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Attaining Near-Zero Linewidth Enhancement in Quantum-Dot Semiconductor Optical Amplifiers

Ö.E. Aşırım* (1), C. Jirauschek (1)

(1) TUM School of Computation, Information and Technology, Technical University of Munich, Hans-Piloty-Str. 1, 85748 Garching, Germany

Abstract

This paper presents a numerical approach to achieve near-zero linewidth enhancement (LE) in Quantum Dot Semiconductor Optical Amplifiers (QD-SOAs). The focus is on leveraging discrete energy levels and the corresponding tunability of Quantum Dots (QDs) to minimize carrier fluctuations by examining QD carrier concentration, tuning the QD emission frequency, and investigating the carrier collision rate to assess the influence of the non-radiative process in LE. The objective is to come up with the optimal electronic structure for QD-SOAs regarding LE minimization and enhanced beam coherence. Numerical simulations demonstrate results consistent with empirical findings.

1. Introduction

The linewidth enhancement factor (α-factor) serves as an important metric in assessing how the refractive index of the active region of a semiconductor optical device evolves with carrier density [1,2]. A high refractive index variation within the active region is often the source of operational instabilities due to the corresponding large variation in carrier and photon lifetimes. A semiconductor device with a low α-factor signifies a suppression in LE, allowing for improved beam coherence by mitigating refractive index fluctuations in response to changes in carrier density throughout its operation [3,4]. This characteristic is highly desirable in optical communication systems regarding signal to noise ratio. QD-SOAs have drawn significant attention due to their potential advantages over traditional Semiconductor Optical Amplifiers (SOAs), one of which is their lower α-factor [3]. The α-factor in QD-SOAs depends on various factors, including the quantum dot material and size, composition and structure of the active region, and the overall gain characteristics of the active region [5,6]. This study aims to investigate the variation of the α-factor in QD-SOAs with respect to the carrier density and the transition frequency of the quantum dots (QDs), which strongly influence all of the aforementioned factors. Through this exploration, we propose a strategic approach for the suppression of the α-factor in QD-SOAs, fostering their employment in photonic devices and applications requiring high optical coherence [3,5].

2. Formulation

The carrier density (N) and the photon density (S) in the active region of a QD-SOA can be evaluated by the rate equations,

$$\frac{dN}{dt} = \frac{\xi_{in} I}{eV} - \frac{N}{\tau_c} - \Gamma G(\omega) S \quad (1)$$

$$\frac{dS}{dt} = \Gamma G(\omega) S - \frac{S}{\tau_p} + \frac{N}{\tau_r}\,, \ \tau_p = \frac{n_{eff} L}{c},\ \tau_r = \frac{1}{BN_{QD}} \quad (2)$$

where the carrier lifetime τ_c, collision time T_c, gain per unit length G, and the QD permittivity ε_{QD} are given as [5]

$$\tau_c = 1/(A + BN_{QD} + CN_{QD}^{\ 2}),\ T_c = K/N_{QD},$$

$$G(\omega) = \frac{(N - N_{th}) \times \left(\frac{\lambda^2}{8\pi\tau_r}\right) \times \left(\frac{\Omega}{2\pi}\right)}{(\omega - \omega_{QD})^2 + \left(\frac{\Omega}{2}\right)^2},\quad \Omega = \left(\frac{2\pi}{\tau_c} + \frac{2\pi}{T_c}\right)$$

$$\varepsilon_{QD}(\omega) = \varepsilon_1 + \left\{\frac{(N_{QD} e^2)/(m\varepsilon_0)}{\omega_{QD}^{\ 2} - \omega^2 - i\Omega\omega}\right\} \quad (3)$$

I: Current, Γ: Confinement factor
n_{eff}: Effective refractive index, λ: Wavelength
c: Speed of light, e: Unit charge
ξ_{in}: Current injection efficiency
τ_p: Photon lifetime, V: Volume,
τ_r: Radiative recombination lifetime
ω: Angular frequency, N_{th}: Threshold carrier density
ω_{QD}: Transition frequency of Quantum Dots
m: Electron mass, ε_0: Permittivity of free space
A: Trap, impurity, or defect based recombination coefficient
ε_1: Background permittivity of the QD material
B: Radiative recombination coefficient,
C: Auger recombination coefficient, L: Length
K: Collision constant, Ω: Linewidth, h: Planck constant

Here the emission frequency of a QD depends on its dimensions (d_1, d_2, d_3) based on the relation

$$\omega_{QD} = \omega_c + \pi h({k_1}^2 + {k_2}^2 + {k_3}^2)/m,$$

where

$$k_1 = \frac{q_1\pi}{d_1},\ k_2 = \frac{q_2\pi}{d_2},\ k_3 = \frac{q_3\pi}{d_3} \qquad (4)$$

$$q_1 = 1,2,3,\ldots \ ,\ q_2 = 1,2,3,\ldots \ ,\ q_3 = 1,2,3,\ldots$$

If one assumes that all carriers in the active region of a QD-SOA are captured by the QDs, the QD carrier density N_{QD} can be approximated as

$$N_{QD} \approx N\frac{V}{M \times V_{QD}} = \frac{N}{\Delta},\quad M: Number\ of\ QDs \quad (5)$$

Using the QD inclusion ratio Δ, the effective permittivity and refractive index of the active region of an InGaAs/GaAs QD-SOA can be found using the Maxwell-Garnett medium-mixing formula,

$$\varepsilon_{eff} = \varepsilon_{QD}\frac{2(1-\Delta)\varepsilon_{QD} + (1+2\Delta)\varepsilon_2}{(2+\Delta)\varepsilon_{QD} + (1-\Delta)\varepsilon_2},\quad n_{eff} = \sqrt{\varepsilon_{eff}} \qquad (6)$$

$$\varepsilon_2: Background\ permittivity\ of\ the\ active\ region\ material\ (GaAs)$$

from which the α-factor is evaluated as $\alpha \approx \frac{\partial[Re\{n_{eff}\}]}{\partial N} / \frac{\partial[Im\{n_{eff}\}]}{\partial N}$.

Based on this formulation, the variation of the α-factor is plotted against InGaAs/GaAs QD-SOA operation frequency and QD carrier density in Figures 1-3. The variations of the α-factor follow the empirical relation in [1] and indicate its suppression under decreasing carrier concentration within the QDs, particularly when the transition frequency (TF) of the dots is tuned away from the operation bandwidth (Figure 4). QDs with lower carrier collision rate (greater T_c) indicate a lower α-factor, which suggests the use of QDs with a greater material constant K (Figure 2). These observations postulate the use of maximum number of QDs with the lowest possible carrier collision rate and a detuning of the QD transition frequency from the operation bandwidth as a means to abdicate from the gain per unit length for LE suppression.

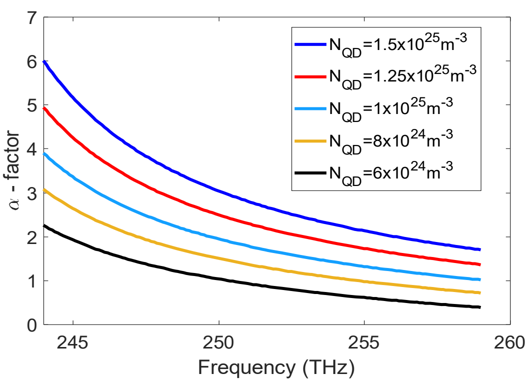

Figure 1. Variation of the α-factor within the operation bandwidth for $\boldsymbol{f_{QD} = 237.5}$THz. The α-factor decreases as the carrier concentration within the QDs gets lower.

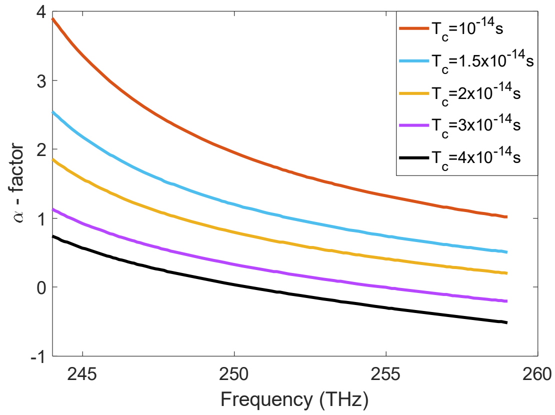

Figure 2. Variation of the α-factor within the operation bandwidth. The α-factor decreases as the carrier collision rate within the QDs gets lower.

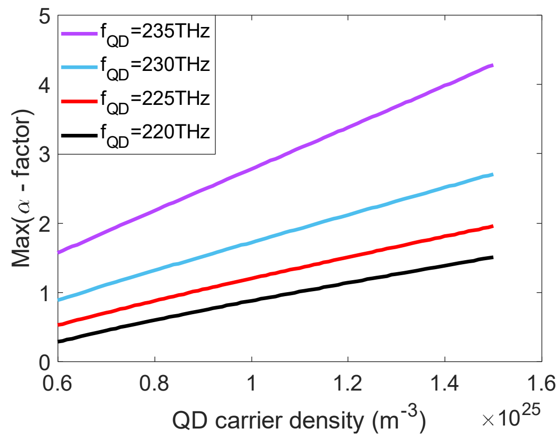

Figure 3. Variation of the maximum value of the α-factor within the operation bandwidth versus the QD carrier density. The α-factor increases as the emission frequency of the QDs gets closer to the operation bandwidth.

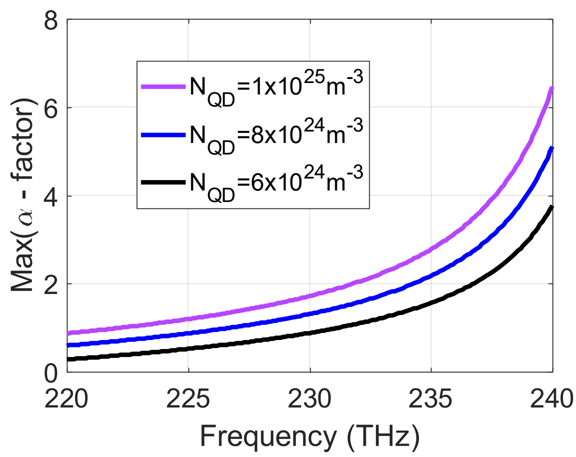

Figure 4. Variation of the maximum value of the α-factor against QD emission frequency f_{QD}. The maximum value of the α-factor increases as the emission frequency of the QDs move towards the operation bandwidth.

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