Ultrafast Characteristics of Quantum Dot Amplifiers

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Outline

• Ultrafast optical spectroscopy in semiconductor optical amplifiers: heterodyne pump-probe experiment

• Measurements in quantum-dot amplifiers:
  gain and refractive index dynamics
dephasing time from 300K to 10K
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Semiconductor optical amplifier (SOA)

Lasing action inhibited by titling and/or anti-reflection coating the end facets

Single pass amplification:

\[ |E_{\text{out}}|^2 = e^{(\Gamma g - \alpha) L} |E_{\text{in}}|^2 \]

- \( g(I_C) \): material gain
- \( \alpha \): losses
- \( \Gamma \): confinement factor

\[ \Gamma = \frac{\int_V |E|^2 \, d^3r}{\int_{-\infty}^{+\infty} |E|^2 \, d^3r} \]

V: active volume
Ultrafast optical spectroscopy in SOA’s

Pump-probe experiment: ~100fs optical pulses

\[
\begin{align*}
\text{without pump:} & \quad |E_0|_{\text{out}}^2 = |E|_{\text{in}}^2 e^{G_0L} \\
\text{with pump:} & \quad |E|_{\text{out}}^2 = |E|_{\text{in}}^2 e^{G(\tau)L} = |E|_{\text{in}}^2 e^{(G_0+\Delta G(\tau))L}
\end{align*}
\]

Differential transmission intensity:

\[
\frac{|E|_{\text{out}}^2}{|E_0|_{\text{out}}^2} = \frac{|E|_{\text{out}}^2 - |E_0|_{\text{out}}^2}{|E_0|_{\text{out}}^2} + 1 = e^{\Delta G(\tau)L}
\]

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Heterodyne detection:

- co-polarized and co-propagating pulses
- sensitive to electric field $I_{\text{det}} \propto E_{\text{ref}} E_{\text{signal}}$ (gain and refractive index dynamics)
- able to measure third-order coherent signal (four-wave mixing $\Rightarrow$ dephasing time)

K. Hall et al., Optics Lett. 17, 874 (1992)
A. Mecozzi et al. Optics Lett. 21, 1017 (1996)
InGaAs quantum dot optical amplifier

- Electrical injection
- Ridge waveguide 5µm x L (0.5, 1mm)
- 10° tilted facets

3 stacked QD layers
35nm GaAs spacers
Areal dot density ~2x10^{10} cm^{-2}

Inhomogeneous broadening: 60meV
GS-ES separation: 65meV
Confinement to wetting layer ~220meV
State Filling versus Injection Current

gain $\propto f_e + f_h - 1$

GS absorption:

GS gain:

transparency

saturation

Spectral gain at 2, 4, 6, 8, 10, 15, 20, 25mA

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Differential Transmission at 300K

\[
\Delta G (dB) = 20 \times \log (1 + \Delta T/T)
\]


Ultrafast gain recovery (high-speed applications)

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Ground state vs excited state gain dynamics

**Ground state**
- $\tau_1 = 450\,\text{fs}$
- $\tau_2 = 6.3\,\text{ps}$
- $G(\text{dB})$ vs $P(\text{ps})$

**Excited state**
- $\tau_1 = 290\,\text{fs}$
- $\tau_2 = 2.5\,\text{ps}$
- $G(\text{dB})$ vs $P(\text{ps})$

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Gain dynamics

Optical signal transmission at high bit rate limited from slow gain recovery of the excited states

Pulse width: 150 fs
Ground-state gain recovery: ~ 100 fs
Excited-state gain recovery: ~ 5 ps

We measure a fast (< 1 ps) gain recovery of both GS and ES!

T.W. Berg et al., IEEE PTL 13, 541 (2001)
Refractive Index Dynamics: The $\alpha$-Parameter

S. Schneider, P. Borri et al., IEEE JQE accepted (2004)

Pump-induced phase change of the probe
$\Delta \Phi = \Delta n(2\pi L/\lambda) \Rightarrow$ refractive index change

$$\alpha = -\frac{4\pi}{\lambda} \left( \frac{d\Delta n}{dN} \right) = -20 \cdot \log(e) \frac{\Delta \Phi (rad)}{\Delta G (dB)}$$

- at $I_C < 2\text{mA}$ the LEF is below 1
- LEF increases with increasing $I_C$
Temperature-Dependent Gain Dynamics

The ultrafast gain recovery depends on bias current and temperature:

The thermal occupation of the excited states is quenched at low temperature for low bias current $\Rightarrow$ slower gain recovery


Ultrafast gain-recovery *once the excited states are occupied with several carriers:*
Low-Temperature Gain Dynamics

A macroscopic configuration is a superposition of microstates. The probability of a specific microstate varies with $I_C$, but each microstate has a given internal dynamics.

We have consistently fitted the DTS data with 4 time constants $\tau_1...\tau_4$ of amplitudes $A_1...A_4$.

After the removal of one $e_0h_0$ by the pump photons microstates with a high number of carriers in the excited states undergo a fast relaxation dynamics modeled by $\tau_1 = 0.33 \pm 0.05\text{ps}$.

Microstates with only one carrier in the excited states have only one relaxation channel modeled by $\tau_2 = 4 \pm 0.3\text{ps}$, $\tau_3 = 35 \pm 4\text{ps}$ for a hole, electron.
Dephasing Time of the 0-X Transition


Without electrical injection, the optical transition 0-X from the crystal ground state to the ground-state exciton in the QD is probed.

At T=7K the long exponential decay dominates the dynamics with a dephasing time of 630 ps corresponding to only 2\(\mu\)eV homogeneous broadening.

At 300K the fast 0.2ps dephasing correspond to 6.6meV homogeneous broadening!

See also:
D. Birkedal et al., PRL 87, 227401 (2001);
M. Bayer and A. Forchel, PRB 65, 041308(R) (2002);
Below 100K, the homogeneous lineshape consists of a narrow Lorentzian line, corresponding to the long exponential decay, and a broad non-Lorentzian band corresponding to the initial fast dephasing.

L. Besombes et al. PRB 63, 155307 (2001)  
B. Urbaszek et al. PRB 69, 035304 (2004)  

Similar findings in photoluminescence spectra of single QDs!

Theory: pure dephasing from coupling with acoustic phonons  
B. Krummheuer et al. PRB 65 195313 (2002)  
With increasing $I_C$ the FWM decay is faster, i.e. the ZPL broadens due to Coulomb interaction with the injected carriers.

For $I_C > 14\text{mA}$ the majority of dots is occupied by two $e_0 h_0$ excitons. When several carriers occupy the excited states, the multiexcitonic transition:

\[ X^n \rightarrow (X^{n-1})^* \]

has a strong final state damping due to the quick relaxation of the $(X^{n-1})^*$ state (which we measure in differential transmission).

The biexciton to exciton transition (XX-X) has a much smaller final state damping than the $X^n-(X^{n-1})^*$ and is distinguished by the long FWM decay.
Dephasing versus Relaxation of Multiexcitonic Transitions

$X^n (X^{n-1})^*$


At 295K pure dephasing processes given by phonon and Coulomb interactions dominate.

\[ \frac{1}{T_2} = \frac{1}{2T_1(I_C, T)} + \frac{1}{T_{2_{ph}}(T)} + \frac{1}{T_{2_{ee}}(I_C)} \]

At 295K pure dephasing processes given by phonon and Coulomb interactions dominate.

\[ X^n \rightarrow (X^{n-1})^* \]

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Dephasing versus Relaxation of Multiexcitonic Transitions

\[ X^n - (X^{n-1})^* \]

\[ \gamma (\text{meV}) \]

- **295K**
  - \( \gamma_h \)
  - \( \gamma_1 \)

- **220K**
  - \( \gamma_h \)
  - \( \gamma_1 \)

- **150K**
  - \( \gamma_h = \frac{2\hbar}{T_2} \)
  - \( \gamma_1 = \frac{\hbar}{T_1} \)

- **25K**
  - \( \gamma_h \)
  - \( \gamma_1 \)

**At 150K** the pure dephasing is given only by phonon interaction

**P. Borri et al. IEEE J. Sel. Topics Q. El. 8, 984 (2002).**

Population relaxation

Pure dephasing from phonon interaction

\[ \frac{1}{T_2} = \frac{1}{2T_1(I_C, T)} + \frac{1}{T_{2,ph}(T)} + \frac{1}{T_{2,ee}(I_C)} \]
Dephasing versus Relaxation of Multiexcitonic Transitions

\[ X^n - (X^{n-1})^* \]


At 25K the broadening is fully given by the population relaxation without pure dephasing.

\[ \frac{1}{T_2} = \frac{1}{2T_1(I_C, T)} + \frac{1}{T_{2,ph}(T)} + \frac{1}{T_{2,p}(I_C)} \]

population relaxation

pure dephasing from Coulomb interaction

pure dephasing from phonon interaction

\[ \gamma_h = \frac{2\hbar}{T_2} \]

\[ \gamma_1 = \frac{\hbar}{T_1} \]
Summary

• At 300K:
  • Ultrafast (~100fs) gain recovery dynamics in InGaAs QD amplifiers
  • Large homogeneous broadening (10-20meV) i.e fast dephasing due to phonon and Coulomb interactions (dominantly pure dephasing)

• Gain recovery is slower (~ps) at low temperature and injection current: fast gain recovery dominated by dots with several carriers in the excited states (i.e. multiexcitons)

• Dephasing (of multiexcitonic transitions) dominated by population relaxation dynamics < 30K