Influence of Coulomb Scattering on the Coupling between Longitudinal Modes in Nitride Laser Diodes

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***Abstract*—Due to their small separation of longitudinal modes, Fabry-Pérot type laser diodes show rich mode competition effects. For example streak camera measurements show cyclic mode hopping, where the currently active longitudinal mode changes from lower to higher wavelengths. This effect can be explained by beating vibrations of the carrier densities in the quantum wells and can be included in rate equation simulations by using an effective mode coupling term. In this work we calculate this effective mode coupling term on a microscopic level using Coulomb scattering. We investigate how the effective coupling term depends on the carrier densities in the quantum wells for a green nitride laser diode and compare the result with coupling terms found in literature. The behavior is similar if the frequency difference of the longitudinal modes is small, deviations are observed for larger frequency differences.**

Using a streak camera, various mode competition effects can be observed in laser diodes [1]. An example is shown in Fig. 1. Here effects of third order in the optical field need to be considered in order to explain these longitudinal mode dynamics. One of these effects is the effect of spectral hole burning, where a strong optical field lowers the carrier distribution functions in regions of the Brillouin zone where a optical transition is possible. This dip of the carrier distribution functions lowers the overall gain and depends heavily on the carrier scattering time [2].

In the following we will instead discuss a different effect, namely the mode coupling caused by beating vibrations of the carrier densities in the quantum wells. As with the effect of spectral hole burning, this effect also depends strongly on the carrier scattering and in this paper we want to discuss the influence of a statically screened Coulomb interaction. In order to describe these beating vibrations, it is beneficial to split the distribution functions into two parts:

$$f_{\mathbf{k}}(z) = f_{\mathbf{k}}^0 + \delta f_{\mathbf{k}}(z).$$

Here $f_{\mathbf{k}}^0$ is the average distribution function and $\delta f_{\mathbf{k}}(z)$ is a small deviation from this average that depends on the longitudinal coordinate z. If two or more longitudinal modes are active, they cause oscillations of the distribution functions and contribute to $\delta f_{\mathbf{k}}(z)$.

The period of these oscillations is given by the frequency difference of the two longitudinal modes and is therefore on the order of magnitude of $10\,\mathrm{ps}$. In simulations we want to look at the mode dynamics on a time scale of $100\,\mathrm{ns}$, therefore considering $\delta f_{\mathbf{k}}(z)$ in the equations of motion directly can be time consuming. It is a lot more convenient to adiabatically eliminate $\delta f_{\mathbf{k}}(z)$ and obtain an effective mode coupling term [3]:

$$\dot{S}_p\Big|_{\text{Coupling}} \approx \sum_{q \neq p} S_p S_q g(\omega_q - \omega_p). \tag{1}$$

Here S_p denotes the number of photons in mode p and ω_p is the respective frequency. Note that unlike spectral hole burning, this effect only causes an interaction between two different longitudinal modes. The coupling between two modes is given by a function $g(\Delta\omega)$, which is assumed to only depend on the frequency difference $\Delta\omega = \omega_q - \omega_p$. This function is often split into a symmetric part $B(\Delta\omega) = B(-\Delta\omega)$ and an asymmetric part $A(\Delta\omega) = -A(-\Delta\omega)$.

Fig. 2 shows how the symmetric and asymmetric parts depend on the carrier density. The band structure, matrix

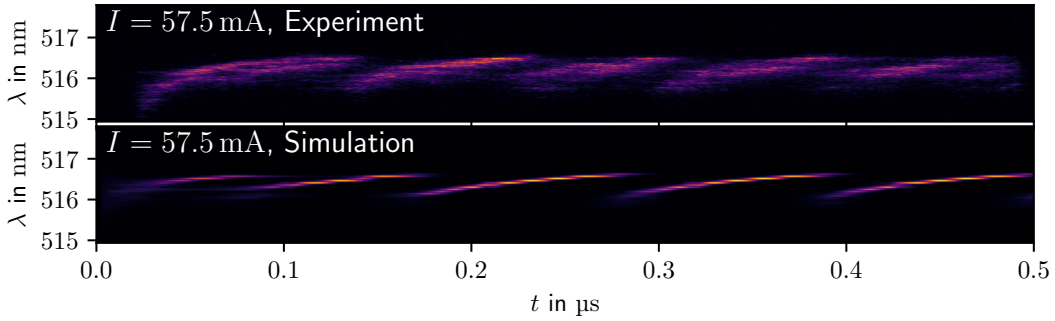

Fig. 1. Measured and simulated streak camera images for a green nitride laser diode with a cavity length of $900\,\mu\mathrm{m}$. Here the laser output is shown as function of time and wavelength. The simulation uses an effective coupling term as given in Eq. (1).

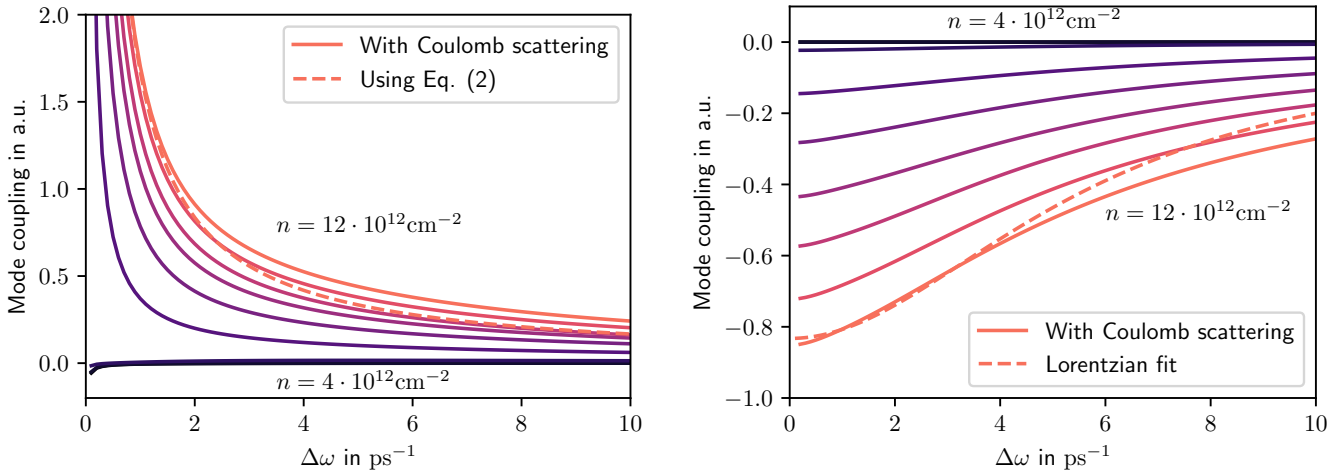

Fig. 2. Asymmetric (left) and symmetric (right) mode coupling terms shown as function of the frequency difference of the two longitudinal modes. Here one of the two modes is chosen to be at the gain maximum.

elements and envelope functions used in the calculations were calculated using the $\mathbf{k} \cdot \mathbf{p}$ method for an $In_{0.21}Ga_{0.79}N$ QW with parameters taken from [4]. The asymmetric term is responsible for the effect of mode rolling, where the currently active mode changes from lower to higher wavelengths. The asymmetric term is negative below transparency and positive for carrier densities above transparency, which agrees with the experiment. If a simple scattering time is used instead of Coulomb scattering, the asymmetric term has the following form, assuming the scattering time is sufficiently small:

$$A(\Delta\omega) \propto \Gamma^2 \mathrm{Im}\chi(\omega_0)\mathrm{Re}\chi'(\omega_0)\frac{1}{\Delta\omega}. \tag{2}$$

Here ω_0 is frequency corresponding to the gain maximum, Γ denotes the confinement factor and χ is the susceptibility of the quantum well. Using $\mathrm{Re}\chi' = \alpha \mathrm{Im}\chi'$, where α is the antiguiding factor, this is equivalent to the asymmetric coupling term found in literature [3]. For a carrier density of $10^{12}\mathrm{cm}^{-2}$ Eq. (2) is also shown in Fig. 2, where it agrees well with the coupling term obtained using Coulomb scattering for low frequency differences. However deviations from the $1/\Delta\omega$ behavior can be observed for higher frequency differences.

The symmetric term, as shown in Fig. 2, becomes more relevant as the carrier density increases and is always negative. This term therefore leads to active longitudinal modes suppressing their neighboring modes, so this term favors only one or two modes being active at any given point in time. If this term is neglected and only the asymmetric term is used in simulations, an equilibrium state is reached, where a few neighboring modes are active at the same time. This is not observed in the experiment, so it is important to include this term in simulations. Using a simple scattering time, this term has the form of a Lorentzian, where broadening is determined by the scattering time τ_s:

$$B(\Delta\omega) = -B\frac{\tau_\mathrm{s}}{\Delta\omega^2\tau_\mathrm{s}^2 + 1}$$

For Coulomb scattering we can obtain a scattering time by fitting a Lorentzian to the data shown in Fig. 2. This scattering time is shown in Fig. 3. Here the scattering time is about 200 fs, which is on the expected order of magnitude.

In this work we discussed the influence of Coulomb scattering on the effective mode coupling term caused by beating vibrations of the carrier density. Compared to the mode coupling terms found in literature, Coulomb scattering shows the same behavior for smaller frequency differences, however deviations can be observed for higher frequency differences.

References

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[3] Ahmed M and Yamada M 2002 *IEEE Journal of Quantum Electronics* **38** 682–693
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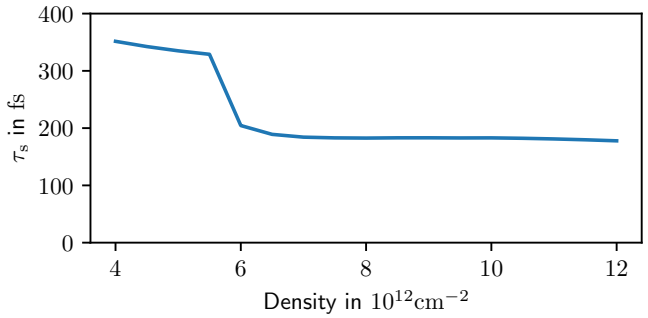

Fig. 3. Scattering times obtained by fitting a Lorentzian to the symmetric mode coupling term as a function of the carrier density.