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Simulation of 1.3μm Quantum Dot laser by Using Four Levels Rate Equations Model

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Abstract

By using four-level rate equations model (4LREM), the dynamics of optical gain and output power in 1.3μm quantum dots laser (QD-laser) is investigated. The numerical model of InAs/GaAs (QD-laser) covers four energy levels for electron. In present model, hole dynamics effect, both homogeneous and inhomogeneous broadening effects are ignored. Present results indicate to, a first and second lasing line, corresponding to the ground state, first excited state respectively appears at low bias current with injection current increasing. As a result, the use of the four -level model described above potentially gives a more complete insight into the dynamics of quantum-dot semiconductor lasers. This result very useful for the design of InAs/GaAs QD laser for communications applications.

Key Word: Quantum Dot Laser, Rate Equation Model

محاكاة لليزرات اشباة الموصلات النقاط الكمية ذات طول موجي1.3μm باستخدام نموذج معادلات المعدل ذو الاربعة مستويات

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الخلاصة

باستخدام نموذج معادلات المعدل ذو الاربعة مستويات ، تم دراسة ديناميكية الكسب و القدرة الخارجة لليزر النقاط الكمية عند طول موجي (١.٣μm). النموذج العددي يغطي مستويات الطاقة للالكترون في ليزر النقاط الكمية . في النموذج الحالي تم الغاء تاثير الفجوات وتاثير التوسيع المتجانس وغير المتجانس. النتائج اشارت الى ان الخط الكسبي الاول والثاني (المخرجات) المترافقة مع الحالة الارضية والحالة المتهيجة تظهر عند قيم قليلة للتيار المستخدم في الضخ. وكنتيجة لذلك فان استخدام نموذج معادلات المعدل ذو الاربعة مستويات يعطينا صورة اوضح لما يجري داخل ليزرات اشباة الموصلات . وهذة النتائج جدا مفيدة لهذا النوع من الليزرات المستخدمة في تطبيقات الاتصالات .

كلمات مفتاحية: ليزرات النقاط الكمية– نموذج معادلات المعدل

1- Introduction

There is currently significant theoretical and experimental interest in the physics and applications of the self-organized QD lasers and has shown the superior electronic and optoelectronic properties obtained by the three-dimensional (3-D) confinement of carriers. The carrier confinement in a few bounded states the ground state and the excited state in quantum dots is obtained by the very small dot size, below or around the exciton Bohr radius[1]. Using a QD ensemble as gain medium for semiconductor lasers and optical amplifiers, significantly different respected to the quantum well and wire cases. These differences include the minimum threshold current density [2], [3], the temperature dependence of threshold [4], and spectral hole burning of the optical gain [4], [5], as well as more subtle differences that change the linewidth broadening and chirp. The most promising application of quantum-dot lasers is the high-frequency direct modulation lasers with low frequency chirp[1]. This paper reports on theoretical investigation of the four-level rate equation model (4LREM) with continuous state (CS), on the performance of 1.3µm QD-laser. The semiconductor laser with lasing at 1.3µm becomes more and more important due to the special requirements of optical communication and data transmission technology. Among various kinds of QD lasers, the InAs/GaAs QD laser lasing at 1.3µm can be widely used in optical communication and its typical properties make it different. For the sake of simplicity, we suppose that the conduction band WL carrier population together with the continuum state population is concentrated on one energy level. As in most of papers that treat rate-equation models for QD materials [1-13], we consider only the electron dynamics assuming that the hole dynamics is so fast respect to the electrons that all the electronic and optical properties of the QDs are almost determined by the electron dynamics in conduction band [9] ; the results show that the dynamics is mainly limited by the electron relaxations and the effect of the different electron and hole distribution are significant only at very low bias of the QD-Laser.

2- Rate Equation Model for QD-Laser

Theoretically, rate equation models, with phonon and Auger-assisted carrier capture and relaxation modeled by relaxation times dependent on the occupation probabilities, were applied to simulate the gain recovery in the QD –laser [9].In our model, the QDs are assumed to have two discrete energy states, i.e., ground state (GS) and excited state (ES), and a continuum state (CS) see Fig. (1), which is an ensemble of dense excited states in each dot. Different dots are interconnected through a two-dimensional (2-D) WL. Our model ignores barrier dynamics and assumes the electrons are injected directly into the WL, then captured by the CS and finally relaxed into the ES and GS. Some of these carriers recombine radiatively or/and nonradiatively in the wetting layer and inside the QDs. The different processes (recombination, capture, escape, etc.) are illustrated in Fig. 1.The corresponding rate equations describing the change in Electron occupation probabilities in the WL (fw), CS (fu) , ES (f2) , and GS (f1) , can be written as [10]

$$\frac{\partial f_w}{\partial t} = \frac{J}{2el_wD_w\widetilde{NQ}} - \frac{f_w(1-f_c)}{\tau_{wc}} + \frac{D_cf_c(1-f_w)}{D_w\tau_{cw}} - \frac{f_w}{\tau_{wr}} \qquad (1)$$

$$\frac{\partial f_c}{\partial t} = \frac{f_wD_w(1-f_c)}{D_c\tau_{wc}} - \frac{f_c(1-f_w)}{\tau_{cw}} + \frac{f_eD_e(1-f_c)}{D_c\tau_{ec}} - \frac{f_c(1-f_e)}{\tau_{ce}} + \frac{f_gD_g(1-f_c)}{D_c\tau_{gc}} - \frac{f_c(1-f_g)}{\tau_{cg}} \qquad (2)$$

$$\frac{\partial f_e}{\partial t} = \frac{f_cD_c(1-f_e)}{D_e\tau_{ce}} - \frac{f_e(1-f_c)}{\tau_{ec}} + \frac{f_gD_g(1-f_e)}{D_e\tau_{ge}} - \frac{f_e(1-f_g)}{\tau_{eg}} - 2BN_\varphi^{ES}N_D\left(f_e - \frac{1}{2}\right) \qquad (3)$$

$$\frac{\partial f_g}{\partial t} = \frac{f_cD_c(1-f_g)}{D_g\tau_{cg}} - \frac{f_g(1-f_c)}{\tau_{gc}} + \frac{f_eD_e(1-f_g)}{D_g\tau_{eg}} - \frac{f_g(1-f_2)}{\tau_{ge}} - \frac{f_1^2}{\tau_{gr}} - 2BN_\varphi^{GS}N_D(f_g - \frac{1}{2}) \qquad (4)$$

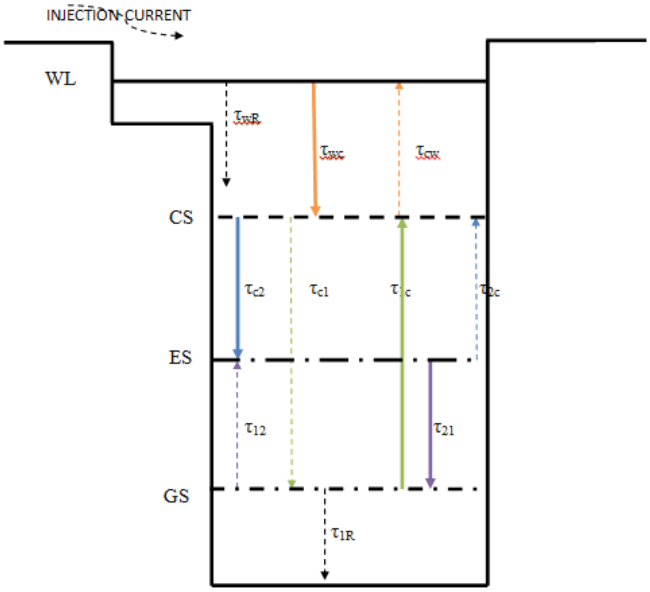

Figure 1: Energy band diagram of the QD-based SOA and the main processes.

N_φ^{ES} and N_φ^{GS} are the number of photons in the cavity per QD, at the GS and ES transition energies, respectively. They are described by

$$\frac{\partial N_\varphi^{GS}}{\partial t} = 2D_gBN_\varphi^{GS}N_D\left(f_g - \frac{1}{2}\right) - \frac{N_\varphi^{GS}}{\tau_\varphi} + \frac{D_g\beta f_g}{\tau_r} \qquad (5)$$

$$\frac{\partial N_\varphi^{ES}}{\partial t} = 2D_eBN_\varphi^{ES}N_D\left(f_e - \frac{1}{2}\right) - \frac{N_\varphi^{ES}}{\tau_\varphi} + \frac{D_e\beta f_e}{\tau_r} \qquad (6)$$

Where D_w,D_c ,D_2 and D_1 are the degeneracies of the corresponding electron states, where J is the injection current density, e is the electron charge, $l_w$is the thickness of the WL, The effective volume density of the QDs is $\widetilde{NQ}$. The electron spontaneous recombination lifetimes in the WL and the GS are $\tau_{wr}$and τ_{1r} ,respectively. The associated time constants are the electron relaxation from the wetting layer to the CS (τ_{wc}) and given by [11]

$$\tau_{wc} = \frac{\tau_{wc0}}{1 + C_{wc} f_w} \tag{7}$$

where τ_{wc0} is the electron capture time solely associated with the phonon-assisted process, C_{wc} is the dimensionless ratio of the Auger-assisted coefficient to the phonon-assisted coefficient in the capture process. The electron escape time from the CS to the WL is τ_{cw} and can be expressed, under the condition of thermal equilibrium, by [11]

$$\tau_{cw} = \tau_{wc} \exp\left(\frac{\Delta E_{wc}}{KT}\right) \tag{8}$$

Where ΔE_{wc} is the energy separation between the WL band edge and the CS in the conduction band of QDs , K is the Boltzmann's constant and T is the room temperature. A similar relationship is applied to the intradot relaxations and excitations thereby the intradot relaxation and excitation times in (2)–(4) can be expressed as [11]

$$\tau_{ij} = \frac{\tau_{ij}}{1 + C_{ij} f_w} \quad i = c, e \;\; ; j = e, g; i \neq j \tag{9}$$

$$\tau_{ji} = \frac{D_j}{D_i} exp\left(\frac{\Delta E_{ij}}{KT}\right) \tau_{ij} \qquad i = c, e \;\; ; j = e, g; i \neq j \tag{10}$$

Where τ_{ij0} is the phonon-dominated relaxation time and $C_{ij}$is the dimensionless ratio of the Auger-assisted coefficient to the phonon-assisted coefficient in the relaxation processes, and $\Delta E_{ij}$is the energy separation between the ith state and the jth state in the conduction band of QDs [12]. We take the interband transition energies of the excited state, continuum state and band edge of the WL as ħw+ 70 meV, ħw+150 meV and ħw + 180 meV, respectively, where ħω is the photon energy corresponding to the ground-state transition [13].

3- Simulation Parameters

The values of the parameters used in modeling the QD SOA are listed in Table I. We consider the QD device to consist of InAs QDs grown on GaAs substrate and use parameter values for this material system. Fig. 2, shows the energy difference diagram of QDs, where the carrier dynamics of electron and hole is treated together. Both QD conduction and valence bands consist of one spin-degenerate GS, three degenerate ES, and a many-fold continuum-like upper state (CS). The InGaAs QW layer works as a common carrier reservoir for QDs. In Fig. 2, the direct carrier capture from the QW to the GS is neglected due to both the large energy difference and the small wave function overlap between the QW and the GS. We assume that carriers in the InGaAs QW layer are first captured by the CS, and then relax into the ES or the GS. This is consistent with the claim that a sequential Auger process is more efficient than a single Auger process for the carrier capture from the QW to the GS.

Figure 1: Energy band diagram of the QD-based SOA and the main processes.

Parameter	Value	Unit	Ref	Parameter	Value	Unit	Ref
l_w	200×10^{-9}	m	10	τ_{c20}	10^{-11}	s	10
NQ	5×10^{-10}	1/cm²	10	τ_{210}	10^{-11}	s	10
D_W	250	-	10	τ_{c10}	10^{-11}	s	10
D_c	10	-	10	τ_{wc0}	10^{-12}	s	10
D_2	3	-	10	C_{c1}	25	-	10
D_1	1	-	10	C_{21}	50	-	10
τ_{gr}	10^{-9}	s	10	C_{c2}	50		10
D_1	1	-	10	C_{wc}	0.25	-	10

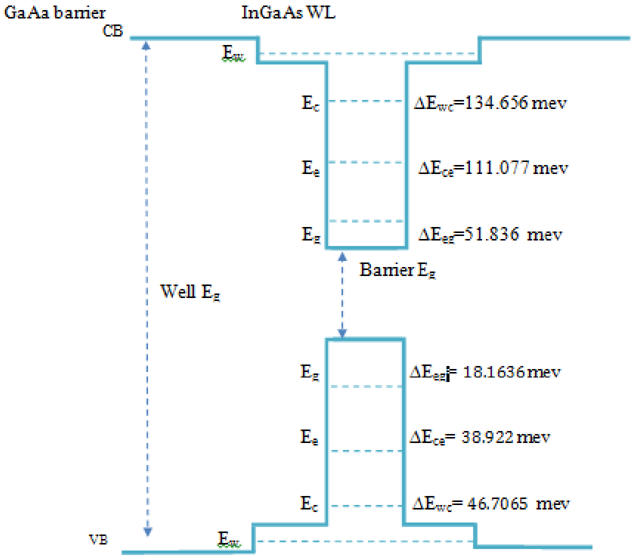

Figure 2: energy difference diagram in present simulation

4- Results and Discussion

In Fig. 3, we plot the electron occupation probability in GS (f_g) ,ES (f_e), CS (f_c) and WL (f_w) as a function of injection current.

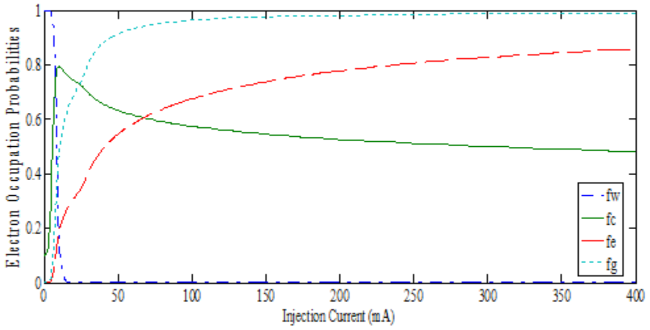

Fig.3: Electron occupation probability in GS ,ES ,CS and WL as a function of injection current.

The performance of optical devices is offered by the quantum dot material characteristics [10] . Because of the three-dimensional (3-D) confinement of carriers., at high injection currents, all quantum dot states are filled with carriers. Any further increase of the current does not lead to a gain alteration while carrier dynamics are accelerated .It is obvious that GS, ES starts to saturate as the injection current increases because of the carrier injection in the quantum dot. At high currents, the GS and ES carrier population is approaching a maximum that is (for the ensemble of the QDs) while the occupation probability tends to unity. Fig. 4 shows the dependence of the gain on the injection currents when charge neutrality for GS only. It is clearly shown that the initial gain value or the unsaturated gain for GS and ES increases significantly with injection current. It is noted that the gain is proportional to the population inversion. According to the photon populations, we can figure output power of GS and ES so PI characteristics (output power vs. current) are shown in Fig.5.

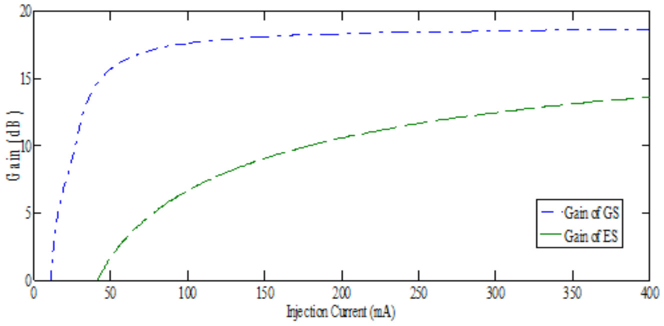

Fig.4: Optical gain in GS and ES as functions of injection current with charge neutrality in GS only.

It is obvious that GS and ES start photon emission one after another, with current increasing. The moment GS output is saturated, and ES starts emission. Through present calculations, we ignored the hole dynamics, therefore, a second lasing line, corresponding to the excited state and transition appears only at high bias current. if we take into account the hole dynamics, a first, second and third lasing line, corresponding to the ground state, excited state and continuous state transition respectively appears at low bias current. This result very useful for the design of InAs/GaAs QD laser for communication applications.This is the main result of present paper. It is clear that, the behavior of gain dynamics is go on to steady value with the increase of injection current i.e. stationary state or full occupation probabilities in GS state and ES state. But, the main difference between these states is the initial value of injection current because we get gain value in ES state at the value of injection current value that corresponding to steady state value of GS gain.

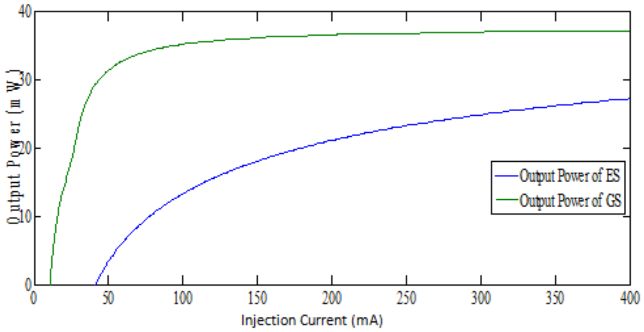

Fig.5: Output power in GS and ES as functions of injection current .

5- Conclusions

In summary, we modeled the relaxation dynamics of QD lasers by using four-level rate equations model. The numerical model of InAs/GaAs QD laser includes four energy levels for electron only. Present results indicate to, a first and second lasing line, corresponding to the ground state, first excited state respectively appears at low bias current with injection current increasing. As a result, the use of the four -level model described above potentially gives a more complete insight into the dynamics of quantum-dot semiconductor lasers. This result very useful for the design of InAs/GaAs QD laser for communications applications. This result very useful for the design of InAs/GaAs QD laser for communications applications.

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