Four-Wave Mixing and Rabi Oscillations in Quantum-Dot Semiconductor Optical Amplifiers

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***Abstract*—Using a self-consistent delay-differential-equation model for the description of the nonlinear light propagation in InAs/InGaAs quantum-dot-in-a-well semiconductor optical amplifiers, we analyze the amplifier in a four-wave-mixing setup in terms of the conversion efficiency. Our model allows us to extract the hierarchy of nonlinear effects that constitute the four-wave-mixing process. We show that spectral hole burning in the quantum-dot medium facilitates wavelength conversion over a spectral detuning of several THz, whereas the effect of carrier heating and global carrier-density pulsations is found to be negligible. Furthermore we show that for high optical field amplitudes the emergence of Rabi oscillations leads to a flattening of the conversion efficiency, potentially allowing for ultra-broad-band wavelength conversion and frequency comb generation.**

I. Introduction

Four-wave mixing (FWM) is a nonlinear optical process that is regularly used for nonlinear wavelength conversion or the creation of optical frequency combs from two or more input fields [1], [2]. It has a variety of applications in spectroscopy, metrology and optical data communication [3]–[6]. Quantum-dot semiconductor optical amplifiers (QDSOAs) based on InAs/InGaAs are a promising nonlinear medium for efficient FWM around the telecommunication wavelength of 1.3 μm [7], [8]. Furthermore, such devices were shown to exhibit pronounced Rabi oscillations due to their relatively long dephasing time, making their signature observable even at room temperature [9]. In this work, we numerically investigate the performance of such QDSOAs and determine the internal mechanisms that contribute to the FWM process. In particular, we consider the limit of high optical intensities, where Rabi oscillations become important, and we investigate the interplay of the Rabi oscillations with the FWM process.

II. Model

We describe a 3 mm long QDSOA device with a 3 μm wide ridge waveguide structure, with an active medium consisting of $a_L = 10$ InGaAs quantum-well (QW) layers (thickness $h^{QW} = 5\,\text{nm}$), each embedding a density of $N^{QD} = 3 \times 10^{10}\,\text{cm}^{-2}$ InAs QDs. The energy structure across one QD is sketched in Fig. 1 [10]. We describe the electric field propagation along the QDSOA device using a delay equation approach [11]. The device is discretized along the propagation axis z into 31 equally spaced points along the device. We consider a single-pass device, neglecting any backward-propagating fields. The slowly varying envelope of the forward-propagating electric field is then given by

$$E(z,t) = E(z-\delta z, t-\delta t) + \frac{1}{2}\left[S(z-\delta z, t-\delta t) + S(z,t)\right] \tag{1}$$

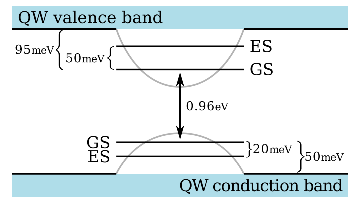

Fig. 1. Sketch of the energy structure across one QD within the QDSOA.

where δz is the distance between space discretization points, and $\delta t = \delta z / v_g$ is the corresponding propagation time, with v_g the group velocity. The source terms $S(z,t)$ describe the stimulated emission process and are evaluated at each space discretization point:

$$S(z,t) = \frac{i\omega\Gamma}{\varepsilon_0 \varepsilon_{bg}} \sum_j \mu^* p^j(z,t) \tag{2}$$

Here, ω is the optical center frequency, Γ is the optical confinement factor, ε_{bg} is the background permittivity. The summation index j includes all QD transitions, with their dipole interaction moment μ_j and microscopic polarization $p_j(z,t)$. We consider the ground and first excited state for electrons and holes in an inhomogeneously broadened QD ensemble, described by the following dynamic equations for electrons (e) and holes (h). Each QD state is labeled by an index j, characterized by its transition frequency ω^j:

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho^j_{e,h} = -W\rho^j_e\rho^j_h - \mathrm{Im}\left[\mu p^{j*} E(z,t)\right] + \left.\frac{\partial \rho^j_{e,h}}{\partial t}\right|_{\mathrm{sc}} \tag{3}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}p^j = -\left[i(\omega^j - \omega) + \frac{1}{T_2}\right]p^j - i\Omega(z,t)\left[\rho^j_e + \rho^j_h - 1\right] \tag{4}$$

Here, we describe the QD occupation probability $\rho^j_{e,h}$, with the spontaneous loss rate W and scattering terms $\left.\frac{\partial \rho^j_{e,h}}{\partial t}\right|_{\mathrm{sc}}$ [12] describing the charge-carrier exchange between the QDs and the surrounding QW charge-carrier reservoir. The light-matter interaction is included via the microscopic polarization p^j, which together with the dynamic equation for the corresponding occupation probability forms a set of optical Bloch equations for each QD transition. The microscopic polarization is driven by the optical field via the Rabi frequency $\Omega(z,t) := \frac{\mu_m E(z,t)}{2\hbar}$ and decays with a dephasing time T_2.

III. Results

The FWM in the considered QDSOA is investigated by injecting two monochromatic electric fields at the input facet: A pump field with amplitude E_1, centered at the QD ground

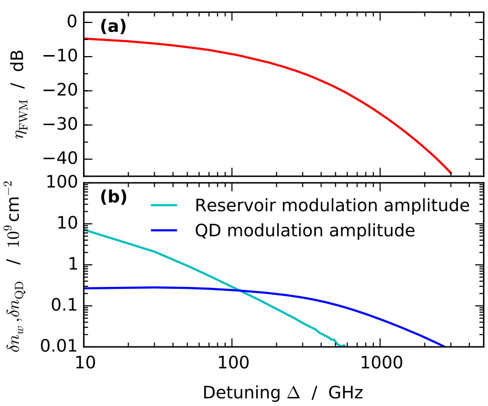

Fig. 2. **(a)** FWM conversion efficiency η_{FWM} and **(b)** the modulation amplitudes of the charge-carrier density in the QW reservoir (δn_w) and in the QD states (δn_{QD}) as a function of the input detuning Δ.

state transition energy, and a probe field with amplitude E_2, detuned by a frequency Δ with respect to the pump:

$$E(z=0,t) = E_1 + E_2 e^{2\pi i \Delta t} \tag{5}$$

A FWM signal is then created during propagation at a detuning of $-\Delta$ with respect to the pump. The FWM efficiency η_{FWM} is evaluated as the power ratio of the created FWM signal at the output facet and the probe signal at the input facet.

Figure 2(a) shows the FWM conversion efficiency for the QDSOA pumped at ten times the transparency current for pump and probe signal powers of 7.45dBm and 1.45dBm, respectively. An investigation of the oscillation amplitudes of the charge-carriers in the reservoir and QD states (Fig. 2(b)) reveals that the carrier-density pulsation, characterized by a strong modulation of the reservoir carrier density, is important only for detunings up to a few tens of GHz. The QD carrier density shows appreciable modulation amplitudes for detunings well beyond 1THz, showing that spectral-hole burning into the QD distribution is the driving effect for FWM at these high frequencies.

For higher input intensities, the Rabi frequency is in the order of 1THz. When the two input beams have a detuning close to this frequency, Rabi oscillations can be excited, leading to a relatively well pronounced resonance peak in the FWM efficiency that moves towards higher frequencies with increasing input power. This is shown in Fig. 3. For very strong input fields this leads to a relatively flat FWM conversion efficiency curve up to high detuning frequencies of several THz. A flat response curve is generally sought after for technical applications. This however comes at the cost of a reduced conversion efficiency for small detunings, as the gain is strongly reduced by the intense input fields.

IV. Conclusion

We have performed numerical simulations of the FWM conversion efficiency in InAs/InGaAs QDSOAs. We find that spectral hole burning in the QD ensemble provides high conversion efficiencies for detunings well above 1THz. For high input intensities, Rabi oscillations can be excited which may provide relatively flat conversion efficiency curves for

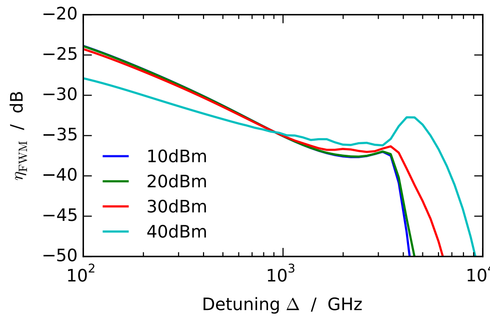

Fig. 3. FWM efficiency η_{FWM} for different probe input powers. The pump beam power is 40dBm.

detunings up to several THz at the expense of a reduced total efficiency.

Acknowledgment

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