Cascading enables ultrafast gain recovery dynamics of quantum dot semiconductor optical amplifiers

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1 Introduction

Quantum dot (QD) optical amplifiers are promising candidates for future high speed telecom applications with low operation currents, high temperature stability, low chirp and ultrafast gain recovery dynamics and hence pattern effect free amplification at high bit rates.

Motivation

- Establish theoretical model for QD SOAs incorporating microscopic Auger scattering contributions for transitions between ground state (GS), excited state (ES), and the carrier reservoir (QW) [1, 2, 3].
- Determine the dominant contribution of carrier scattering processes to the ultrafast gain recovery dynamics [4, 5, 6].
- Investigate spectral properties and linewidth enhancement factor.
- Treat electro-optical interactions using semiconductor Bloch equations also in the QW.

2 Model

Bloch Equations for interband polarizations \( p_{\text{sp}} \) and QD carrier occupation probabilities \( \rho_{\text{cap}} \) coupled to a reservoir \( \rho_{\text{rel}} \):

\[
\frac{\partial \rho_{\text{cap}}}{\partial t} = -\text{Im} \left[ \chi_0 \rho_{\text{cap}} \right] + \frac{1}{\hbar} \sum_{j=1}^{2} \delta_0 \left( \rho_{\text{sp}} \right)_{j}\frac{1}{\hbar}
\]

\( \omega_{\text{rel}} \) - 2 \( \sum_{j=1}^{2} \delta_0 \left( \rho_{\text{sp}} \right)_{j} \)

QW Bloch equations:

\[
\frac{\partial \rho_{\text{rel}}}{\partial t} = -\text{Im} \left[ \chi_{\text{QW}} \rho_{\text{rel}} \right] + \frac{1}{\hbar} \sum_{j=1}^{2} \delta_0 \left( \rho_{\text{sp}} \right)_{j}\frac{1}{\hbar}
\]

\( \omega_{\text{rel}} \) - 2 \( \sum_{j=1}^{2} \delta_0 \left( \rho_{\text{sp}} \right)_{j} \)

\( \sigma \): index of QD subensemble

- \( \epsilon_{\text{GS}} \): Rabi frequency

• Gain: \( g(\omega, \chi) = -\text{Im} \left[ \chi_{\text{QW}}(\omega) / \epsilon_{\text{QW}}(\omega) \right] \)

Temperature: \( T(\omega_0) = 3.7 \times 10^{-10} + 300.0 \)

3 Nonlinear Auger scattering rates [7, 8]

Coulomb scattering contributions split into capture (\( R_{\text{cap}} \)) and relaxation (\( R_{\text{rel}} \)).

Direct capture (\( R_{\text{cap}} \))

Boltzmann equation:

\[
R_{\text{cap}} = \frac{2 \pi}{\hbar} \sum_{i<j} \int V_{\text{sc}} \text{det} \left( \chi_{\text{QW}} \right) \left[ \delta(1 - \rho_{\text{cap}}) \delta(1 - \rho_{\text{rel}}) \right] \text{det} \left( \chi_{\text{QW}} \right) \left[ \delta(1 - \rho_{\text{cap}}) \delta(1 - \rho_{\text{rel}}) \right]
\]

with scattering rate:

\[
\frac{\partial \rho_{\text{cap}}}{\partial t} = \chi_{\text{QW}} \rho_{\text{rel}} - \chi_{\text{QW}} \rho_{\text{cap}}
\]

Screened Coulomb matrix element involving QD and QW wave functions.

Relaxation (\( R_{\text{rel}} \))

In-scattering rates increase monotonically until Pauli blocking sets in.

Out-scattering is related to in-scattering via detailed balance [1].

4 Gain spectra (T=300K)

- QW has a great impact on the spectral properties.

Linewidth enhancement factor \( \alpha \)

Linewidth enhancement factor describes the amplitude-phase coupling and is defined as:

\[
\alpha(\omega) = \frac{\text{Im} \left( \chi_{\text{QW}}(\omega) / \epsilon_{\text{QW}}(\omega) \right)}{N} \text{total carrier density}
\]

\( \alpha \) is a pure QD system has a lower \( \alpha \) factor \( \alpha > 1 \).

QDs embedded in a QW show a larger \( \alpha \) factor \( \alpha > 3 \).

5 Pump-probe experiments

Gain recovery dynamics (experiment and theory)

- Gain recovery dynamics with temperature dependent microscopic scattering rates show very good agreement to the experiment. (Experimental data: U. Wagen, TU Berlin)

6 Conclusion

A systematic microscopic analysis of different Auger scattering channels combined with a fully nonlinear simulation of the coupled polarization and population dynamics of carriers has established that cascading Coulomb scattering processes constitute the major contribution to the ultrafast recovery dynamics of QD SOAs. While a coherent treatment of the QW has a strong influence on spectral properties and the linewidth enhancement factor of QD-QW systems it does not show a great impact on the ultrafast gain recovery dynamics of QD SOAs. This work is supported in the framework of Sfb 787.

References


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