Numerical modelling of the two-state lasing in 1.55μm (113)B InAs/InP quantum dot lasers for optical telecommunications

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Abstract — **Two rate equation models (REM) based on the intraband energy competition and efficient carrier relaxation are presented. The comparison between these two theoretical approaches leads to qualitative understanding of the origin of the two-state lasing in 1.55 μm InAs/InP quantum dot lasers.**

Index Terms — **Quantum dots, semiconductor lasers, rate equa- tions, optical telecommunications.**

I. INTRODUCTION

While optics has proven to be the most practical response to the high traffic rate demand for long-haul transmission, its extension to the metropolitan networks down to the home remains an open challenge. The implementation of optics at transmission rate where other technical solutions exist requires cost reduction. As a consequence, semiconductor lasers based on low dimensional heterostructures such as quantum dots (QDs) laser are very promising. Indeed, QDs structures have attracted a lot of attention in the last decade since they exhibit many interesting and useful properties such as low threshold current, temperature insensitivity, chirpless behavior and optical feedback resistance. As a result, thanks to QDs lasers, several steps toward cost reduction can be reached such as: improving the laser resistance to temperature fluctuation in order to remove temperature control elements, or designing feedback resistant laser for isolator-free and optics-free module. Most investigations reported in the literature deal with In(Ga)As QDs grown on GaAs substrates [1,2]. Also numerous theories about carrier dynamics in these structures have been introduced [3,4]. It is however important to stress that In(Ga)As / GaAs QDs devices do not allow a laser emission above 1.35 μm which is detrimental for optical transmission. In order to reach the standards of long-haul transmissions, 1.55 μm InAs QD lasers on InP substrate have been developed. In this paper, based on a rate equations model, carrier dynamics is at first investigated. Numerical results reporting the double laser emission are then shown exhibiting two different behaviors. All these recent results will be reviewed in the following.

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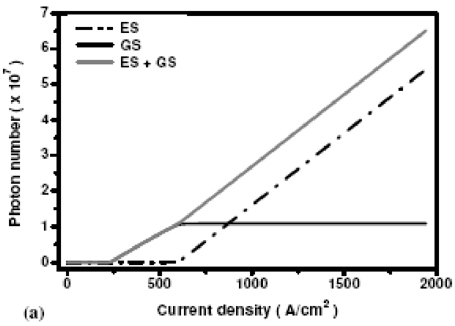

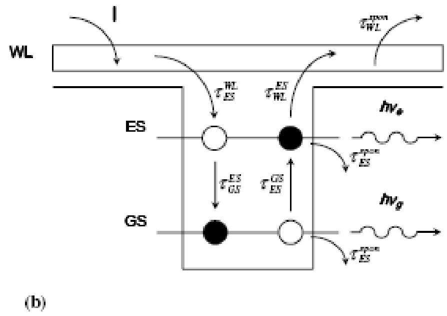

Fig. 1. Calculated photon number in the active region as a function of the injected current density (a). Schematic representation of the intraband energy competition model (b).

II. TWO-STATE LASING COMPETITION

A numerical model based on a set of rate equations is used to study carrier dynamics in a QD laser. Its active region consists of a QD ensemble, where different dots are interconnected by a wetting layer (WL) as shown in Fig. 1(b). In this ensemble, two energy levels are assumed: the ground state (GS) and the excited state (ES) [7]. It is also assumed that there is only one QD ensemble, i.e., all dots have the same size meaning the inhomogeneous broadening is neglected. Electrons and holes are considered to be captured and emitted in pairs. Carriers are supposed to be injected directly from the contacts into the WL levels, so the barrier dynamics is not taken into account in the model. Calculated photon number in the cavity is reported in Fig. 1(a) as a function of the injection current density. Once the threshold of the ES lasing is reached, the emission of the GS saturates and the ES emission increases linearly. This behaviour has been already reported for the InAs/GaAs system [4] as a two-state lasing competition between the GS and ES due to the finite

GS relaxation time. However, this approach do not match with recent experimental results obtained on the InAs/InP system which have shown no saturation of the GS lasing [3].

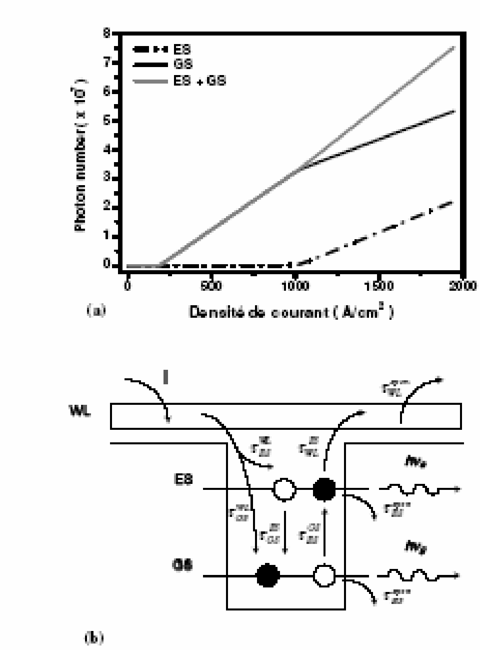

Fig. 2. Calculated photon number in the active region as a function of the injected current density (a). Schematic representation of the efficient carrier relaxation model (b).

III. EFFICIENT CARRIER RELAXATION

Using the same simulation parameters, carriers are this time captured into the ES or directly into the GS within the same time $\tau_{WL} = \tau_{WL}$ (Fig. 2(b)) whereas they can also relax from the ES to the GS. It is assumed that at low injection rate, the relaxation is phonon-assisted while the Auger effect dominates when the injection gets larger [6]. In order to investigate the properties of the InAs/InP(113)B QD device under electrical pumping, steady-state solutions of the REM have been determined. Simulation of the lasing performance is shown in Fig. 2(a) where the the calculated ES and GS photon number is reported as function of the injection current density showing two thresholds corresponding to the two laser emissions. A single longitudinal mode is assumed and the gain nonlinearities are not taken into account. When the ES stimulated emission appears, only a slight decrease of the GS slope efficiency is predicted. At the same time, the global slope efficiency increases. This behaviour is different from the one associated to the InAs/GaAs QD laser. Here, the double laser emission seems to result from the efficient carrier relaxation into the GS [7]. Although the competition between GS and ES transitions of different QDs is not taken into account, these numerical results are in good agreement with experimental ones recently reported for an optical pumped InAs/InP diode laser [5].

IV. CONCLUSION

In summary, calculated photon number has been predicted versus the injected current density. Using a rate equation model based on the intraband energy competition and on an efficient carrier relaxation, two theoretical approaches have been investigated. On one hand, numerical results describing carrier dynamic behaviour have been presented confirming previously observed phenomena for InAs/GaAs system. On the other hand, it has been shown that the direct relaxation channel included in the model matches very well the different experimental results already published and leads to qualitative understanding of InAs/InP QD lasers. These results show that laser characteristics such as threshold current or external efficiency can be predicted. It is of first importance for the realization of QD semiconductor devices for optical telecommunications.

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