Impact of gain factor on simultaneous two-state operation in quantum dot lasers

M. Abusaa [1,2], J. Danckaert [2], E.A. Viktorov [2,3], T. Erneux [3]

[1] Arab American University, Jenin, Palestine
[2] Vrije Universiteit Brussel, Applied Physics research group (APHY), Pleinlaan 2, B-1050 Brussels, Belgium
[3] Université Libre de Bruxelles, Optique Nonlinéaire Théorique, Campus Plaine, CP 231, 1050 Bruxelles, Belgium

Semiconductor lasers based on quantum dots may operate at different transitions known as the ground state (GS) and the excited state (ES). We analyze an electron-hole model for simultaneous two state operation in semiconductor quantum dot laser and investigate the role of the gain factor during steady state operation.

Introduction

Characteristics of quantum dot (QD) lasers such as low threshold current, low chirp, high modulation bandwidth, temperature stability, and ultrafast pulse generation [1] are very appealing for applications and currently attract significant attention. The discrete structure of the energy levels in QD allows simultaneous lasing at the ground (GS) and excited (ES) states [2]. At low currents, the recombination of a GS electron–hole pair results in GS emission. Increasing the injection current leads to a larger population of the ES, to the appearance of a second threshold, and to dual (simultaneous) lasing in both the GS and the ES. The simultaneous lasing has been already investigated in steady state operation [3, 4], in specific dynamical regimes [5], and mode locking [6]. But the role of the gain factor and the material time scales was not studied in detail. The aim of this paper is to analytically investigate the role of the gain factor in simultaneous lasing .

Model

The electron-hole asymmetry model consists of rate equations for the electromagnetic field intensities ($I_{g,e}$) and GS and ES occupational probabilities for electrons and holes ($n^g_{e,h}, n^e_{e,h}$), and the carriers in a wetting layer ($w_{e,h}$):

$$I'_g = [2g\,(n^g_e + n^g_h - 1) - 1]\,I_g, \tag{1}$$
$$I'_e = [4g\,(n^e_e + n^e_h - 1) - 1]\,I_e, \tag{2}$$
$$n^{g\prime}_{e,h} = \eta\,[2F_{e,h} - n^g_e n^g_h - g\,(n^g_e + n^g_h - 1)\,I_g]\,, \tag{3}$$
$$n^{e\prime}_{e,h} = \eta[B^w_{e,h} w_{e,h}\left(1 - n^e_{e,h}\right) - R_{e,h} n^e_{e,h} - F_{e,h} - n^e_e n^e_h - g\,(n^e_e + n^e_h - 1)\,I_e] \tag{4}$$
$$w'_{e,h} = \eta\left[J - w_e w_h - 4B^w_{e,h} w_{e,h}\left(1 - n^e_{e,h}\right) + 4R_{e,h} n^e_{e,h}\right], \tag{5}$$

where prime means differentiation with respect to $t \equiv t'/\tau_{ph}$ where t' is time and τ_{ph} is the photon lifetime. $\eta \equiv \tau_{ph}\tau^{-1} << 1$ where τ denotes the carrier recombination

time. The factors 2 and 4 account for the degeneracy in the quantum dot energy levels. J is the pump current per dot. The gains $2g(n_e^g + n_h^g - 1)$ and $4g(n_e^e + n_h^e - 1)$ are defined by the dot population and a g-factor. The nonlinear interaction $F_{e,h} \equiv B_{e,h} n_{e,h}^e \left(1 - n_{e,h}^g\right) - C_{e,h} n_{e,h}^g \left(1 - n_{e,h}^e\right)$ between the different states is provided by the Pauli blocking factor $\left(1 - n_{e,h}^{g,e}\right)$. $B_{e,h}$ ($C_{e,h}$) and $B_{e,h}^w$ ($R_{e,h}$) are the capture (escape) rates to (from) the GS and the ES, respectively. The charge neutrality remains fully preserved in the model.
The model (1-5) supports the GS intensity decrease for a certain set of the parameters, but is too complicated for analytical treatment. We consider a number of simplifications which qualitatively preserve the dynamical characteristics, and allow some analytical conclusions on the role of the g-factor in simultaneous lasing. We assume a direct pumping of the excited state from the wetting layer represented by the rates J, and replace $B_{e,h}^w w_{e,h} \left(1 - n_{e,h}^e\right)$ by $J\left(1 - n_{e,h}^e\right)$ in (4).The slowness of the recombination processes motivates neglecting the terms $n_e^{g,e} n_h^{g,e}$. We assume the electron-hole asymmetry $C_e \ll B_e, C_h \approx B_h$ and consider the simplifications $B_h = B_e = B$; $C_e = 0; C_h = B$. Typical values of the recombination time (1 ns), GS capture time (10 ps) and the photon lifetime (10 ps) are implying $\eta = 0.01$ and $B = 10^2$.

Steady states

In addition to the zero intensity solution, there exist three nonzero intensity steady states: $i) I_g \neq 0$, $I_e = 0$; $ii)$ $I_g \neq 0$, $I_e \neq 0$; and $iii)$ $I_g = 0$, $I_e \neq 0$. We are interested in the transition $i) \rightarrow ii)$, and the properties of the two state regime $ii)$. The single mode GS only regime $i)$ is stable up to the appearance of the ES output. The GS intensity increases with the injection current as shown in Fig.1(a). It is the solution of the quadratic equation:

$$-\frac{I_g}{2B}(J - \frac{I_g}{4g} + J + R_e) + \left(\frac{2g}{J + R_h}(J - \frac{I_g}{4g}) - 1\right)\left(J - \frac{I_g}{4g}\right) = 0, \tag{6}$$

which admits the following approximation for large B :

$$I_g = 2\left[(2g - 1)J - R_h\right] > 0. \tag{7}$$

The two state lasing appears through a secondary bifurcation. The corresponding threshold J_{ge} can be obtained from the equations for the single mode steady state ($I_g \neq 0, I_e = 0$) and the condition $4g_0^e(n_e^e + n_h^e - 1) - 1 = 0$. It reads

$$\left(\frac{4gJ_{ge} - I_g(J_{ge})}{J_{ge} + R_e} + \frac{4gJ_{ge} - I_g(J_{ge})}{J_{ge} + R_h} - 1\right) - 1 = 0, \tag{8}$$

where $I_g(J_{ge})$ is a solution of Eq.6 (or Eq.7 in the case of large B). It is worth to emphasize that the condition (8) does not depend on the capture rate in the case B large (fast capture rates). Fast capture rates are observed for most QD lasers, and the threshold for appearance of the ES output is essentially determined by the gain factor g.
The steady state solution of two state lasing is complicated even for the reduced model, and depends strongly on all the material parameters: gain factor g and the capture/escape rates B and $R_{e,h}$:

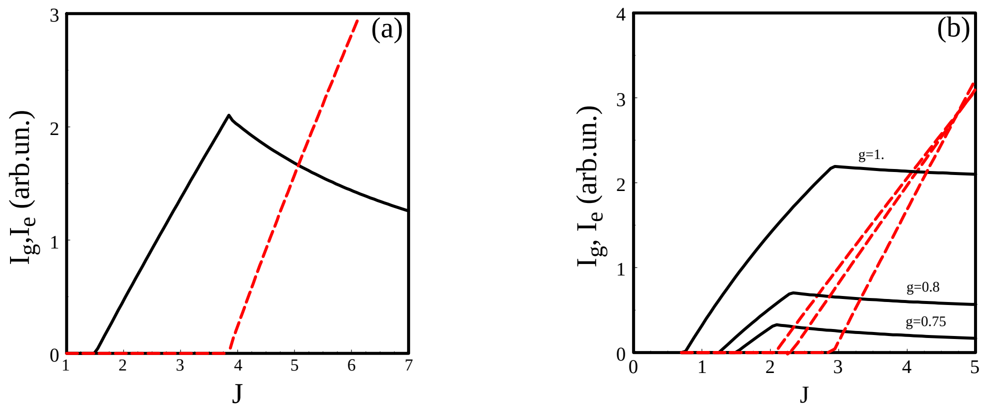

Figure 1: Bifurcation diagrams of the stable steady states. (a) the reduced model for $g = 0.75; \eta = 0.01; B = 100, R_h = 0.75, R_e = 1$.The diagram has been obtained numerically from the orginal equations. We have verified that the various branches are matching the analytical expressions. (b) Effect of g. As $g - 0.75$ increases from zero, the secondary bifurcation exhibits larger intensities and I_g approaches a constant value. Other parameters as in Fig.1(a).

$$I_g = B\frac{4g-3-2\varepsilon_1}{(2+\varepsilon_1)}\frac{1}{\left(\frac{4g(2+\varepsilon_2)}{1+4g}+1\right)} \tag{9}$$

$$I_e = 4gJ - \frac{1+4g}{(2+\varepsilon_2)}(J+R_e) - I_g > 0, \tag{10}$$

where $\varepsilon_1 = \frac{R_h - R_e}{J+R_e}$ and $\varepsilon_2 = \frac{R_e - R_h}{J+R_h}$ are the important parameters, which determine the tendency of the GS output with J. While both $\varepsilon_{1,2}$ are vanishing with J, the value of I_g is proportional to $4g - 3 - 2\varepsilon_1$. It reveals the role of the gain factor g in the two state lasing.

Gain factor

The gain factor g is important for the stability analysis of a single mode GS output [7]. For the two state lasing, the value of g may play an important role in the large B limit. In the case $4g - 3 = 0$ as in Fig. 1(a), we obtain from Eqs.(9-10)

$$I_g \simeq \frac{4}{10}B\frac{R_e - R_h}{(J+R_e)}, \tag{11}$$

$$I_e \simeq J - 2R_e - I_g > 0, \tag{12}$$

assuming $|R_e - R_h| = O(B^{-1})$ as $B \to \infty$. In this approximation, the GS output intensity I_g decreases with J and vanishes in the limit of large pumping currents $J \gg 1$. The ES output I_e steadily increases for the full range of currents.

On the other hand if $4g - 3 \neq 0$, we need to assume that $I_g = O(B)$, $I_e = O(B)$, and $J = 0(B)$. With $\varepsilon_1 = \varepsilon_2 = 0$, we obtain

$$I_g = B\left(\frac{1+4g}{1+12g}\right)\frac{4g-3}{2}, \quad (13)$$

$$I_e = \frac{4g-1}{2}J - \frac{4g+1}{2}R_e - I_g > 0. \quad (14)$$

The ES output I_e remains linearly increasing with the pump current, but I_g becomes independent on J, and is only determined by the value of the gain factor. We illustrate the role of g in Fig.1(b). The figure shows that increasing the gain factor leads to a saturated value of I_g. This tendency is similar to the excitonic models of the two state lasing [2].

In summary, a theoretical analysis of the simultaneous two-state operation in quantum dot lasers as a function of the gain factor is presented. We find that larger values of the $g-$factor prevent the decrease of the GS output. It may explain that the experimentally observed decrease of the GS for operation at $1.3\mu m$ [2, 3], is not reported for operating wavelength of $1.5\mu m$ [8]. The QD materials operating at $1.5\mu m$, reportedly possess a stronger gain ($\sim 30cm^{-1}$) compared to the gain ($\sim 15cm^{-1}$) of the QD materials with the wavelength centered at $1.3\mu m$.

Acknowledgments

This work was supported by the Belgian Science Policy Office under the project "Photonics@be" (IAP VII-35), by the Fonds National de la Recherche Scientifique (Belgium), and by the Research Foundation-Flanders (FWO).

References

[1] D. Bimberg, M. Grundmann, and N. N. Ledentsov, "Quantum Dot Heterostructures," Wiley, New York, 1999.

[2] A. Markus, J. X. Chen, C. Paranthoen, A. Fiore, C. Platz, and O. Gauthier-Lafaye, “Simultaneous two-state lasin in quantum -dot lasers," *Appl. Phys. Lett.*, vol. 82, pp. 1818-1820, 2003.

[3] E. A. Viktorov, P. Mandel, Y. Tanguy, J. Houlihan, and G. Huyet, “Electron-hole asymmetry and two-state laing in quantum dot lasers,” *Appl. Phys. Lett.*, vol. 87, pp. 053113, 2005 .

[4] M. Gioannini, "Ground-state power quenching in two-state lasing quantum dot lasers," *J. Appl. Phys.* 111, pp. 043108, 2012

[5] E. A. Viktorov, P. Mandel, I. O’Driscoll, O. Carroll, G. Huyet, J. Houlihan, and Y. Tanguy, "Low-frequency fluctuations in two-state quantum dot lasers," *Optics Letters*, vol. 31, pp. 2302, 2006.

[6] M. A. Cataluna, W. Sibbett, D. A. Livshits, J. Weimert, A. R. Kovsh, and E. U. Rafailov, “Stable mode locking via ground- or excited-state transitions in a two-section quantum-dot laser,” *Appl. Phys. Lett.*, vol. 89, pp. 081124 , 2006.

[7] T. Erneux, E.A. Viktorov, P. Mandel, "Time scales and relaxation dynamics in quantum-dot lasers," *Phys. Rev. A* 76, pp. 023819, 2007.

[8] K. Veselinov, F. Grillot, Ch. Cornet, J. Even, A. Bekiarski, M. Gioannini, and S. Loualiche "Analysis of the Double Laser Emission Occurring in 1.55μm InAs–InP (113)B Quantum-Dot Lasers," *IEEE J. Quantum Electron.*, vol.43, pp. 810-815, 2007.