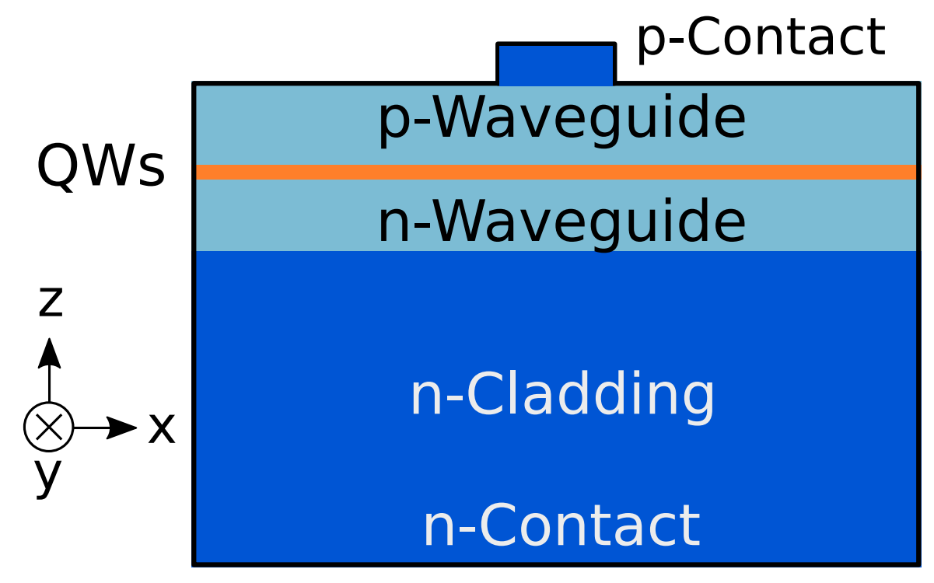
Mode Dynamics in Nitride Laser Diodes

Eduard Kuhn, Lukas Uhlig, Matthias Wachs, Ulrich T. Schwarz and Angela Thränhardt

Introduction

Laser diodes show interesting mode competition phenomena. For example streak camera measurements show cyclic mode hopping, where the currently active mode changes from higher to lower wavelengths. This can be explained by third order effects such as beating vibrations of the carrier density [1].



Theory

The modes functions are assumed to be standing waves in the longitudinal direction:

$$\mathbf{u}_p(\mathbf{r}) = \mathbf{t}(x,z)\sqrt{2/L}\,\sin\left(\pi p y/L\right).$$

If there are at least two active modes p and q then there a might be a change in the electron and hole distribution functions proportional to $\sin(\pi p y/L)\sin(\pi q y/L) \approx \cos(\pi(p-q)y/L)/2$. Therefore the position dependent Bloch Equations [2]

$$\begin{aligned}\frac{\partial}{\partial t}\psi_{\mathbf{k}}(\mathbf{r}_\parallel) &= -\frac{i}{\hbar}\left(\varepsilon^e_{\mathbf{k}}+\varepsilon^h_{\mathbf{k}}\right)\psi_{\mathbf{k}}(\mathbf{r}_\parallel)\\ &\quad + i\Omega(\mathbf{r}_\parallel)(1-f^h_{\mathbf{k}}(\mathbf{r}_\parallel)-f^e_{\mathbf{k}}(\mathbf{r}_\parallel))\\ \frac{\partial}{\partial t}f^{e,h}_{\mathbf{k}}(\mathbf{r}_\parallel) &= 2\mathrm{Im}\left\{\psi_{\mathbf{k}}(\mathbf{r}_\parallel)\Omega^*(\mathbf{r}_\parallel)\right\} \qquad (1)\end{aligned}$$

should be used to describe the carrier dynamics in the QWs. Here $f_{\mathbf{k}}$ denote the distribution functions and $\psi_{\mathbf{k}}$ is the microscopic polarization. It is convenient to use a Fourier expansion

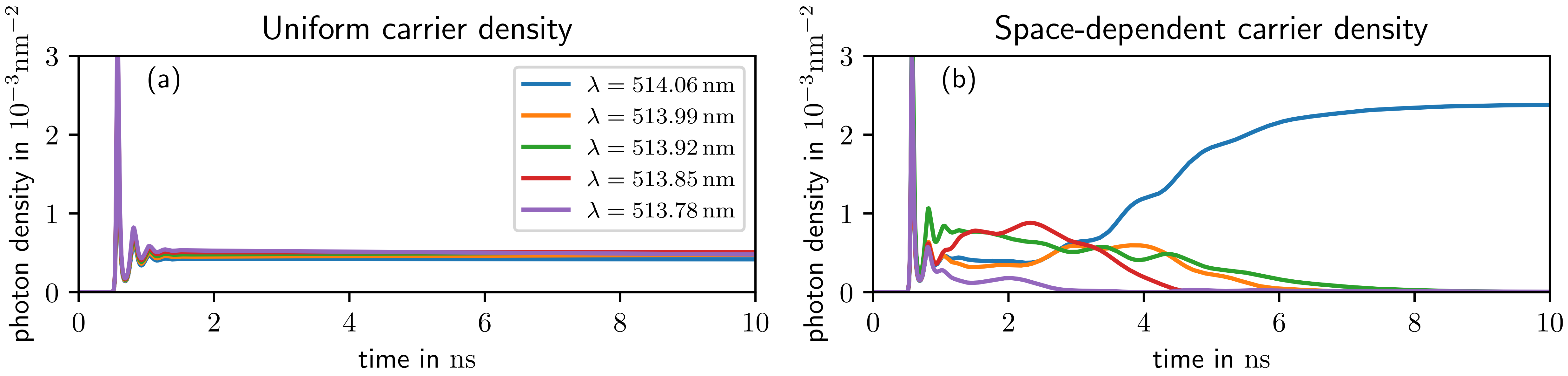
$$f_{\mathbf{k}} = f^0_{\mathbf{k}} + \sum_{n=1}^{\infty} f^n_{\mathbf{k}}\cos\left(\pi n y/L\right).$$

for the distribution functions. In order to look at µs timescales and a large number of modes, the quasiequilibrium approximation is used and contributions up to third order in the field are considered. If there are only two active modes the influence of the Fourier components of the carrier density on the dynamics of the photon densities s_p can be approximated to

$$\dot{s}_p \approx \frac{C^2}{2}\omega_q\omega_p s_q s_p \mathrm{Im}\chi(\omega_q)\mathrm{Re}\chi'(\omega_q)\frac{1}{\omega_q-\omega_p},$$

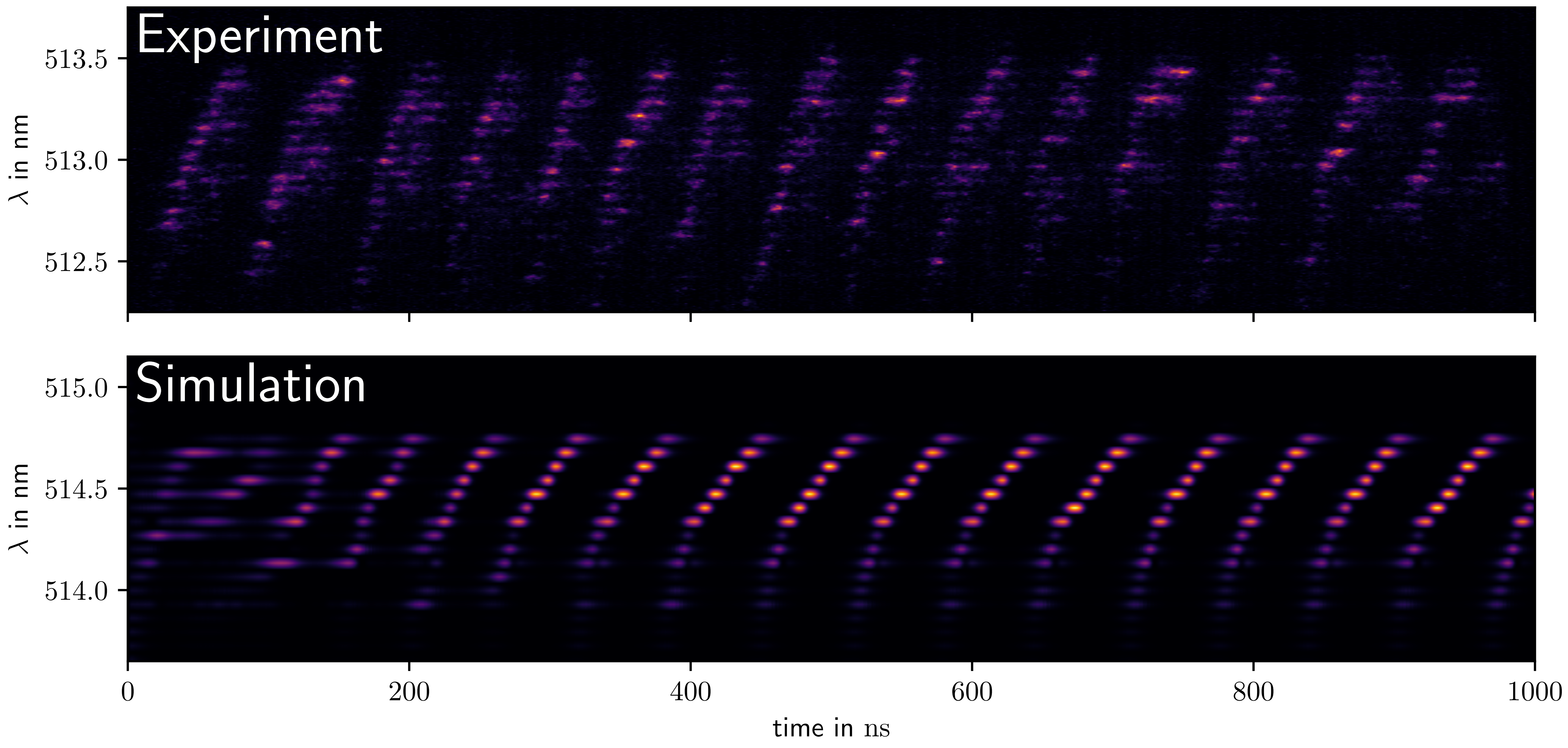
where C is a coupling factor and χ denotes the electric susceptibility. This term is positive for the mode with the higher wavelength and negative for the other one, as long as the gain $g \propto -\mathrm{Im}\chi$ is positive.

Influence of spatial inhomogeneities on the mode dynamics

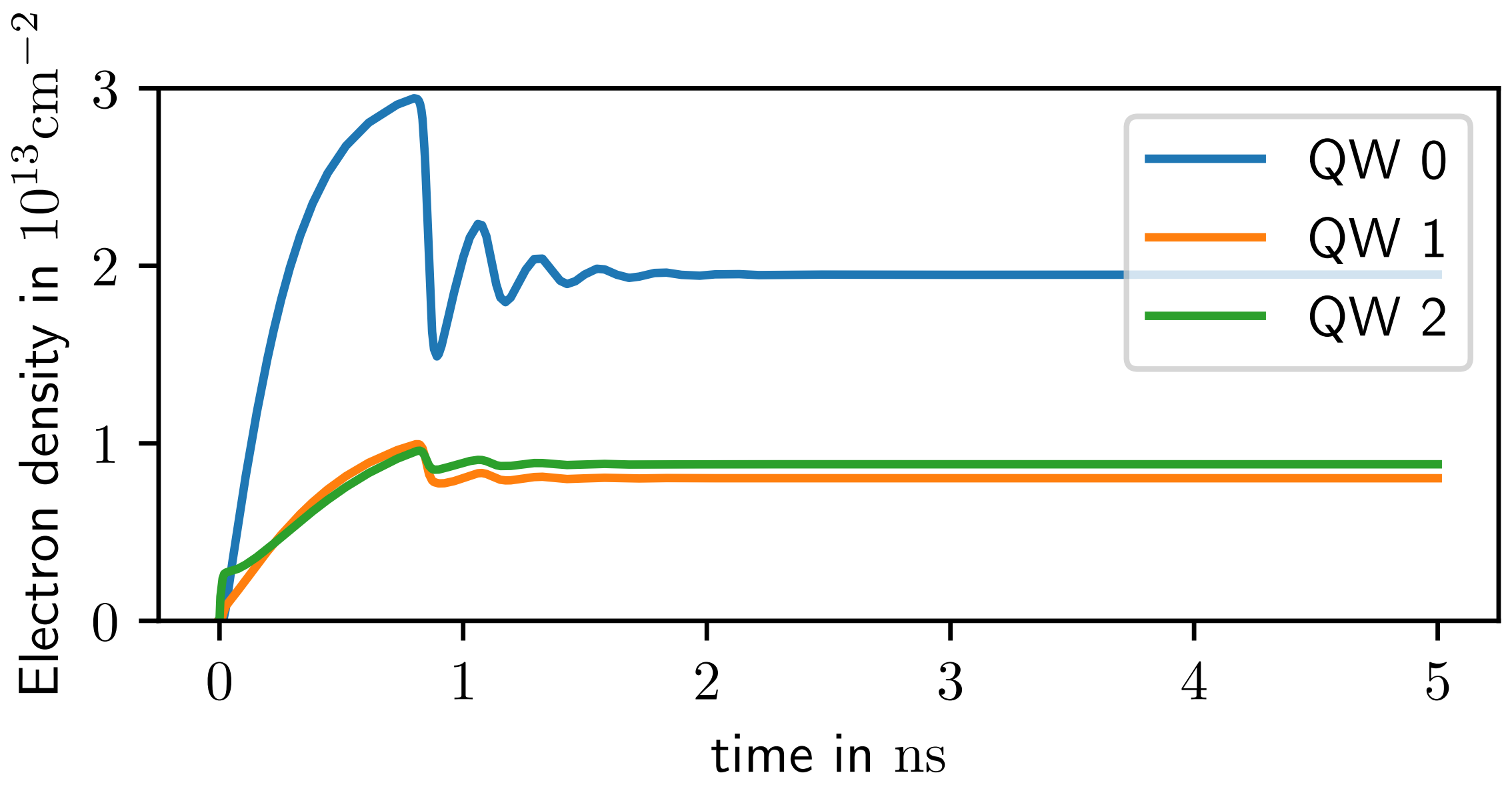


Mode dynamics obtained from the Maxwell-Bloch Equations (1), here spatial inhomogeneities of the carrier density were considered in (b), but not in (a).

Comparison of theory and experiment (nitride laser diodes)

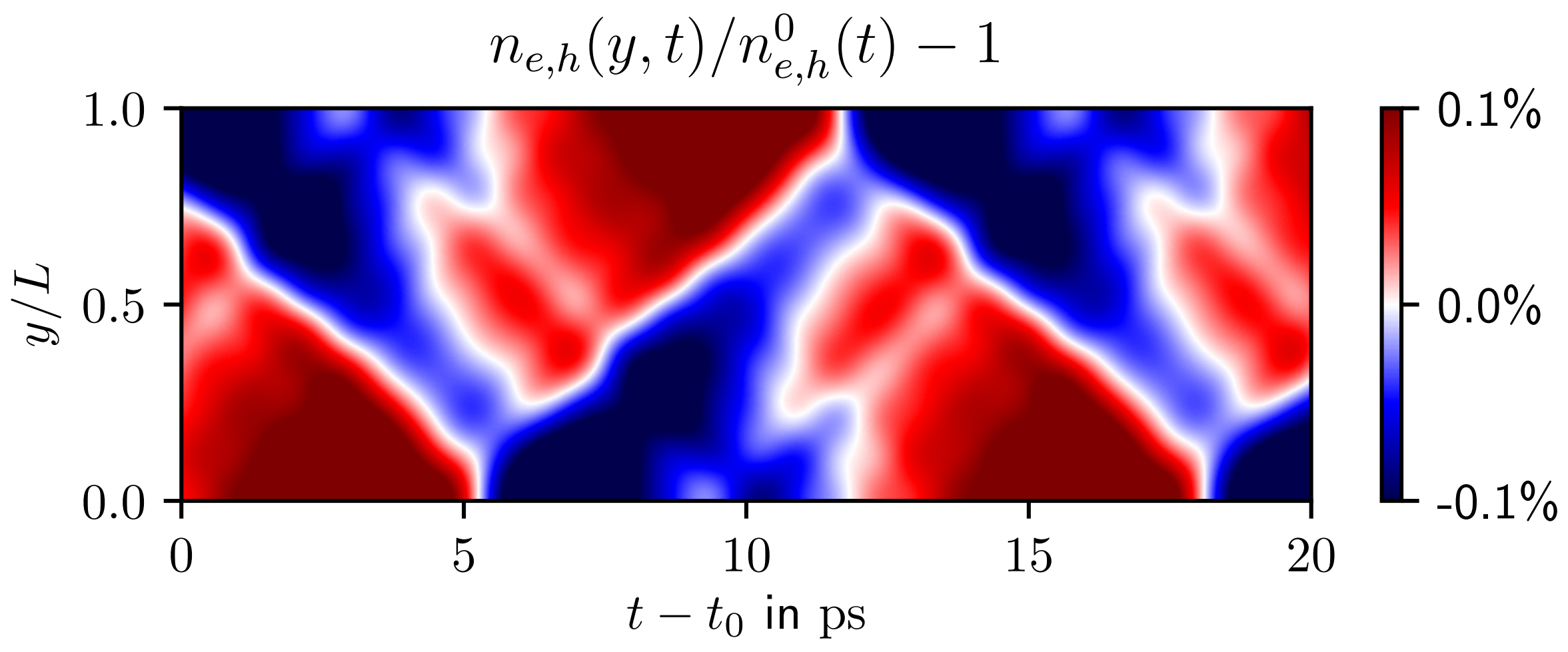


Multiple QWs



One way to describe the pumping of multiple QWs is to use the Drift Diffusion equations. An example is shown above, where the QW on the p-doped side is responsible for the stimulated emission and the other QWs are transparent.

Beating vibrations



Deviation of the carrier density $n_{\mathrm{e,h}}$ from the average around $t_0 = 200\,\mathrm{ps}$. The period of these vibrations is determined by the frequency difference of two neighbouring modes. In this case $\Delta\omega \approx 0.5\,\mathrm{ps}^{-1}$, therefore $T \approx 12.6\,\mathrm{ps}$.

Conclusion

The mode rolling observed in laser diodes can be explained using the position-dependent Semiconductor-Bloch equations. In the future we will also consider the temperature dynamics inside the diode.

References:

[1] M. Yamada, Journal of Applied Physics **66**(1), 81 (1989). DOI 10.1063/1.343860

[2] O. Hess, T. Kuhn, Physical Review A **54**(4), 3347 (1996). DOI 10.1103/physreva.54.3347