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Carrier Temperature In Quantum Dot Optical Amplifiers

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Abstract

The effect of increasing of carrier temperature in wetting layer of semiconductor optical amplifier has been modeling. The occupation probability, carrier heating relaxation, spontaneous emission and free carrier absorption have been included in our formalization. The numerical calculations showed the occupation probability directly proportion with carrier heating time as a result of reduction of carrier density in wetting layer. Also, the reservoir carrier temperature is directly proportional with the full width at half maximum of injected pulse and carrier heating lifetime. The numerical calculations that are showed; the carrier heating in the rate equations satisfies the thermal equilibrium between the lattice and carriers.

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الخلاصة

ان تاثير ارتفاع درجة حرارة الحاملات في الطبقةالرخوة خلال عمل المضخم البصري الكمي شبه الموصل تم حسابها نظريا. ان احتمالية الاشغال , زمن الاسترخاء للحاملات الساخنة ,الانبعاثات المحفزة وامتصاص الحاملات الحرة كانت ضمن النموذج الرياضي الخاص بالعمل . ان الحسابات النظرية اظهرت ان الاشغال يتناسب طرديا مع زمن استرخاء الحاملات الحاملات الساخنة كنتيجة لانخفاض الحاملات في الطبقة الرخوة . لذلك فان تاثير درجة حرارة الحاملات تتناسب طرديا مع العرض عند منتصف الحزمة للنبضة الداخلة للمضخم وزمن الحاملات الساخنة . وقد اظهرت النتائج العددية ان تاثير الحاملات الساخنة في معادلات التغير الزمني يحقق الاتزان الحراري بين الشبيكة والحاملات .

1. Introduction

Carrier heating (CH) in Quantum dot semiconductor optical amplifiers (QD SOAs) has been attracted more attention in the last years [1-3]. Several of theoretical studies have been introduced for simulating nonlinear gain coefficients and carrier temperature in quantum dot structure [4-7]. From the theoretical results [8,9], it is become clear that the carrier heating and spectral hole burning effected strongly on nonlinear gain coefficient. Carrier heating and spectral hole burning in semiconductor optical amplifiers defined the gain suppression which strongly related with modulation bandwidth [10] and four-wave mixing [11,12].

The major sources of heating effects in semiconductors are current injection, stimulated emission, Auger process and free carrier absorption (FCA). The injected carriers must release their access energy before reaching the lowest energy subbands. This energy will contribute to increase carrier temperature [6]. In stimulated emission the "cold carriers" which are close to the band edge are removed [13]. The FCA mechanism includes photon absorption by the interaction of free carriers within the same band [14]. This process transforms the carriers into higher energy states, and consequently the temperature and energy of the carriers will increase. As the temperature of the carriers is higher than that of the lattice, thermalization will occur where the carriers transfer their excess energies to the crystal lattice through interaction with phonons [15].

In this paper, a theoretical model has been introduced to simulate carrier temperature in QD SOAs taking into account carrier reservoir. This model is more general than the model introduced by [3,16], which included the most of heating sources and inclusion of excited state which does not studying earlier.

2. Carrier Heating Temperature Model

The carrier dynamics are described by the rate equations for electrons in GS, ES, and WL which is serving as a carrier reservoir. This is because of the much larger effective mass of holes and lower quantization energies of QD levels in the valence band results in a faster relaxation of holes. Therefore, electrons behavior limits the carrier dynamics [17]. It is assumed that carriers are injected directly from the contacts into WL and thus, the barrier dynamics are ignored. The rate equations in the QD SOA can be written as [18]

$$\frac{dN_w}{dt}=\frac{J}{eL_w}-\frac{N_w(1-f_{ES})}{\tau_{w2}}+\frac{N_w f_{ES}}{\tau_{2w}}-\frac{N_w}{\tau_{wr}} \qquad (1)$$

$$\frac{df_{es}}{dt}=\frac{N_w L_w (1-f_{ES})}{NQ\,\tau_{w2}}+\frac{f_{GS}(1-f_{ES})}{\tau_{12}}-\frac{N_w L_w f_{ES}}{NQ\,\tau_{2w}}-\frac{f_{ES}(1-f_{GS})}{\tau_{21}} \qquad (2)$$

$$\frac{df_{ys}}{dt}=\frac{f_{ES}(1-f_{GS})}{\tau_{21}}-\frac{f_{GS}(1-f_{ES})}{\tau_{12}}-\frac{f_{GS}{}^{2}}{\tau_{1r}}-a(2f_{GS}-1)S \qquad (3)$$

where N_w is the carrier density in WL. f_{GS} and f_{ES} are occupation probabilities in GS and ES respectively, *e* is the electron charge, τ_{w2} is the carrier relaxation time from WL to the ES, τ_{2w} is the carrier escape time from ES to WL, τ_{wr} τ_{1r} are the spontaneous radiative lifetimes in WL and QDs, respectively, *NQ* is the surface density of QDs, L_w is the effective thickness of the active layer, τ_{21} is the carrier relaxation time from ES to GS, and τ_{12} is the carrier escape time from GS to ES. From density matrix theory, the carrier density and energy density in wetting layer defined as [2],

$$N_w(t)=\frac{1}{V}\sum_k \rho_{\alpha,k}(t) \qquad (5)$$

$$U_\alpha(t)=\frac{1}{V}\sum_k \rho_{\alpha,k}(t)\,E_{\alpha,k} \qquad (6)$$

Where ρ is the density operator, $N_w(t)$ and $U_\alpha(t)$ are the carrier density and energy density in wetting layer. Using Eq. (5 and 6) and summing over *k*, one obtains

$$\frac{dU_\alpha}{dt}=\frac{I\langle E_\alpha\rangle}{eV}+-\frac{U_\alpha(1-f_{ES})}{\tau_{w2}}+\frac{U_\alpha f_{ES}}{\tau_{2w}}-\frac{NU_\alpha f_{ES}}{\tau_{wr}}-\frac{U_\alpha}{\tau_s}-\frac{U_\alpha-U_\alpha^L}{\tau_{CH}}+\mathrm{h}\omega\upsilon_g N_w\sigma_{fca}S \qquad (7)$$

$\langle E_\alpha\rangle$ is average of carrier energy and U_α^L are the lattice-energy densities, it define as [2],

$$U_\alpha^L(t)=\frac{1}{V}\sum_k f_{\alpha,k}^L(t)\,E_{\alpha,k} \qquad (8)$$

$f_{\alpha,k}$ is Fermi distribution function at lattice temperature (T^L). Inside the amplifier,

Consider the energy density U_α is a function of carrier density and temperature, so the rate of U_α can be written as [16]

$$\frac{dU_{\alpha}}{dt}=\left(\frac{dU_{\alpha}}{dN}\right)_{T}\frac{dN}{dt}+\left(\frac{dU_{\alpha}}{dT}\right)_{N}\frac{dT}{dt}$$
$$=\langle \Delta U_{\alpha}\rangle\frac{dN}{dt} \qquad (9)$$

The rate of carrier temperature is more convenient than for the energy density, and by using Eqs.(1 and 9), one obtains [16]

$$\frac{dT}{dt}=\left(\frac{dU_{\alpha}}{dT}\right)_{N}^{-1}\left[\langle \Delta U_{\alpha}\rangle-\left(\frac{dU_{\alpha}}{dN}\right)_{T}\right]\frac{dN}{dt} \qquad (10)$$

By using Eqs.(2, 7, 8 and 9), the carriers temperature in QD SOA has been derive as,

$$\frac{dT}{dt}=\left(\frac{dU_{\alpha}}{dT}\right)_{N}^{-1}\left[\begin{array}{l}\left[\left(\langle E_{\alpha}\rangle-\left(\frac{dU_{\alpha}}{dN}\right)_{T}\right)\frac{I}{eV}\right]+\left[h\omega\upsilon_{g}N_{w}\sigma_{fca}S\right]-\left[\frac{U_{\alpha}-U_{\alpha}^{L}}{\tau_{CH}}\right]\\+\left[\left(\frac{dU_{\alpha}}{dN}-\langle U_{\alpha}\rangle\right)N_{WL}\left(\left(\frac{1}{\tau_{w2}}+\frac{1}{\tau_{s}}\right)+f_{ES}\left(\frac{1}{\tau_{wr}}-\frac{1}{\tau_{w2}}-\frac{1}{\tau_{2w}}\right)\right)\right]\end{array}\right] \qquad (11)$$

The dot parameters, such occupation probability, time relaxation between dot and wetting layer, are included in Eq.(11). Also the carrier absorption and carrier heating contribution are phenomenologically added, where σ_{fca} is the cross section of free carrier absorption (*fca*). The solution of Eq.(11) can be calculated depending on energy density solution in two-dimensional system [16],

$$U_{\alpha}(T_{\alpha})=N_{w}\kappa_{\beta}T_{\alpha}\frac{F_{1}(\eta_{\alpha})}{F_{0}(\eta_{\alpha})} \qquad (12)$$

$F_{j}(\eta_{\alpha})$ is the Fermi-Dirac integral of j-order, The partial derivation of U_{α} respected with temperature and carrier density is given as [16],

$$\frac{\partial U_{\alpha}}{\partial T_{\alpha}}=N\kappa_{\beta}T_{\alpha}\left[\frac{F_{1}(\eta_{\alpha})}{F_{0}(\eta_{\alpha})}+\eta_{\alpha}\left(\frac{F_{1}(\eta_{\alpha})F_{-1}(\eta_{\alpha})}{F_{0}^{2}(\eta_{\alpha})}-1\right)\right]$$
$$\frac{\partial U_{\alpha}}{\partial N}=\kappa_{\beta}T\frac{F_{0}(\eta_{\alpha})}{F_{-1}(\eta_{\alpha})} \qquad (13)$$

3. Results and Discussion

The theoretical simulation is achieved for InAs QD grown on InGaAs which is lattice match with GaAs. The semiconductor device has 5mm in high, 20 μm of with and 10 nm layer thickness [2]. The values of parameters at room temperature are listed in Tab. (1). To perform the numerical calculations, a strong pump pulse with a Gaussian shape and full width at half maximum of (1 ps) has been send through QD SOA.

Tab.(1): parameters for numerical calculations used in simulation [2,5,6 and 16].

Name	value	Unit	Name	Value	Unit
T_L	300	K	$\partial g / \partial N$	10^{-20}	m^2
τ_c	1	ps	m_e	0.41 m_o	kg
τ_s	200	ns	σ_{fca}	$3.5x10^{-22}$	m^2
τ_{CH}	1	ps	I	100	mA
N_Q	10^{14}	m^2	n_g	3.12	
E_g	0.79	eV	ΔE	80	meV
λ	1.33	Mm	D	$4x10^{22}$	m^2

Figure (1) shows the occupation probability of electrons in conduction band versus time response of device. It has been found that the occupation probability of ES is reduced in presence of carrier heating effect. The reduction of occupation probability due to carrier heating effect is result to decreasing carrier density. the fast relaxation of carriers from ES to GS (of about 0.16 ps) recoups the recombined carriers due to SOA operation and enhanced of time recovery with heating injection.

The dependence of reservoir carrier temperature on carrier heating relaxation time is shows in figure (2). With increasing of τ_{CH} , the amplitudes of reservoir carrier heating are higher, and the trend are boarded.

The pulse effect on performance of SOA is illustrated in figure (3), the temperature of carriers' isdirectly increase with the full width of half maximum of injected pulses. The pulse shape is enhanced of time recovery of carriers between WL and QD levels, and then it reduces the effect of CH. [12]

Figure (4) shows the response of system equations with existing of CH parameters. Actually, the CH parameter satisfies the thermal equilibrium between carrier and lattice, and without it, the system equations will be failed in describing of carrier-phonon scattering and the balance of energy flow.

Finally, our model has been compared with other model [3] (as shown in figure (5)) , the inclusion of ES level has more stability for long time response.

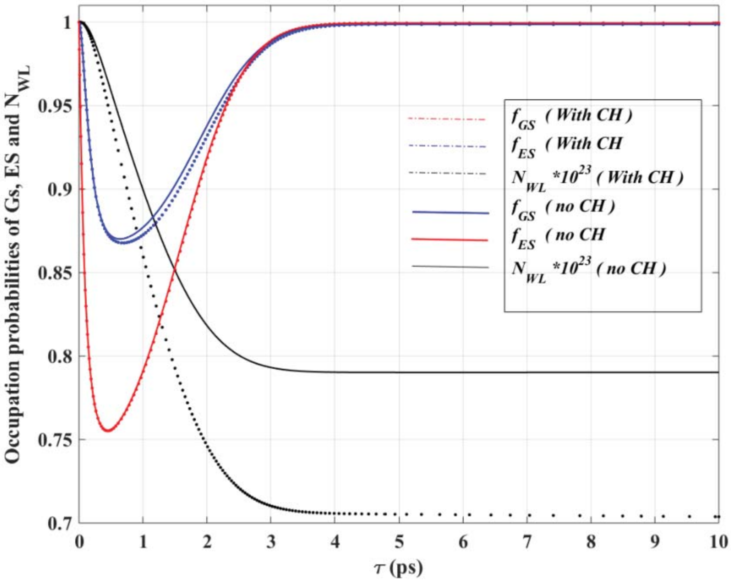

Figure (1): The effect of carrier injection on the temporal of carrier occupation probability in QD structure.

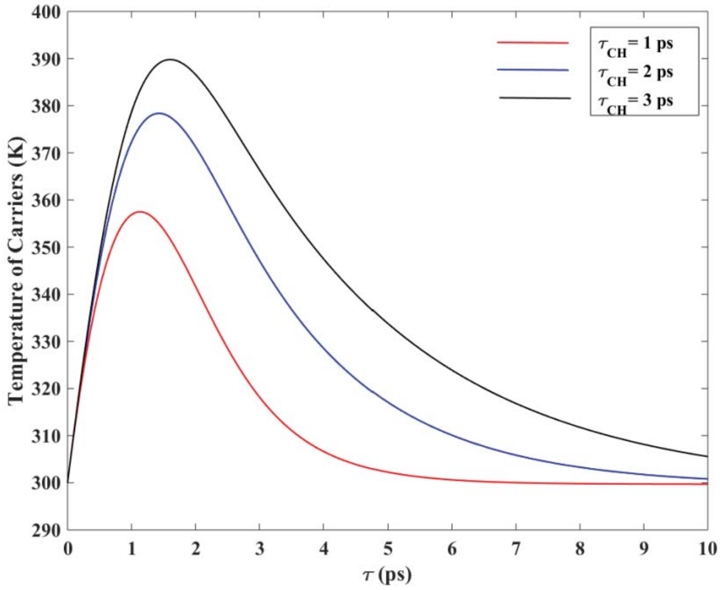

Figure (2): The effect of time relaxation carrier heating on the temporal of carrier temperature at reservoir.

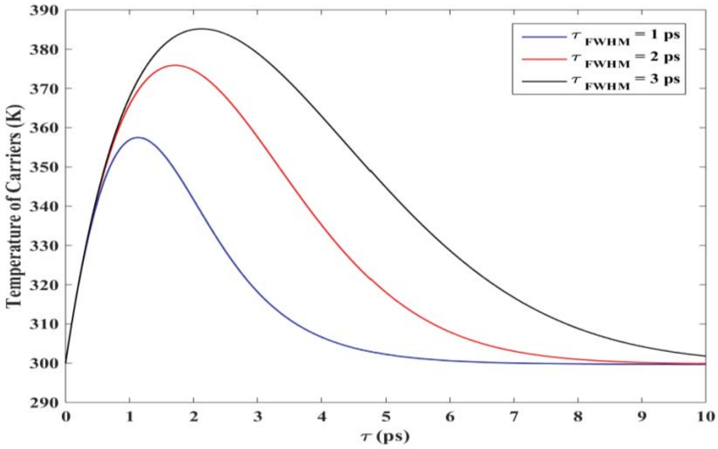

Figure (3): The dependence of reservoir carrier temperature on carrier heating relaxation time.

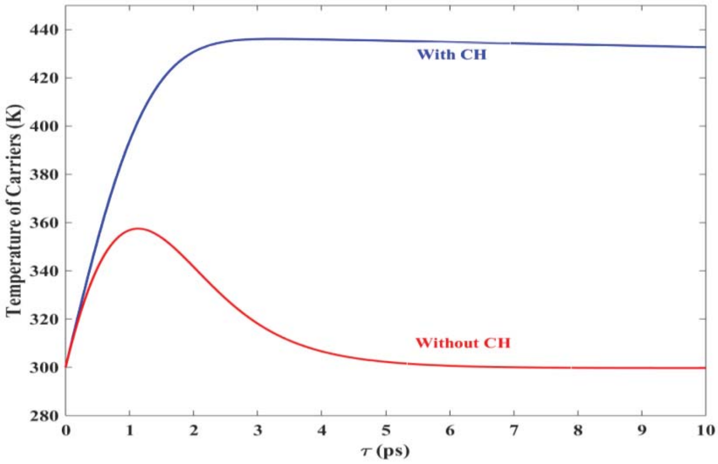

Figure (4): The influence of CH on the reservoir carrier temperature.

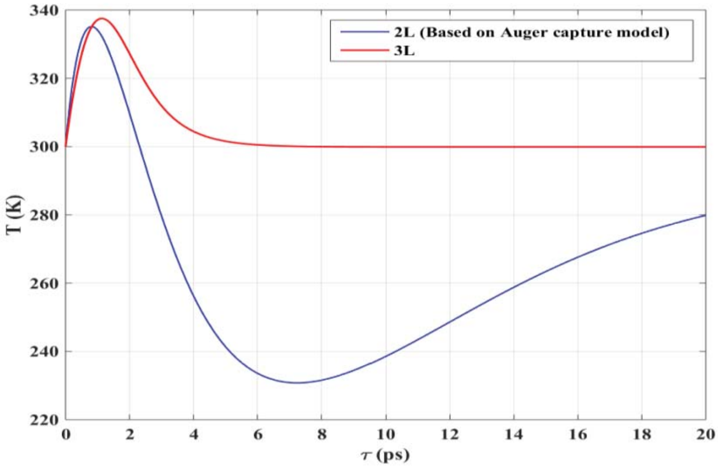

Figure (5): comparing between our model and two-level system.

4. Conclusion

The numerical calculation are showed the dependence of occupation probability on carrier heating time. With the long life time of carrier heating relaxation, the occupation probability increased, this behavior results of reduction of carriers in WL. Also, reservoir carrier temperature is directly increased with a width of half maximum and life time of CH. Finally, the CH in system equations satisfies the thermal equilibrium between the carrier and lattice.

References

[1] Majer N., Woggon U., Lu¨ dge K., Gomis-Bresco J. et al. , “Impact of carrier-carrier scattering and carrier heating on pulse train dynamics of quantum dot semiconductor optical amplifiers”, Applied physical letters, 99, 131102, 2011.

[2] Nielsen.D and S. Chuang.L, "Four-wave mixing and wavelength conversion in quantum dot", Physical Review B 81, 035305, 2010.

[3] Uskov A. ,Meur C., Schmeckebier H. and Bimberg D. , “Auger Capture Induced Carrier Heating in Quantum Dot Lasers and Amplifiers”, Applied physics express, 4, 022202, 2011.

[4] Bardan K., “Investigation of the Mole Fraction Effect for Wetting Layer on the Carrier Heating phenomena in Quantum Dot Semiconductor material”, International Journal of Science and Research (IJSR), 3 , 9, 2014

[5] Al-Kursan A. and Flayyih A., “Carrier Heating in Quantum Dot Structure”, Modern Physics Letters, 28, 145002, 2014.

[6] Uskov. A, Mork. J, and J. Mark, "Wave Mixing in Semiconductor Laser Amplifiers Due to Carrier Heating and Spectral-Hole Burning", IEEE J. Quantum Electronics, 30, 1769-1781, 1994

[7] Sarkiyan T. and Oraevsky A. “Nonlinear gain and carrier temperature dynamics in semiconductor material” Optical Society of America, 15, 3, 1998.

[8]Ahn D. Chuang S. , “Optical Gain and Gain Suppression of Quantum-Well Lasers with Valence Band Mixing”, IEEE Journal of Quantum Elect., 1990

[9] Wang J. and Schweizer H. “Nonlinear Gain Suppression in Quantum-Well Lasers Due to Carrier Heating: The Roles of Carrier Energy Relaxation, Electron-Hole Interaction, and Auger Effect”, IEEE Photonic Tech. 1996

[10] Ahmed M. and El-Lafi A., “Analysis of small-signal intensity modulation of semiconductor laser taking in account gain suppression”, Indian Academy of Sciences, 71, 1, 99-115, 2008.

[11] Flayyih. A. H. and Al-Khursan. A. H., "Four-wave mixing in quantum dot semiconductor optical amplifiers", Applied Optics 52, 3156-3165, 2013.

[12] Flayyih. A. H. and Al-Khursan. A. H., "Theory of Four-wave mixing in quantum dot semiconductor optical amplifiers", IOP, 46, 2013.

[13] Lester. L. F. and Ridleya. B. K., "Hot carriers and the frequency response of quantum well lasers", Journal of applied physics, 72, 2579-25887, 1992.

[14] Clugston. D. A. and Basore. P. A., "Modelling Free-carrier Absorption in Solar Cells", Progress in Photovoltaic, 5, 229-236, 1997.

[15] Siegret. J, "Carrier dynamics in semiconductor quantum dots", PhD Thesis, Sweden, 2006.

[16] Wang J. and Schweizer H.," A Quantitative Comparison of the Classical Rate-Equation Model with the Carrier Heating Model on Dynamics of the Quantum-Well Laser:The Role of Carrier Energy Relaxation, Electron–Hole Interaction, and Auger Effect", IEEE Journal of Quantum Elec., 33, 8, 1997.

[17]] Borri. P, Langbein. W, Hvam. J. M, Heinrichsdorff. F, Mao. M. H. and Bimberg, "Spectral Hole-Burning and Carrier-Heating Dynamics in InGaAsQuantum Dot Amplifiers", IEEE Journal of Selected Topics in Quantum Electronics, 6, 3, 544-551, 2000.

[18] Qasaimeh O., "Characteristics of Cross-Gain (XG) Wavelength Conversion in Quantum Dot Semiconductor Optical Amplifiers", IEEE Photonic Technology letters, 16, 2, 542-544, 2004.