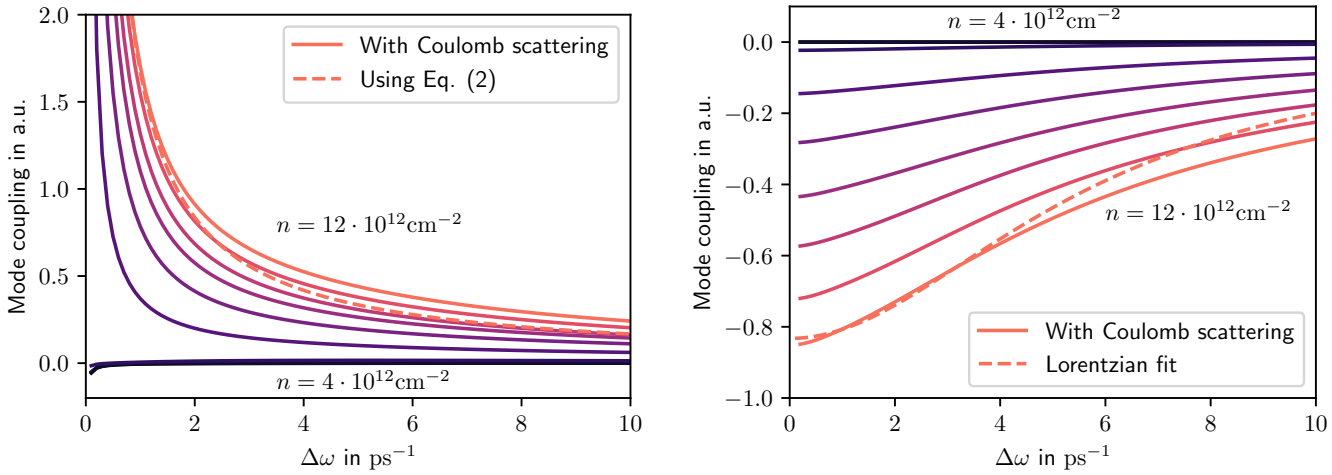

Fig. 2. Asymmetric (left) and symmetric (right) mode coupling terms shown as function of the frequency difference of the two longitudinal modes. Here one of the two modes is chosen to be at the gain maximum.

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

[1] Weig T, Hager T, Brüderl G, Strauss U and Schwarz U T 2014 *Optics Express* **22** 27489
[2] Thränhardt A *et al.* 2004 *Applied Physics Letters* **85** 5526–5528
[3] Ahmed M and Yamada M 2002 *IEEE Journal of Quantum Electronics* **38** 682–693
[4] Piprek J 2007 *Nitride Semiconductor Devices: Principles and Simulation* (Wiley) ISBN 9783527610716

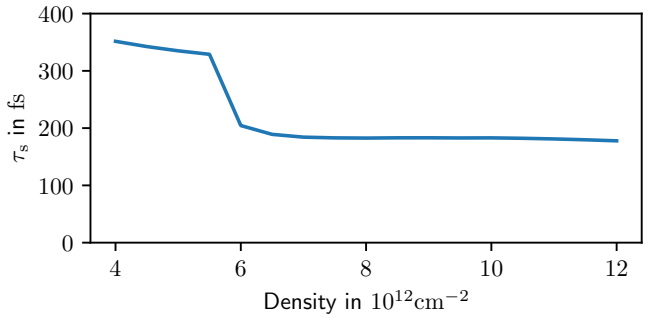

Fig. 3. Scattering times obtained by fitting a Lorentzian to the symmetric mode coupling term as a function of the carrier density.