Investigation of Amplified Spontaneous Emission in Quantum Dot Semiconductor Optical Amplifier in Presence of Second Excited State

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Abstract—**In this paper, amplified spontaneous emission (ASE) in quantum dot semiconductor optical amplifier (QDSOA) is investigated. The presented theoretical model is based on set of rate equations that consider all possible carriers transitions including the second excited state (ES2) transition. These coupled equations are solved numerically. It is illustrated that the obtained ASE spectrum has three peeks which are related to ground, first excited and second excited states. Furthermore, optical gain for 500 fs Gaussian input pulse train is calculated. Based on the results, it is shown that in presence of ES2, gain recovery time and noise figure (NF) are reduced and the QDSOA can be used for ultra-high bit-rate signal processing (up to 450Gbps).**

I. Introduction

Quantum dots (QDs) based semiconductor devices such as QD laser and QD semiconductor optical amplifier (QDSOA) have characteristics like low injection current, weak temperature sensibility and wide bandwidth gain [1], [2]. These nanosize semiconductor islands can be grown via the Stranski-Krastanow growth mode under highly mismatched molecular beam epitaxy (MBE) [2]. Using these nanostructures in SOAs results in unique features like fast gain recovery, high saturation power, high optical nonlinearity, low noise figure (NF) and free pattern performance [3], [4]. Therefore, QDSOA can be a good replacement for bulk and quantum well SOAs, which are not able to process high bit-rate signals because of low gain recovery time. These features make QDSOA an ideal candidate for next generation of all optical networks.

Using coupled rate equations for carriers with propagation equation of signal is one of the conventional methods to model and analyze QDSOA. One approach considers electrons in conduction band (CB) and holes in valence band (VB) as excitons and rate equations are written for carriers [3], [5]. Another approach includes separate rate equations for electrons and holes [6]. In this paper, in order to involve homogeneous and inhomogeneous broadening of optical gain, electrons and holes act as excitons and rate equations are written for carriers. Furthermore, density matrix approach is used to achieve optical gain [3]. Based on the room temperature lasing report of second excited state (ES2) as well as ground state (GS) and first excited state (ES1) at high injection current [7] and structural similarity of QD laser with QDSOA, ES2 has been involved in the energy band diagram and rate equations of QDSOA. Based on presented model's results, ultra-fast gain recovery time can be achieved if QDs are grown in such a way that the presence of ES2 could be observable in transition processes. It is assumed that ES2 as well as ES1 and continuum state (CS) act as carriers' reservoirs. It is shown that in presence of ES2 gain recovery decreased and 450 Gbps input pulse train can be amplified without any pattern effect.

Generally, recombination processes in direct bandgap semiconductor devices are divided in two categories: radiative and nonradiative. There are two types of radiative recombination which are stimulated emission (SE) and amplified spontaneous emission (ASE). ASE is an effective factor in low power amplification regime and is the main optical field noise source in SOAs. This type of emission occurs due to spontaneous recombination of electrons in CB and holes in VB. ASE and gain saturation are two important mechanisms that degrade the signal quality in SOAs [2]. Furthermore small signal gain of SOA can be directly related to ASE [8]. NF of SOA can be also calculated numerically by analyzing of ASE power. Therefore, in this paper, propagation equation of ASE has been involved in the modeling of QDSOA. ASE spectrum and NF of QDSOA are investigated by taking into consideration of ES2 in the rate equations. It is shown that in the presence of ES2, ASE spectrum has three peaks which are related to GS, ES1 and ES2.

II. Simulation Results

In order to model QDSOA, rate equations have been written for carriers at GS, ES1, ES2, CS and wetting layer (WL) [9]. Homogeneous and inhomogeneous broadening of optical gain have been involved by grouping dots based on interband transition resonant frequency of GS between CB and VB. The homogeneous broadening is due to intrinsic gain of single dot and the inhomogeneous broadening is due to size distribution of QDs because of grown process. QDs and photon modes have been divided to $2M$+1 groups which M is a natural number and in this paper, M=400. Carriers in each state have $2M$+1 rate equations. Therefore, $8M$+5 rate equations with $2M$+1 propagation equations should be calculated numerically

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to analyze QDSOA performance. It is assumed that each QD is spatially isolated and exchange carriers only with WL. Furthermore, it is supposed that signal amplification is due to carrier recombination in GS of CB and VB. Upper states are supposed to be carrier reservoir. To solve the rate and propagation equations, the QDSOA is divided to 60 equal sections. Therefore at each section 4006 coupled differential equations should be simultaneously solved numerically.

First result has been obtained to show the improvement of QDSOA performance in the presence of ES2. Fig. 1 shows the optical gain as a function of time for a Gaussian pulse train for three cases: without ES2 and with ES2 at two different relaxation times. Input pulse width is 500 fs and its peak power is 40 mW, which give the average power of 21.3 mW. This pulse train bit-rate is 450 Gbps. Simulation parameters are the same as [3]. As it can be seen, gain recovery time has been improved in the presence of ES2. Furthermore, by reducing the relaxation time (τ_d) the recovery time has been decreased.

Fig. 2 illustrates the ASE power of QDSOA in the presence and absence of ES2. As it can be seen, in the presence of ES2, there are three peaks which are related to GS, ES1 and ES2. The main reason which gives such a high ASE power is the resonant energy and degeneracy of ES2. The effect of these parameters appear in optical gain equation. The NF of presented QDSOA is calculated using obtained ASE power spectrum with parameters mentioed in [3], [10]. For J=1 to 16 kA/cm^2 the NF is approximately constant and equal to 5.68 dB which is the same as [10]. But in the presense of ES2, the NF decreases to 5.2 dB for the same current densities which is comparable with experimental results shown in [2].

III. Conclusion

In this paper, QDSOA was modeled by taking into consideration of ES2 in band diagram and optical transitions. It was shown that high bit-rate signal processing (450 Gbps) was possible in the presence of ES2. ASE and NF of QDSOA was calculated numerically. Three peaks was obtained for ASE spectrum of QDSOA. Furthermore, NF of 5.2 dB was calculated in the presence of ES2.

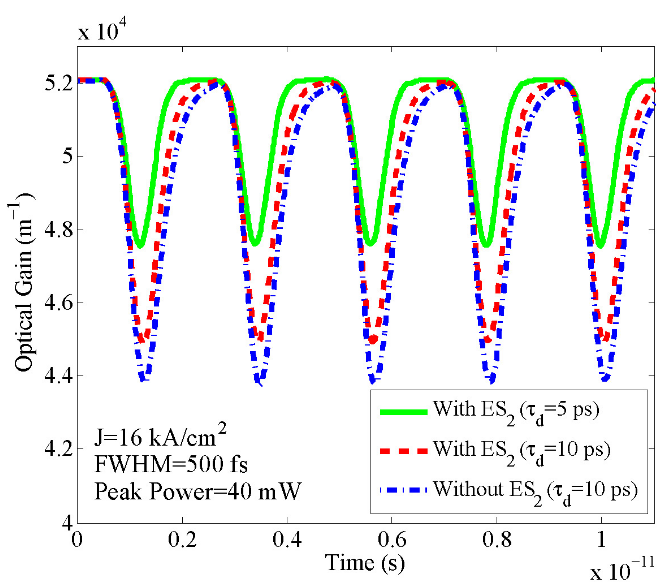

Fig. 1. Optical gain as a function of time for input Gaussian pulse train. Bit-rate is 450 Gbps.

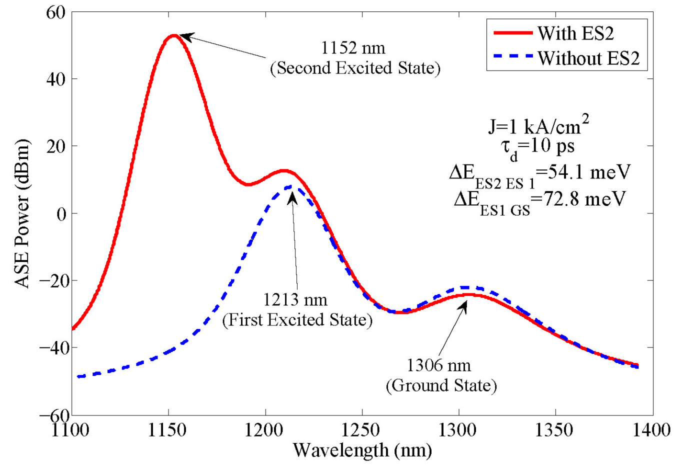

Fig. 2. ASE power vs. wavelength in the presence and absence of ES2.

References

[1] M. Sugawara and M. Usami, "Quantum dot devices: Handling the heat," *Nature Photonics*, vol. 3, no. 1, pp. 30–31, 2009.

[2] T. Akiyama, M. Ekawa, M. Sugawara, K. Kawaguchi, H. Sudo, A. Kuramata, H. Ebe, and Y. Arakawa, "An ultrawide-band semiconductor optical amplifier having an extremely high penalty-free output power of 23 dbm achieved with quantum dots," *IEEE Photonics Technology Letters*, vol. 17, no. 8, pp. 1614–1616, 2005.

[3] M. Sugawara, T. Akiyama, N. Hatori, Y. Nakata, H. Ebe, and H. Ishikawa, "Quantum-dot semiconductor optical amplifiers for high-bit-rate signal processing up to 160 gb s-1 and a new scheme of 3r regenerators," *Measurement Science and Technology*, vol. 13, no. 11, p. 1683, 2002.

[4] S. Dommers, V. V. Temnov, U. Woggon, J. Gomis, J. Martinez-Pastor, M. Laemmlin, and D. Bimberg, "Complete ground state gain recovery after ultrashort double pulses in quantum dot based semiconductor optical amplifier," *Applied physics letters*, vol. 90, no. 3, p. 033508, 2007.

[5] A. Bilenca and G. Eisenstein, "On the noise properties of linear and nonlinear quantum-dot semiconductor optical amplifiers: the impact of inhomogeneously broadened gain and fast carrier dynamics," *IEEE Journal of Quantum Electronics*, vol. 40, no. 6, pp. 690–702, 2004.

[6] M. van der Poel, E. Gehrig, O. Hess, D. Birkedal, and J. M. Hvam, "Ultrafast gain dynamics in quantum-dot amplifiers: Theoretical analysis and experimental investigations," *IEEE Journal of Quantum Electronics*, vol. 41, no. 9, pp. 1115–1123, 2005.

[7] S. Chen, K. Zhou, Z. Zhang, O. Wada, D. Childs, M. Hugues, X. Jin, and R. Hogg, "Room temperature simultaneous three-state lasing in hybrid quantum well/quantum dot laser," *Electronics letters*, vol. 48, no. 11, pp. 644–645, 2012.

[8] Q. Miao, D. Huang, D. Liu, T. Wang, and X. Zeng, "Rapid evaluation of gain spectra from measured ase spectra of travelling-wave semiconductor optical amplifier," *Chin. Opt. Lett.*, vol. 3, no. 8, pp. 483–485, 2005.

[9] S. M. Izadyar, M. Razaghi, and A. Hassanzadeh, "Quantum dot semiconductor optical amplifier: Role of second excited state on ultra high bitrate signal processing," *Applied Optics*, To be published, 2017.

[10] M. Sugawara, H. Ebe, N. Hatori, M. Ishida, Y. Arakawa, T. Akiyama, K. Otsubo, and Y. Nakata, "Theory of optical signal amplification and processing by quantum-dot semiconductor optical amplifiers," *Physical Review B*, vol. 69, no. 23, p. 235332, 2004.