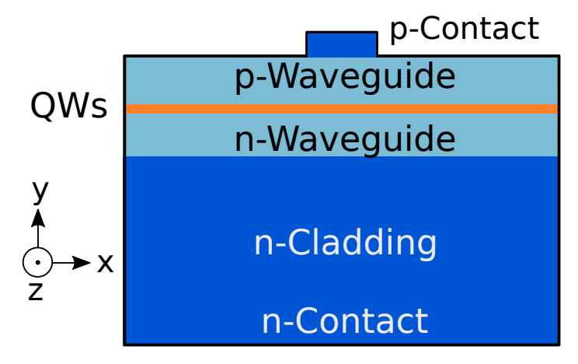
Simulation of Mode Competition Phenomena in Nitride Laser Diodes

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]. The simulations are based on the Semiconductor-Bloch equations[2], where band structure and momentum matrix elements are given by $\mathbf{k}\cdot\mathbf{p}$ theory. The coupling of electrons and holes with the relevant modes can be obtained using a waveguide solver and the pump currents are calculated from Drift-Diffusion simulations.



Waveguide Modes

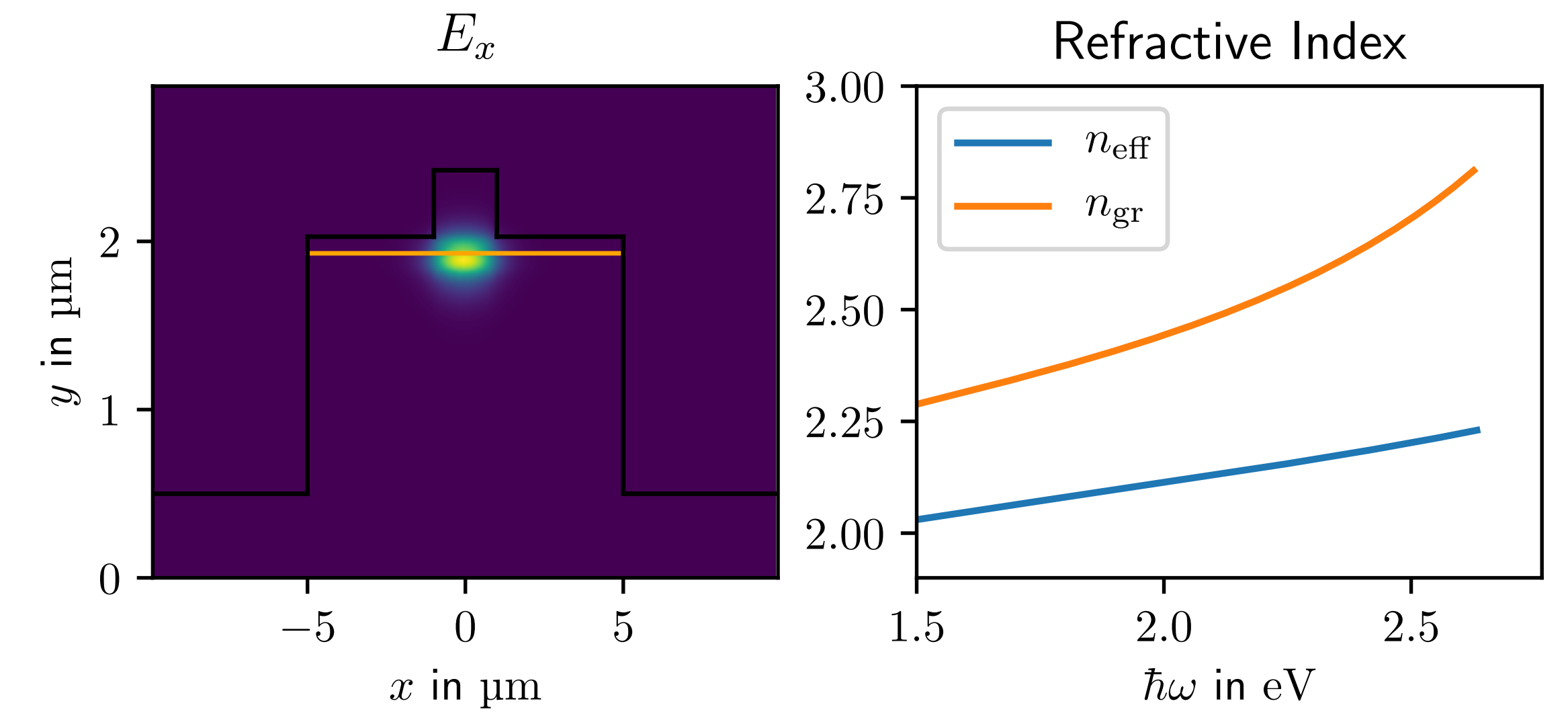
The TE modes and their effective refractive indices can be obtained by solving the eigenequation

$$c_0^2 \Delta E_x + \omega^2 n^2 E_x = \omega^2 n_{\text{eff}}^2 E_x .$$

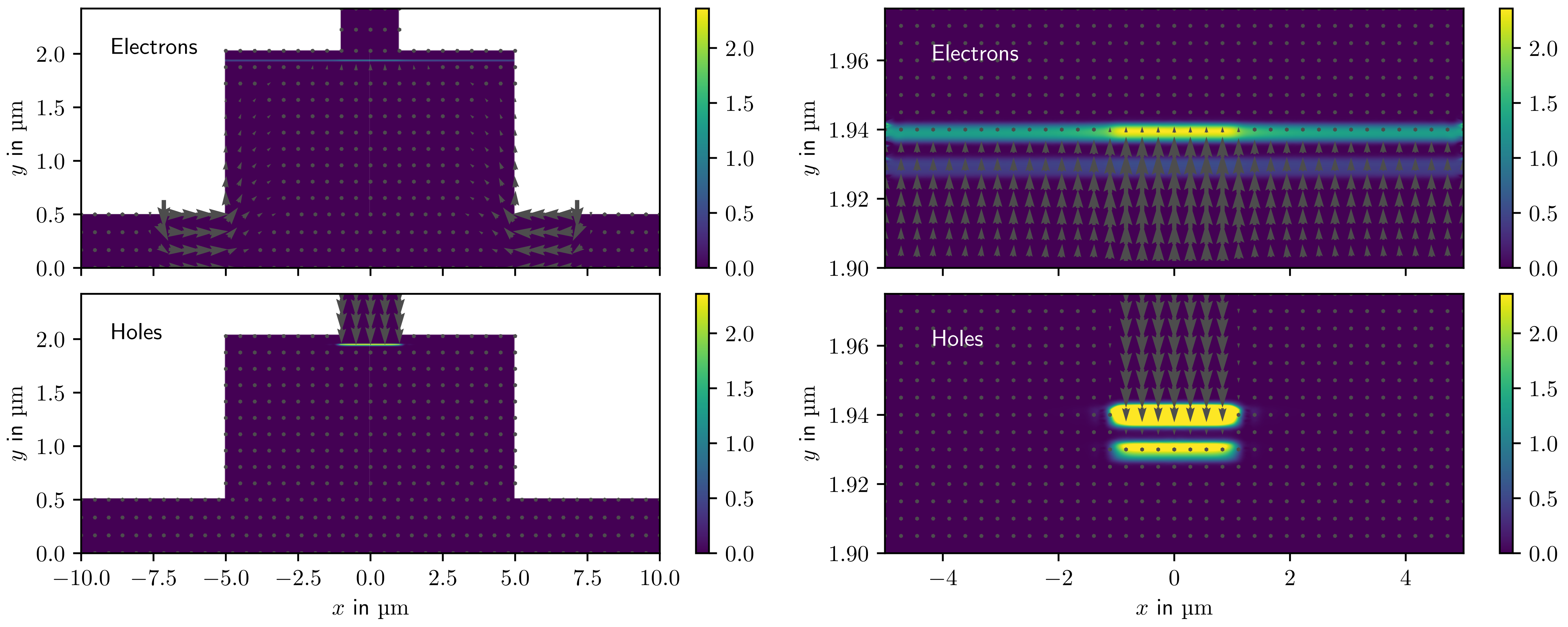
The group refractive index

$$n_{\text{gr}} = n_{\text{eff}} + \omega \frac{\partial n_{\text{eff}}}{\partial \omega}$$

determines the mode spacing $\Delta\omega$ and is therefore important for the mode dynamics.



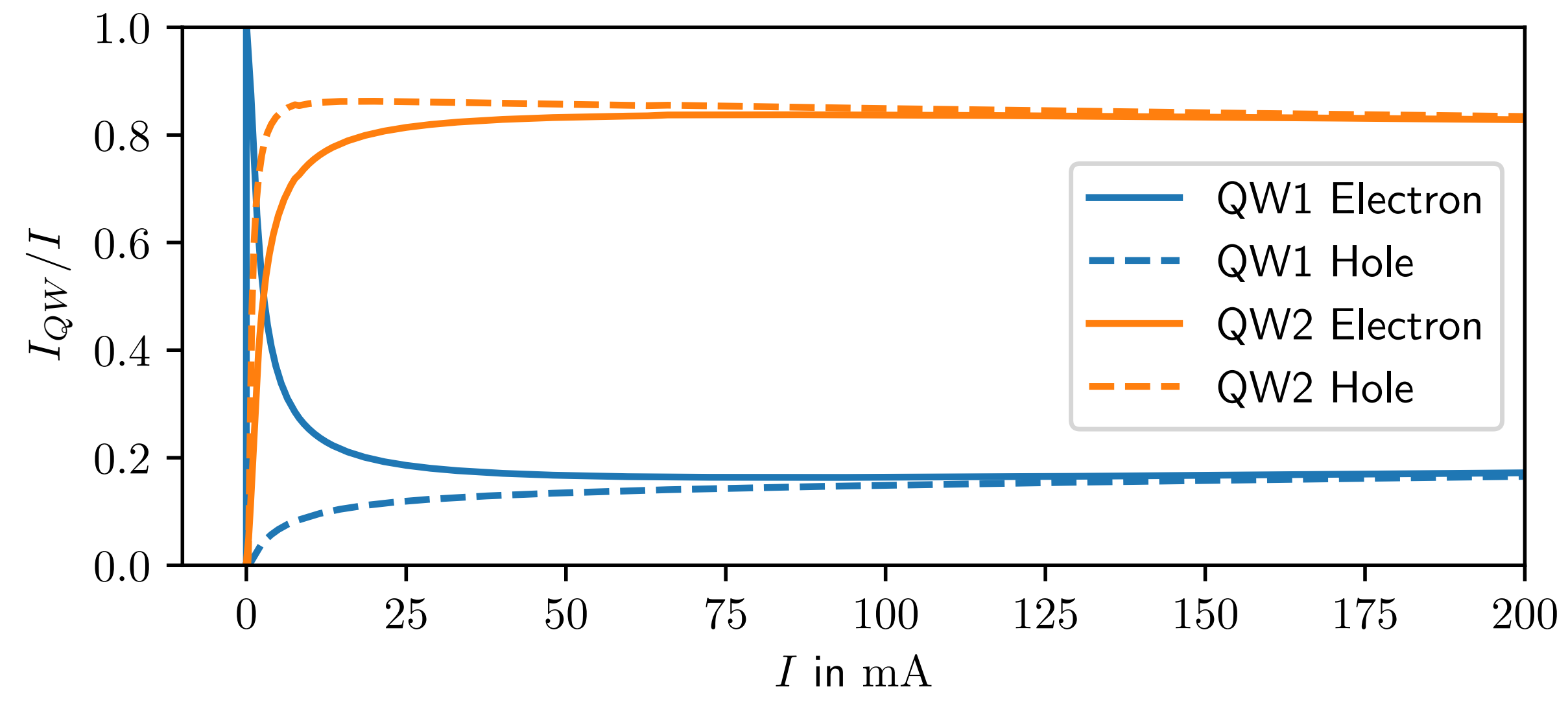
Drift-Diffusion Simulations with Capture Term



The figure above shows electron/hole losses and current densities for a voltage above threshold, here the capture process is described by a term

$$\left.\frac{\partial}{\partial t} f_{\mathbf{k}}^{3\text{D}}\right|_{\text{Capture}} = -C f_{\mathbf{k}}^{3\text{D}} \left(1 - f_{\mathbf{k}_\parallel}^{\text{QW}}\right).$$

The figure on the right shows the fraction of the total current that ends up in each of the two QWs.

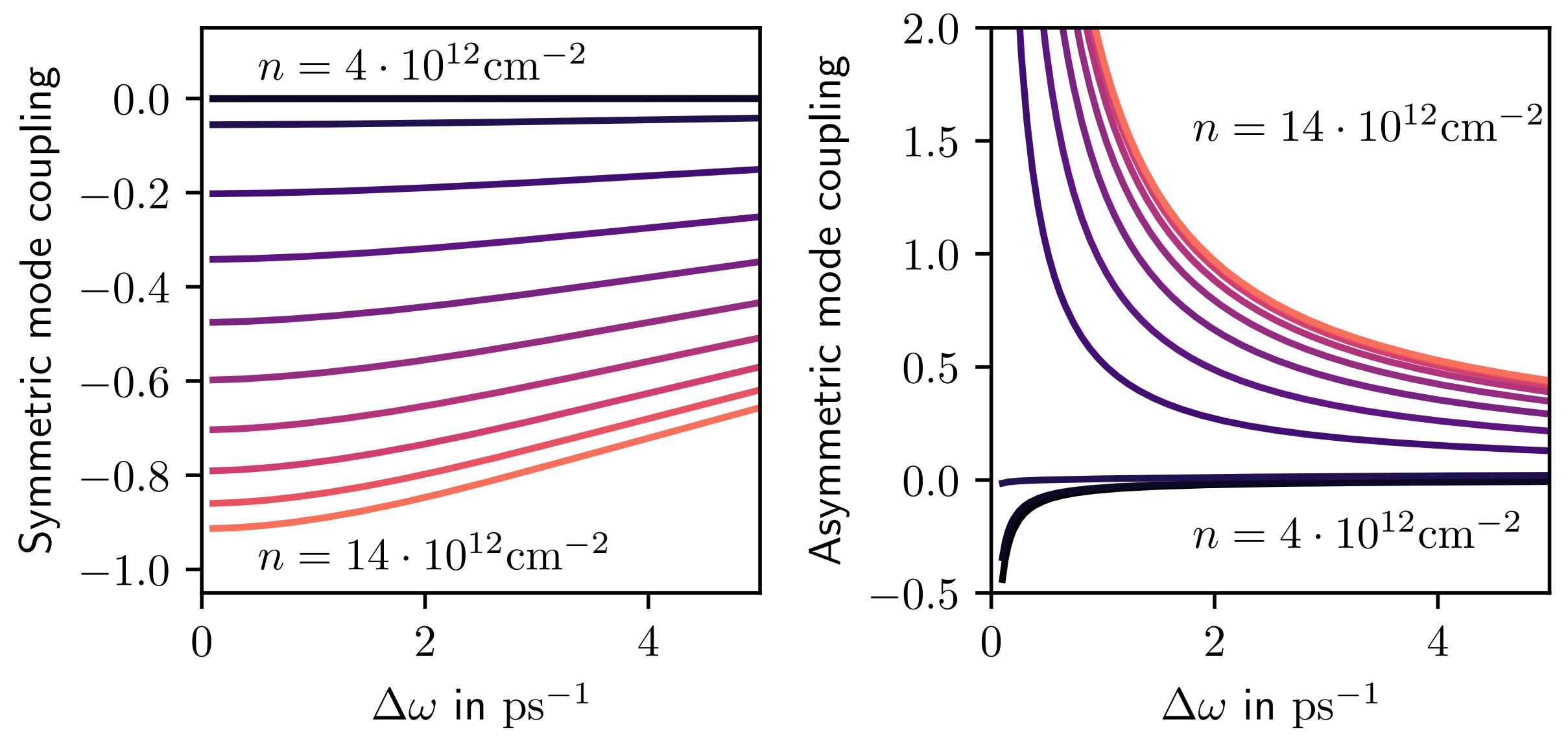


Mode Coupling

Third order terms due to spatial variations of the carrier densities in the QWs cause an effective coupling between photon numbers in different modes. This coupling between two modes depends mostly on the frequency difference and can approximately be written as

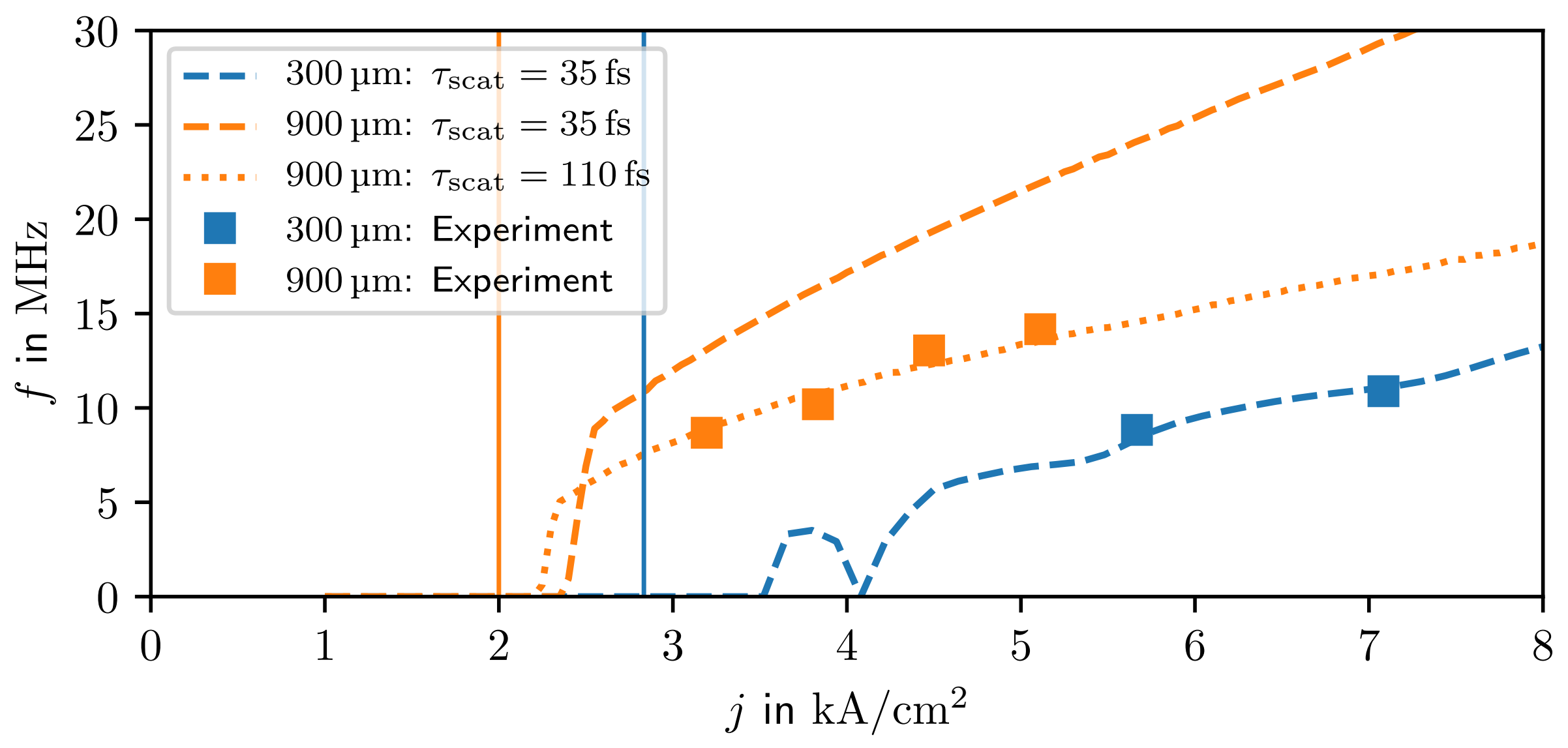
$$\left.\frac{\partial}{\partial t} s_p\right|_{\text{Coupling}} = \sum_q f(\omega_p - \omega_q) s_p s_q$$

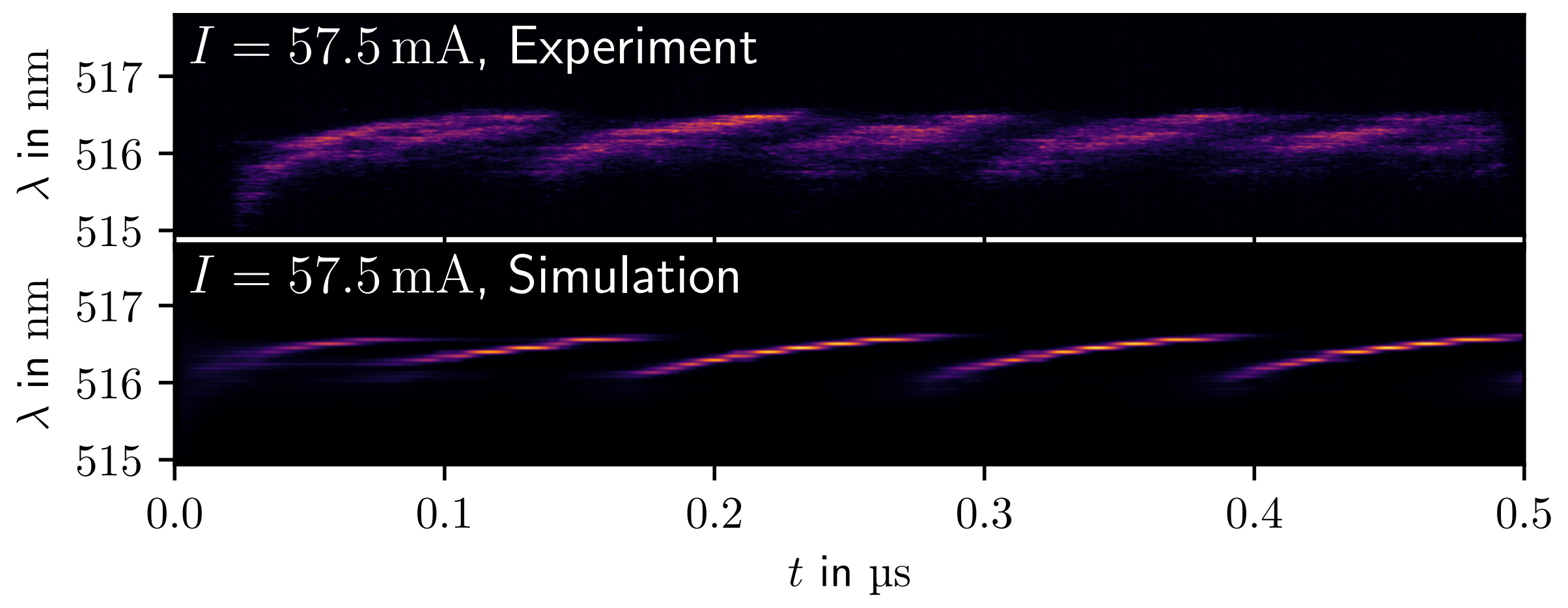
The symmetric contribution can be described by a Lorentzian $B/(\Delta\omega^2 \tau_s^2 + 1)$, where the broadening is determined by a scattering time τ_s. The asymmetric contribution approximately has the form $A/\Delta\omega$ which favors the mode with the lower frequency. The figure below shows the symmetric and asymmetric coupling terms for different carrier densities using Coulomb-Scattering.

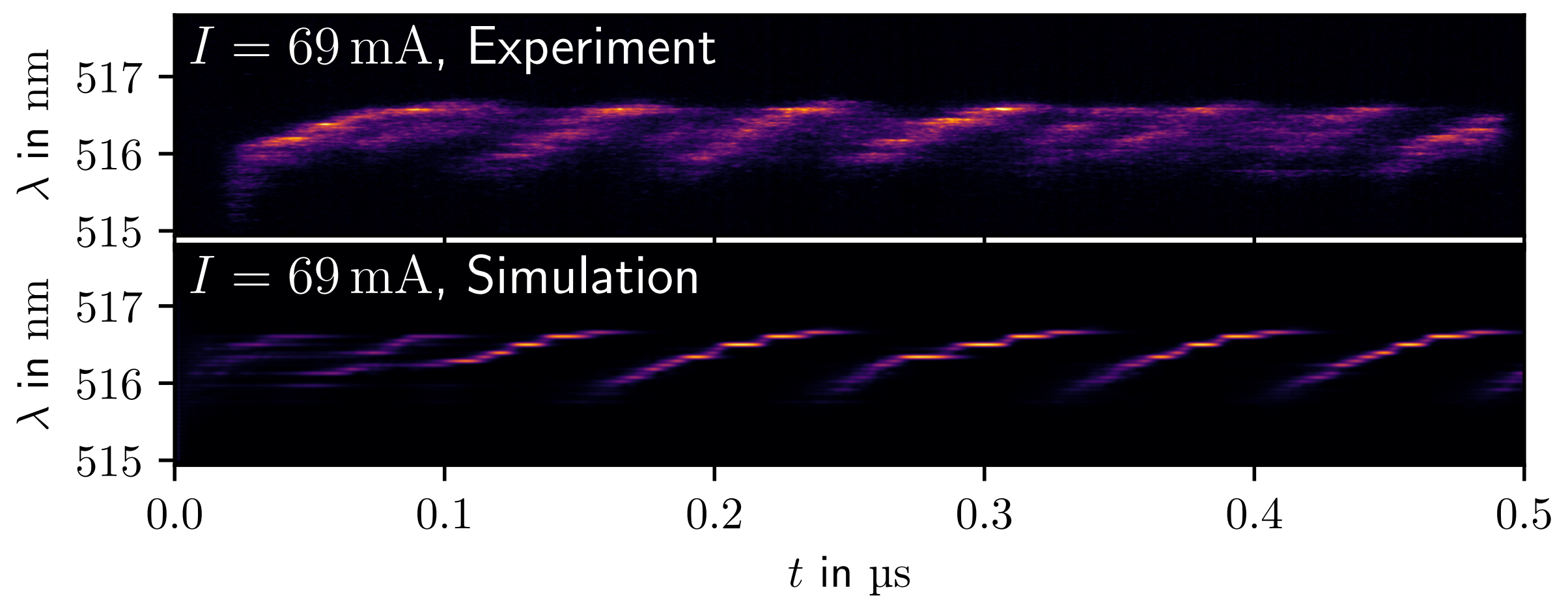


Comparison with Streak Camera Measurements

The figure on the right shows simulated and measured mode dynamics for a laser diode with a length of $900\,\mu\text{m}$. The average time between two peaks defines the mode rolling frequency. This frequency depends strongly on the scattering time τ_s, which is shown in the figure below.







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] E. Kuhn, A. Thränhardt, Optical and Quantum Electronics **51**(6), 206 (2019). DOI 10.1007/s11082-019-1916-7