction and z the growth direction. In order to investigate the mode dynamics of a laser diode, the objective is to understand how the number of photons in each mode changes over time. One possibility would be to solve the Maxwell equations and project the solution onto the different modes. In the model presented here, equations of motion for these photon numbers are solved instead, they are given by

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t} S_{mp} = &-\omega_{mp} S_{mp} \int \mathrm{d}x\, \bar{t}_m^2(x) \mathrm{Im}\,\chi\left(\omega_{mp}, n_\mathrm{e}(x), n_\mathrm{h}(x)\right) \\ &+ \int \mathrm{d}x\, \bar{t}_m^2(x) \mathrm{Im}\,\chi_\mathrm{SE}\left(\omega_{mp}, n_\mathrm{e}(x), n_\mathrm{h}(x)\right) \\ &+ \frac{\mathrm{d}}{\mathrm{d}t} S_{mp}\bigg|_\mathrm{WW} - \frac{S_{mp}}{\tau_\mathrm{photon}}, \end{aligned} \tag{1}$$

where $\bar{t}_m(x) = |\mathbf{t}_m(x, z_\mathrm{QW})|$ is the tranversal mode function near the quantum well and the angular frequencies of the different modes are given by ω_{mp}. The susceptibility of the quantum well $\chi(\omega, n_\mathrm{e}, n_\mathrm{h})$ and the spontaneous emission spectrum $\mathrm{Im}\,\chi_\mathrm{SE}(\omega, n_\mathrm{e}, n_\mathrm{h})$ depend on the lateral coordinate via the carrier densities $n_\mathrm{e,h}$. In the simulations a $\mathbf{k}\cdot\mathbf{p}$ bandstructure is used to calculate χ and $\mathrm{Im}\,\chi_\mathrm{SE}$ for different carrier densities assuming Fermi-Dirac distributions.

The photon losses are described by the lifetime τ_photon, which depends on the mirror reflectivities and the absorption coefficient inside the cavity. The term $\frac{\mathrm{d}}{\mathrm{d}t} S_{mp}\big|_\mathrm{WW}$ describes the interaction of modes via beating vibrations of the carrier densities in the longitudinal direction and is responsible for the mode dynamics. This interaction can be found in literature [4] for laser diodes with a small ridge width. For broad ridge laser diodes the overlap between different lateral modes also needs to be considered and the mode interaction is given by the integral

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t} S_{mp}\bigg|_\mathrm{WW} = &\sum_{nq} \frac{1}{2L} \frac{S_{mp} S_{nq}}{\omega_{mp}\omega_{nq}} \cdot \\ &\int \mathrm{d}x\, \bar{t}_m^2(x) \bar{t}_n^2(x) A\left(\omega_{nq} - \omega_{mp}, n_\mathrm{e}(x), n_\mathrm{h}(x)\right),\end{aligned}$$

where the strength of the interaction is determined by the function $A(\Delta\omega, n_\mathrm{e}, n_\mathrm{h})$. This function depends strongly on the frequency difference $\Delta\omega = \omega_{nq} - \omega_{mp}$ of the modes and the carrier densities, an example is shown in Fig. 1. It can be determined from the quantum well bandstructure and the relaxation of the beating vibrations due to different scattering processes such as Coulomb scattering. The equations of motion for the carriers inside the quantum well are given by

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t} n_\mathrm{e,h}(x) = &-B\left(n_\mathrm{e}(x), n_\mathrm{h}(x)\right) - \frac{n_\mathrm{e,h}(x)}{\tau_\mathrm{nr}} \\ &+ D_\mathrm{e,h} \frac{\partial^2}{\partial x^2} n_\mathrm{e,h}(x) + \frac{\mathrm{d}}{\mathrm{d}t} n_\mathrm{e,h}(x)\bigg|_\mathrm{Pump} \\ &+ \sum_{mp} \bar{t}_m^2(x) \frac{\omega_{mp} S_{mp}}{L} \mathrm{Im}\,\chi\left(\omega_{mp}, n_\mathrm{e}(x), n_\mathrm{h}(x)\right),\end{aligned}$$

where $B(n_\mathrm{e}, n_\mathrm{h})$ describe the losses due to spontaneous emission, τ_nr the nonradiative losses, $D_\mathrm{e,h}$ is the diffusion constant and L is the cavity length. The pumping of the

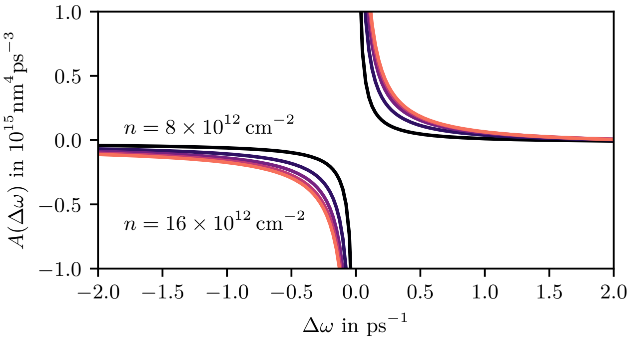

Fig. 1. Mode interaction strength $A(\Delta\omega)$ for an InGaN quantum well and different carrier densities as a function of the frequency difference $\Delta\omega$ of the two interacting modes.

quantum well is described by the term $\frac{\mathrm{d}}{\mathrm{d}t}n_{\mathrm{e,h}}(x)\big|_{\mathrm{Pump}}$ which is calculated in a preceeding steady-state simulation using the drift-diffusion equations for the bulk carriers. In this steady-state simulation the time derivatives of the quantum well carrier densities and the photon numbers are set to zero and only one longitudinal mode is considered for each lateral mode. The bulk carriers are coupled to the carriers in the quantum well via a capture term of the form [6]

$$\frac{\mathrm{d}}{\mathrm{d}t}n^{\mathrm{3D}}_{\mathrm{e,h}}(x)\bigg|_{\mathrm{Capture}} = -C_{\mathrm{e,h}}n^{\mathrm{3D}}_{\mathrm{e,h}}(x,z)\eta_{\mathrm{e,h}}\left(n_{\mathrm{e,h}}, n^{\mathrm{3D}}_{\mathrm{e,h}}\right),$$

where $n^{\mathrm{3D}}_{\mathrm{e,h}}$ are the bulk carrier densities, $C_{\mathrm{e,h}}$ are simulation parameters and the efficiency $\eta_{\mathrm{e,h}}$ is given by

$$\eta\left(n, n^{\mathrm{3D}}\right) = \frac{\sum_{\mathbf{k}} f^{\mathrm{3D}}_{\mathbf{k}}\left(1 - f^{\mathrm{QW}}_{\mathbf{k}_{\mathrm{2D}}}\right)}{\sum_{\mathbf{k}} f^{\mathrm{3D}}_{\mathbf{k}}}.$$

Here $\mathbf{k}\cdot\mathbf{p}$ bandstructures are used to determine Fermi-Dirac distribution functions for $f^{\mathrm{QW}}_{\mathbf{k}_{\mathrm{2D}}}$ and $f^{\mathrm{3D}}_{\mathbf{k}}$. using the densities n and n^{3D}. The resulting pump current densities are then used in the simulation of the mode dynamics. The dynamics of the bulk carrier densities are not considered anymore.

In Fig. 2 an example for the simulation of the mode dynamics of a green laser diode with a ridge width of $10\,\mu\mathrm{m}$ is shown for different currents. As multiple lateral modes participate in the mode dynamics, it is difficult to distinguish between the individual longitudinal modes. The effect of mode rolling can be observed, where the currently active mode changes over time from lower to higher wavelengths. As expected, the mode rolling frequency increases with increasing current. While in the simulation only one mode cluster is shown, in the experiment multiple spectrally separated mode clusters can be observed [3]. One explanation could be fluctuations of the indium concentration in the quantum wells. These fluctuations can locally change the maximum of the optical gain and are not yet included in the simulation.

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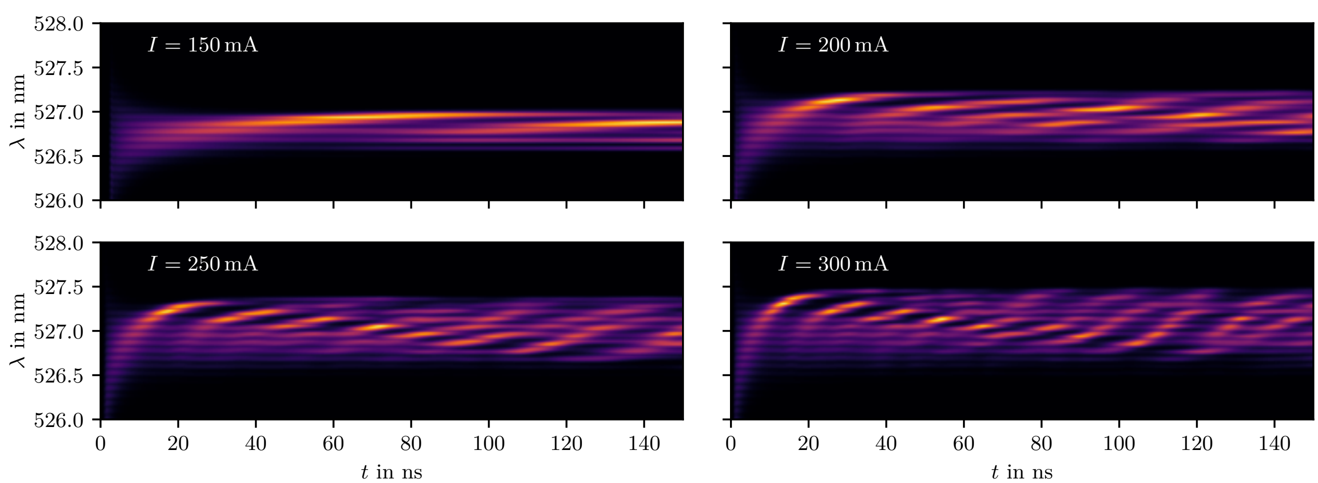

Fig. 2. Simulated mode dynamics for a green laser diode with a ridge width of $10\,\mu\mathrm{m}$ and a cavity length of $L = 600\,\mu\mathrm{m}$ and different currents. Here, the laser output is presented as a function of both wavelength and time. The data is acquired by multiplying the time-dependent photon numbers $S_{mp}(t)$ with a Gaussian function. This Gaussian function is centered at the respective mode wavelengths and has a width of $5 \times 10^{-3}\,\mathrm{nm}$.