Simulation on Gain Recovery of Quantum Dot Semiconductor Optical Amplifiers by Rate Equation

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Abstract- **The gain recoveries in quantum dot semiconductor optical amplifiers are numerically studied by rate equation models. Similar to the optical pump-probe experiment, the injection of double optical pulses is used to simulate the gain recovery of a weak continuous signal for the QD SOAs. The gain recoveries are fitted by a response function with multiple exponential terms. For the pulses duration of 10 ps, the gain recovery can be described by three exponential terms with the time constants, and for the pulse with the width of 150 fs, the gain recovery can be described by two exponential terms, the reason is that the short pulse does not consume lot of carriers.**

I. INTRODUCTION

Quantum dot semiconductor optical amplifiers (QD SOAs) have great advantages as compared to traditional bulk and quantum well SOAs, among which ultrafast gain recovery character has attracted lot of attentions for the next-generation photonic networks. To demonstrate ultrafast gain recovery in QD SOAs, femtosecond pump-probe measurements were performed after single-pulse [1] and double-pulse [2] amplification in InGaAs QDs. In addition, two-color pump-probe measurements revealed ultrafast gain transients in the QD SOAs with a picosecond timescale of the hole recovery and intradot electron relaxation, 10 ps order of the electron capture time, and hundreds of picoseconds related to carrier recovery in the wetting layer [3]. Theoretically, rate equation models, with phonon and Auger-assisted carrier capture and relaxation modelled by relaxation times dependent on the occupation probabilities and Maxwell-Block equations, were applied to simulate the gain recovery in the QD SOAs [3-6]. Recently, slow phase recovery of QD SOAs is simulated in the case with four consecutive rectangular shape pump pulses [7].

In this article, detailed rate equation models are applied to simulate the gain dynamic characteristics in the QD SOAs, which was used to analyze the gain saturation, carrier distribution and noise figure in [8] and gain recovery in [9]. Similar to the pump-probe experiment, the gain recoveries are simulated for a weak continuous signal under two pump pulses with pulse widths of 10 ps and 150 fs. The pattern effects at different injection currents are observed, which are greatly reduced at high injection current. Furthermore, the obtained gain recoveries are fitted by a function with multiple exponential terms for extracting the response times. The results show that the gain recovery at the long wavelength gain peak can be described by three exponential terms for 10 ps pulse case, and two exponential terms for 150 fs pulse case.

II. RATE EQUATION MODEL

QD SOAs' dynamic model is established based on the envelope functions of the electric fields at the border between the consecutive sections [4] and the gain and rate equation model [5]. Four-order Runge-Kutta method is applied to solve the dynamic rate equations. The cavity length and stripe width are taken to be 1 mm and 2 μm, and time constants of carrier capture from WL to ES and relaxation from ES to GS are taken to be 1 and 0.2 ps, respectively. Two 10 ps or 150 fs rectangular pulses with 10 ps or 5 ps time interval are injected into the QD SOA, respectively, which has the wavelength of 1305.3 nm at gain peak of gain spectrum contributed by the GS carriers. Considering the quantum dots inhomogeneous broadening, Gauss functions are adopt with full-width at half –maximums (FWHM) Σ_{GS}/Σ_{ES}, which takes as 67/80 meV [10].

III. RESULTS AND DISCUSSIONS

The obtained gain spectra of the QD SOAs at injection current of 10, 20, 30, and 40 mA are plotted in Fig. 1, which varies from single peak to double peaks with the increase of the injection current, where the long-wavelength and the short-wavelength peaks are attributed to the ground and excited state transitions, respectively. The blue shift of the gain peaks with the increase of injection current is due to the band filling. Furthermore, the gain of ground state carriers saturates at low injection current, so the gain peaks move to the shorter wavelength at higher injection level due to the increase of gain contributed by excited state carriers.

Assuming two 10 ps rectangular pulses with power 20 mW and time interval 10 ps at wavelength 1308.2 nm are injected into the QD SOA, we calculate the gain recovery for a weak continuous signal at wavelength of 1305.3 nm. Fig. 2 shows the gain recovery of the QD SOA at the injection current of 20, 30, and 40 mA. According to the carriers variation process, the gain recovery can be fitted by the following relations:

$$G = G_0 - \sum_{i=1}^{3} A_i \exp[-(t-t_0)/\tau_i] \qquad (1)$$

The obtained lifetimes τ_1, τ_2, τ_3 and the corresponding amplitudes A_1, A_2 and A_3 versus the injection current are present in Table I. The time constants τ_1, τ_2, and τ_3 are related to three processes, i.e., carrier relaxation from the excited states to the ground states of the QDs, carrier captured by the excited states from the states of the wetting layer, and the carrier supply to the wetting layer, respectively.

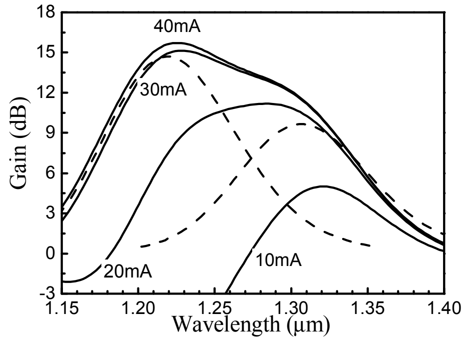

Fig. 1 Gain spectra of the QD SOAs at injection current of 10, 20, 30, and 40 mA, two dash lines represent the gain contributed by excited state carriers and ground state carriers at the injection current of 40 mA

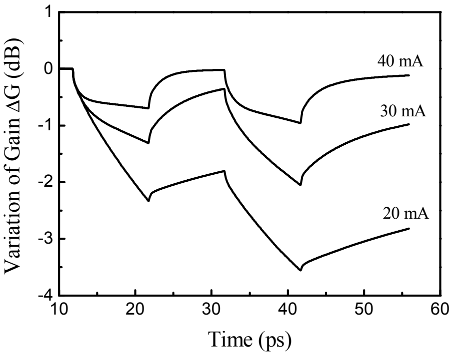

Fig. 2 Gain recovery for the weak continuous signal at wavelength of 1305.3 nm in the QD SOAs under two 10 ps rectangular input pulses at injection current is 20, 30, and 40 mA, respectively

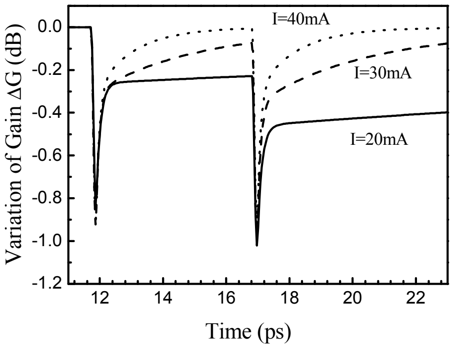

Fig. 3 Gain recovery for the weak continuous signal at wavelength of 1305.3 nm in the QD SOAs under two 150 fs rectangular width and 133.3 mW power with pulse interval of 5 ps at the injection of 20, 30, and 40 mA.

TABLE I FITTING RESULTS

Current (mA)	A_1	A_2	A_3	τ_1 (ps)	τ_2 (ps)	τ_3 (ps)	χ^2
20	0.199	0.104	4.32	0.202	3.73	73.6	2.2×10^{-7}
30	0.412	1.528	1.71	0.152	3.58	18.6	1.3×10^{-6}
40	0.468	1.477	0.116	0.127	1.71	15.0	2.0×10^{-6}

For comparison, two 150 fs rectangular pulses with power 133.3 mW and time interval 5 ps at the same wavelength are plotted in Fig. 3. The numerical results of gain recovery can be fitted by (1) with two exponential terms very well. Two time constants are obtained even by fitting with three exponential terms. We have τ_1 = 0.146, 0.120, and 0.119 ps, τ_2 = 4.137, 3.575, and 1.266 ps, and G_0 = 11.1, 14.0, and 14.3 at the injection current of 20, 30, and 40 mA, respectively, with the Chi-sqaures χ^2 in the order of 10^{-4}. The two time constants are corresponding to carrier relaxation from the excited state to the ground state, and carrier captured by the excited state from the wetting layer. Because the excited state has high occupation, the supplement of the wetting layer carriers is not exhibited in the case with such short pulses.

IV. CONCLUSIONS

The gain recoveries of QD SOAs are studied by rate equation models by simulating the gain variation caused by input pulse with 10 ps and 150 fs duration. The gain recoveries are simulated under different injection currents and then fitted by the function with multiple exponential terms. The results show that the gain recovery in the ground states under the 10 ps pulse of 20 mW power are mainly governed by three time constants of carrier relaxation from the excited state to the ground state of QDs, carrier capture from the wetting layer to the excited state, and the supply of carrier to the wetting layer. For the 150 fs pulse of 133.3 mW, only two time constants are obtained without the carrier supply to the wetting layer.

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