Novel Time-domain Model of Quantum-Dot Semiconductor Optical Amplifiers for Wideband Optical Signals.

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Abstract- **We present a novel time-domain model for quantum-dot semiconductor optical amplifiers, which allows the calculation of phase- and power-based effects for optical signals with very broad spectra by using digital filters.**

I. INTRODUCTION

Quantum-dot (QD) semiconductor optical amplifiers (SOAs) have been extensively investigated during the last years due to the atom-like energy level structure. This allows to receive higher saturation power and gain recovery rate compare to bulk and quantum well devices. This behaviour may allow to receive paternless signal processing for high speed telecommunication signal.

II. CARRIER DYNAMIC AND SIGNAL PROPAGATION

To model a carrier dynamic in the device, all dots are splited into N groups, corresponding to their resonance energies, what gives an inhomogeneous broadening and has a normal distribution [1,2]. Each dot include three energy levels, ground state (GS), excited state (ES) and upper state (US), and carrier dynamics are described by multiple rate equations separately for each dot. Dots do not interact with each other directly, only throw the wetting layer (WL) which is common for all dots. Electron and holes dynamics are calculated separately to receive a better agreement with experimental results.

The usual way to model light propagation through a QD-SOA is to divide the optical power into many separate time-domain models with different centre frequencies, i.e. to create a “spectral resolution” for a signal and calculate the influence from each carrier group to each photon group [1,2]. All QDs are separated into many groups with different transition frequencies, corresponding to inhomogeneous broadening. All time-domain models do not interact with each other directly, only throught the gain (cross-gain modulation, XGM). Phase-based processes are not possible between them. This allows to include power-based effects for signals with different wavelengths and to calculate a carrier dynamic in a time.

To include phase-based effects, like a four-wave mixing (FWM), we have used one broad (50 THz, time step dt=20 fs) time-domain model for a complex envelope to include a signal phase. A frequency dependency of the gain is described by an approach of superposed digital filters [3], which have a Lorentzian shaped magnitude response, similar to the spectral characteristic of a singular QD. Each filter provide a gain corresponding to a material gain from each dot.

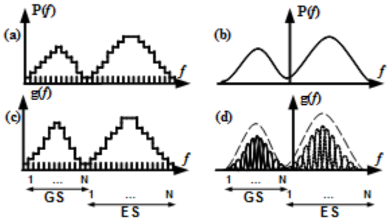

Figure 1: Optical power spectrum (top) and material gain (bottom) for a common (left) and presented (right) QD-SOA models

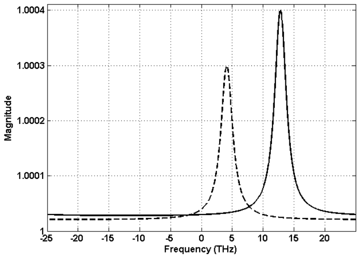

Figure 2: Magnitude responses of two digital filters

Figure 1 shows optical power spectrum $P(f)$ and gains $g(f)$ for a common QD-SOA model (left) where optical power is divided into multiple time-domain model and the presented modell (right). Homogeneous broadening depends on carriers scattering time and can be in a range from 10 meV for unsaturated device to 15 meV for a device with sufficient stimulating recombination.

Fig. 2 shows magnitude responses of two digital filters with different frequencies and gains. Coefficients for each filter are calculated separately in dependence of inhomogeneous broadening and resonance transition energies.

To obtain the required amplification and phase shift for one length step, the signal “propagate” series through all filters (all dots), see

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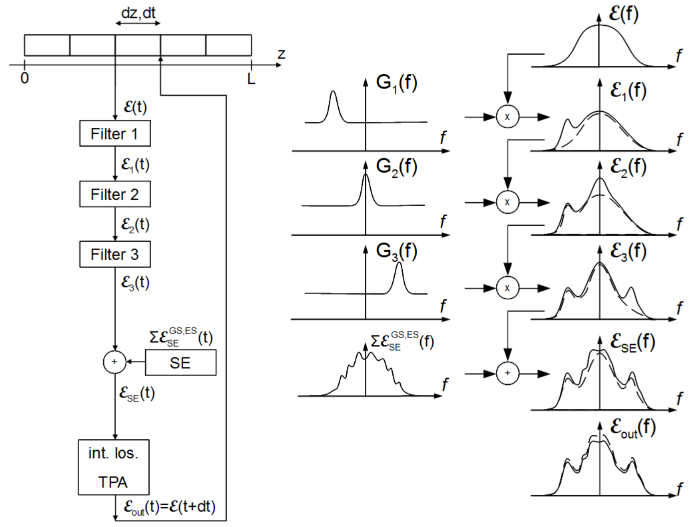

Figure 3: The principle of filter-based signal amplification for one length and time step. Left part show the signal processing schematically, right part represent corresponding spectrum: $\mathcal{E}(t)$ - input signal for current length step and $\mathcal{E}_n(t)$ - signal on the output of n-th filter. $\mathcal{E}_N(t)$ - output signal of the last filter, $\mathcal{E}_{SE}(t)$ - signal with spontaneous emission and $\mathcal{E}(t+dt)$ - output signal for the current step and input signal for next length step and time moment. Dashed line in the right part of the figure shows spectrum after the previously effect for a comparison.

Fig. 3. Each of initial signals $\mathcal{E}_{F,R}(t,l)$ (forward and reverse) series propagate through all digital filters that simulate matherial gain. Amplification value for each filter depends on carrier distribution for corresponding QD in this time moment. Stimulated recombination is calculated as a difference between optical powers on filters output and input. After that spontaneous emission (SE) in dependens of spontaneous recombination is added to both signals. Internal losses and two-photon absorption (TPA) are included as last effects. After that a forward signal propagate to the next segment $(l+dl)$, reverse signal - to the previous segment $(l-dl)$ and the simulation of next time moment $(t+dt)$ begins.

III. RESULTS AND DISCUSSIONS

The cross-gain modulation for a 2mm InGaAs/GaAs QD-SOA with 18 dB unsaturated gain is plotted in Fig. 4 for different injection currents and pulse repetition rates. The pump pulses (sech^2 1.9 ps FWHM, 10GHz, +4.5 dBm average power) wavelength was set to the ASE peak of the ground state (1310 nm), probe wavelength is 1302 nm. The fastest recovering occurs due to the TPA and retrace the shape of pump pulses. Two others consist of fast hole and slow electron transitions. Due to shorter transition times and p-doping, holes density recovering occur on the time scale of 30 ps, while electron recovering time has a scale of hundreds picoseconds and creates the slow recovering part. Modulation depth is decreasing for higher pulse repetition rate, because the device can not recover in shorter time between pulses. This leads to a smaller gain and therefore smaller gain suppression. Another reason is a decreasing of the pulse energy in case of equal average input power.

Figure 5 (left) shows the output spectra with a FWM for pump (λ_1=1310 nm, P_1=5.9 dBm) and probe (λ_2=1295 nm, P_2=5.9 dBm) CW signals and FWM efficiency for different detuning (right) and injected currents (λ_1=1310 nm, P_1=P_2=5.9 dBm). Higher efficiency can be received for small detuning between both signals. In this case cross-modulation occurs inside homogeneous broadening of one dot and the beating period is much higher then the transition times. The visible increasing of the efficiency for high detuning is not observed in the experiment and may occur in the simulation due to wrong phase dynamic, that should be in dependence of WL carrier dencity.

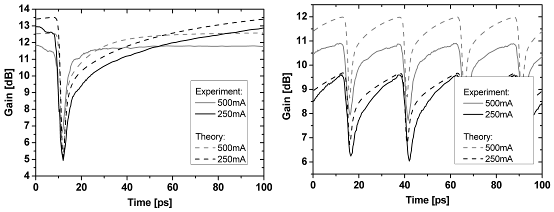

Figure 4: Pump-probe dynamics for 10 GHz (left) and 40 GHz (right) pulses

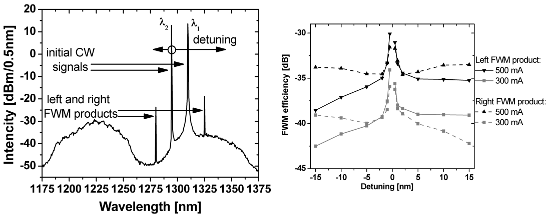

Figure 5: Fourier transformation of an output spectra with a FWM (left) and FWM efficiency (right).

IV. CONCLUSIONS

The presented model allows to simplify the calculation of nonlinear effects in QD-SOAs and in particular the interaction between two or more broadband optical signals during their propagation inside the device.

The model can be applied to the simulation of:

- power-based effects like cross-gain modulation,
- phase-based effects like four-wave mixing and cross-phase modulation.

This allow to model a QD-SOA devises for all-optical signal processing in telecommunication networks.

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