Impact of the carrier relaxation paths on two-state operation in quantum dot lasers

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ABSTRACT

We study InGaAs QD laser operating simultaneously at ground (GS) and excited (ES) states under 30ns pulsed-pumping and distinguish three regimes of operation depending on the pump current and the carrier relaxation pathways. An increased current leads to an increase in ES intensity and to a decrease in GS intensity (or saturation) for low pump range, as typical for the cascade-like pathway. Both the GS and ES intensities are steadily increased for high current ranges, which prove the dominance of the direct capture pathway. The relaxation oscillations are not pronounced for these ranges. For the mediate currents, the interplay between the both pathways leads to the damped large amplitude relaxation oscillations with significant deviation of the relaxation oscillation frequency from the initial value during the pulse.

Keywords: Qunatum dots, laser diodes, two-state operation, relaxation oscillations

1. INTRODUCTION

Short pulsed laser diode operation is important for multiple applications in material processing [1] and biomedicine [2-4] because it allows lasing at pumping levels of 10s to 100s of threshold values due to reduction of the overheating effects. The devices based on self-assembled InAs quantum dots (QDs) as active media have shown significant advantages as high power pulse generators. They provide faster gain recovery, high gain efficiency and low threshold [5]. In QD lasers, the recombination of ground-state (GS) and excited-state (ES) electrons and holes allows lasing operation at both states.

For cw operation, a secondary (ES) threshold occurs at high bias, and increasing the current further, the ES output becomes the dominant at the expense of the GS transition. It eventually leads to the ES only lasing mode of operation at higher bias. The mode of operation depends significantly on the cavity length. Normally, the long (≥1mm) devices emit exclusively in the GS, 1-mm-long devices may emit simultaneously in the GS and the ES and the short (≤1mm) devices emit exclusively in the ES for all currents. This scenario has been experimentally confirmed [6] and became a subject of the intense theoretical study [7,8]. To explain the experimental results, a rate equation model for the electron and hole populations in both the ground and excited states assumes a cascade-like (wetting layer (WL)-ES-GS) relaxation pathway for the carriers in the dot: the carriers first captured by the ES, with the followed relaxation into the GS.

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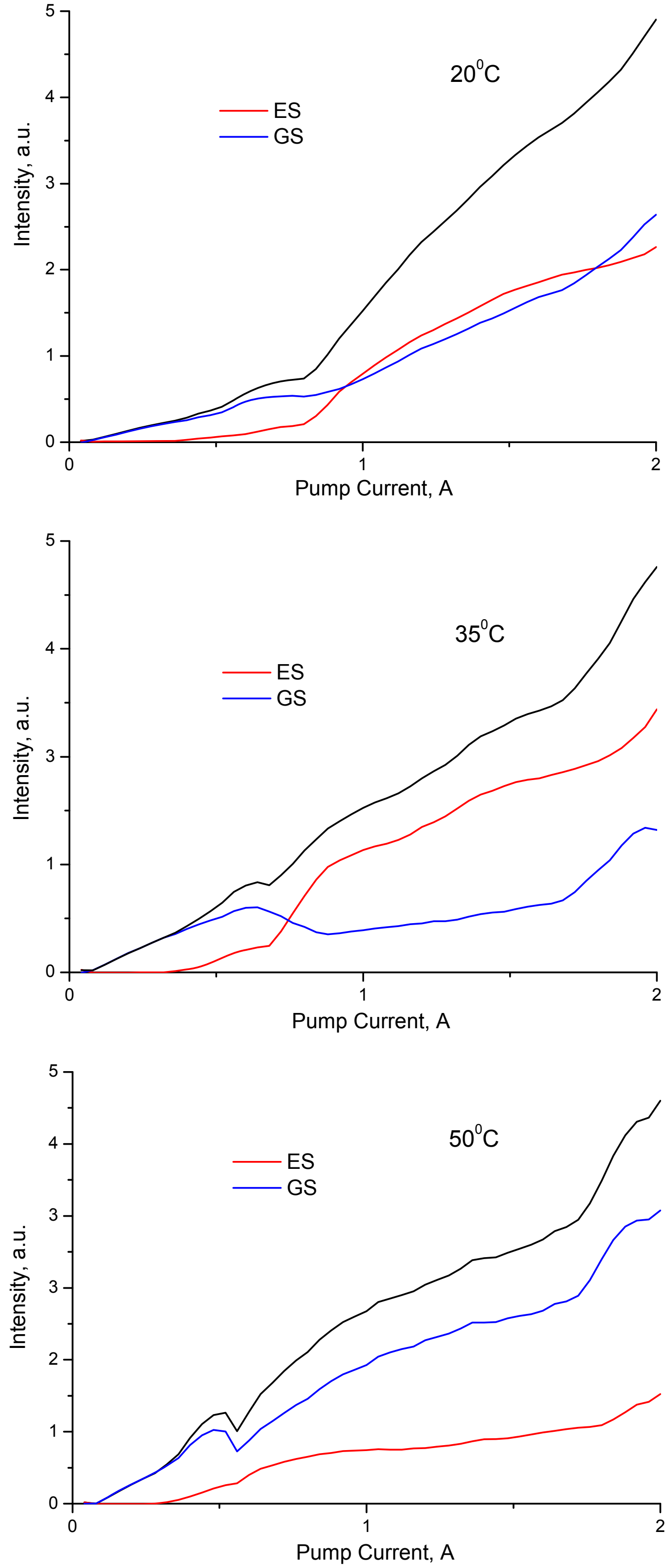


Figure 1. The plot of optical output (*L*) as a function of current (*I*) for different temperatures. *L-I* curves show the total (black), GS (blue) and ES (red) outputs in arbitrary units.

Recent time-resolved experiments at InGaAs/GaAs QDs semiconductor optical amplifiers indicate the existence of a direct capture relaxation pathway to GS from a 2D (WL) reservoir in electrically pumped QD structures [9]. The conclusion is based on the delayed ES population drop-off to the nonlinear GS pulse amplification that is incompatible with the dominance of the cascade-like capture/escape processes.

In this work, we experimentally examine the high power pulsed operation in an electrically pumped QD laser, and find that either the cascade-like or the direct capture relaxation pathways to GS can be dominant in InGaAs/GaAs QDs structures. For the low or the high ranges of the pump current, either the cascade-like or the direct capture pathway is dominant. For the mediate current range (0.5-1.2A), the interplay between the both pathways leads to an excitation of the large-amplitude relaxation oscillations. The oscillations appear simultaneously at GS and ES and are always damped, but can be either in-phase or anti-phase depending on the temperature conditions. The relaxation oscillations are not pronounced for the low and high ranges of the pump current with only one dominant relaxation pathway.

2. EXPERIMENT

Experimentally, the active region of the studied lasers included five layers of self-assembled InAs QDs grown on a GaAs substrate by molecular-beam epitaxy. The structure, with a 5.3nm thick covering layer of $In_{0.14}Ga_{0.86}As$, was processed into 4μm-wide mesa stripe devices. The device lase at either the GS (around 1265nm) or simultaneously at the GS and ES (around 1190nm) in the whole range of pump current (up to 2A). The laser had high- and antireflection coatings on the rear and front facets, and the 2mm cavity length. Short-pulsed electrical pumping was used to achieve high output power operation and avoid the effect of overheating on the output pulse shape. Pulses of ~30ns duration were obtained from a high power digital pulse source and the laser output was detected using a high-speed pin detector with a cut-off frequency of 30GHz and a 50GHz digital oscilloscope. Further details of the experiment are similar to that reported elsewhere [10].

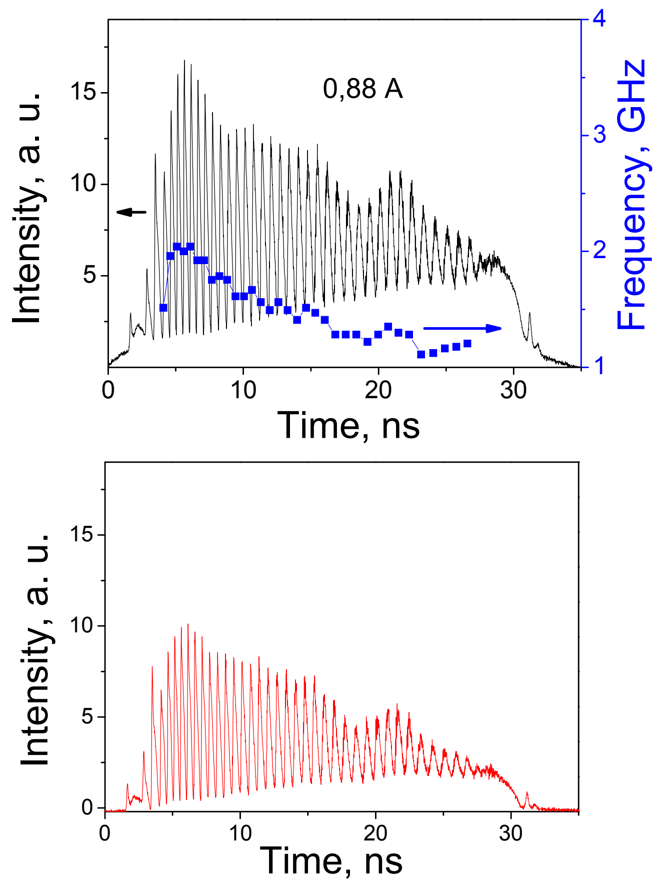


Figure 2. Weakly damped relaxation oscillations for the pump current of 0.88A. The time traces show the total (black), and filtered ES (red) outputs. Relaxation oscillations frequency is shown in blue.

The experimental output intensities vs current are shown in Fig.1 for different temperatures. For all temperature values, we distinguish between the regimes in relation to the pump current on the basis of the *LI* curves and dynamical instabilities of the outputs. For the low range of currents (up to ~ 0.4A) the laser operates exclusively in GS. The GS output pulse shape is similar to that of the pulsed pump, with relaxation oscillations frequencies being not pronounced which is typical for QD lasers [11]. The *LI* curve remains strictly linear, and the secondary (ES) threshold does not significantly depend on the temperature.

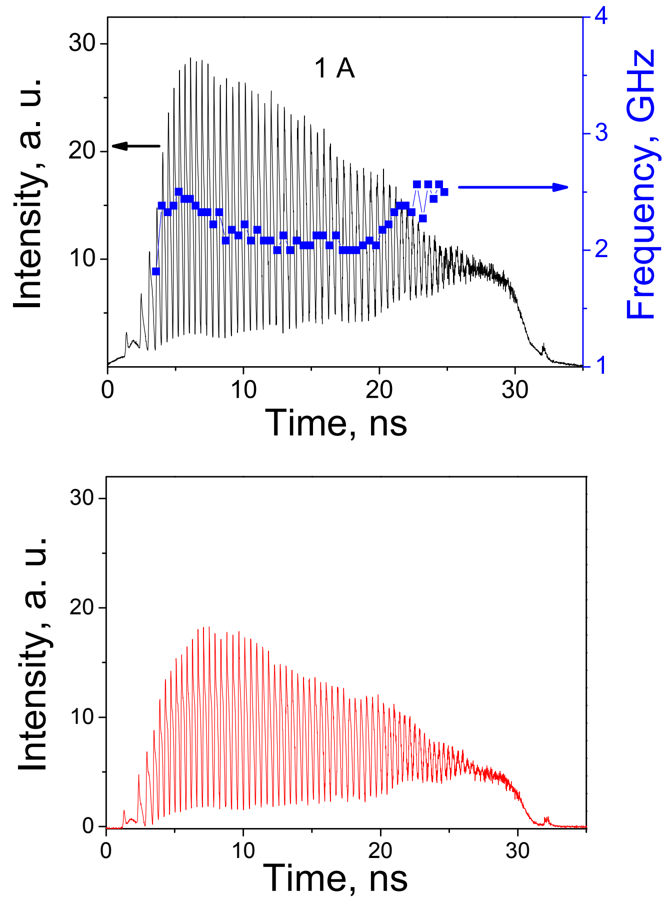
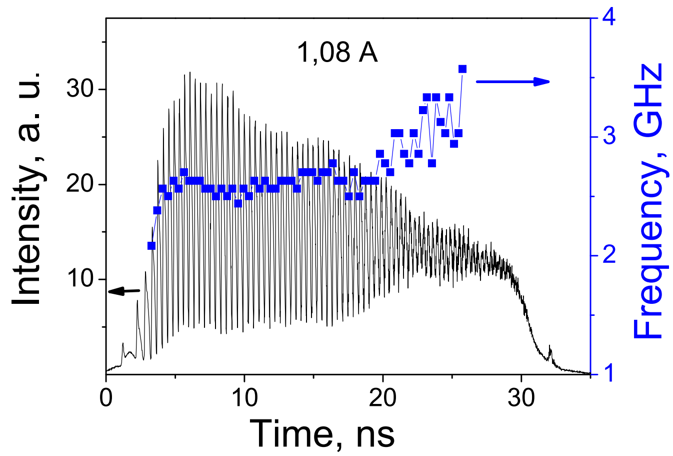


Figure 3. Weakly damped relaxation oscillations for the pump current of 1A. The time traces show the total (black), and filtered ES (red) outputs. Relaxation oscillations frequency is shown in blue.

For the high (≥ 1. 2A) currents, both GS and ES *LI* curves are nearly linear, with the gradual simultaneous increase of the intensity vs pump current and only minor impact of the temperature change. The cascade-like pathway does not support the observation, which can only be explained by the dominance of the direct capture pathway to GS. Similar to the low current range (below the ES threshold), the lasing does not show any dynamic instabilities, and the output pulse mimics the electrical pump pulse profile. It also suggests the absence or the negligible impact of the intradot interactions on the simultaneous two state operation and supports the hypothesis of the dominance of the direct capture pathway.

For the mediate current range (above the ES threshold, but ≤ 1. 2A), the interplay between both pathways leads to an excitation of the large-amplitude relaxation oscillations. The oscillations appear simultaneously at GS and ES and are always damped, but can be either in-phase or anti-phase depending on the temperature conditions as shown in Figs.2-4.

In the cascade-like scenario for the relaxation pathway there is a current range where the intensity in GS is decreased while the intensity in ES is increased. This scenario is only partially supported in Fig.1. The GS intensity does not start to decrease immediately after the ES threshold and the effect becomes pronounced at sufficiently higher pump currents. It can be explained by the transient dynamical instabilities which impact on the *LI* curves and is difficult to evaluate. We should stress that due to the anti-phase character of the instabilities, the slope of the total intensity remains largely unchanged for some ranges of current.



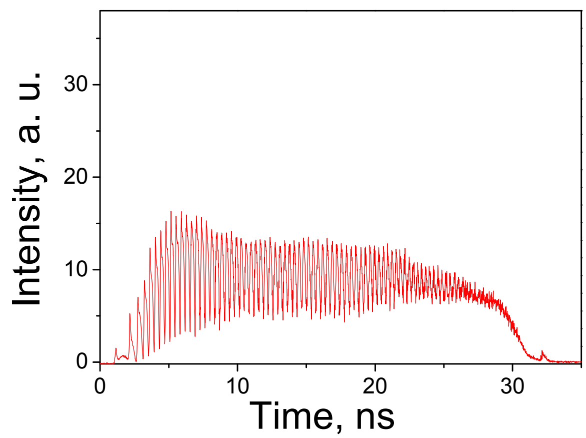


Figure 4. Weakly damped relaxation oscillations for the pump current of 1.08 A. The time traces show the total (black), and filtered ES (red) outputs. Relaxation oscillations frequency is shown in blue.

Large amplitude weakly damped relaxation oscillations are not reported for simultaneous GS-ES cw operation. The cascade-like relaxation pathway modeling of simultaneous operation predicts significant change of the relaxation oscillation frequency which depends on a linear asymmetric combination of the two-state intensities [12], but does not explain weak damping of the oscillations. We propose that the weak damping can be the result of complicated combination of the two pathways in which neither the cascade-like nor the direct capture are dominant.

3. SUMMARY

An InGaAs quantum dot laser operating simultaneously at the ground and excited states was studied in the regime of the short electrical pulse pumping. There are merely two carrier relaxation pathways in quantum dot materials: the cascade-like pathway (wetting layer (WL)-ES-GS) and the direct capture pathway (WL-GS). They determine three different regimes of operation depending on the pump current. For the low or the high ranges of the pump current, either the cascade-like pathway or the direct capture pathway is dominant, and the output pulse is stable. For the mediate current range a set of the damped large amplitude relaxation oscillations was observed. The dynamical behavior was the result of interplay between both pathways.

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REFERENCES

[1] W. Qin, Y. Liu, Y. Cao, J. Gao, F. Pan, Z. Wang, “2000W high beam quality diode laser for direct materials processing,” Proc. SPIE 8197, 81971J (2011).

[2] V.B. Campos, C.C. Dierickx, W.A. Farinelli, T.Y.D. Lin, W. Manuskiatti, R.R. Anderson, “Hair removal with an 800-nm pulsed diode laser”, Journal of the American Academy of Dermatology 43, 442 (2000).

[3] I. Greppi, “Diode laser hair removal of the black patient” Lasers in Surgery and Medicine 28, 150 (2001).

[4] G.S.Sokolovskii, S.B.Onikienko, K.K.Soboleva, A.V.Zemlyanoi, N.A.Pikhtin, I.S.Tarasov, B.A.Margulis, I.V.Guzova, “Hsp70 and ceramide release by diode laser-treated mouse skin cells in vivo”, Journal of Physics: Conference Series 572**,** 012017 (2014).

[5] E.U.Rafailov, M.A.Cataluna, W.Sibbett, “Mode-locked quantum-dot lasers”, Nature Photonics 1, 395 (2007).

[6] A. Markus, J. X. Chen, C. Paranthoen, A. Fiore, C. Platz, and O. Gauthier-Lafaye, “Simultaneous two-state lasing in quantum-dot lasers,” Appl. Phys. Lett. 82, 1818 (2003).

[7] E.A.Viktorov, P. Mandel,Y. Tanguy, J. Houlihan, and G. Huyet, “Electron-hole asymmetry and two-state lasing in quantum dot lasers,” Appl. Phys. Lett. 87, 053113 (2005).

[8] M. Gioannini, “Ground-state power quenching in two-state lasing quantum dot lasers,” J. Appl. Phys. 111, 043108 (2012).

[9] J. Gomis-Bresco, S. Dommers-Völkel, Schöps, Y. Kap tan, O. Dyatlova, D. Bimberg, and U. Woggon, “Time-resolved amplified spontaneous emission in quantum dots,” Appl. Phys. Lett. 97, 251106 (2010).

[10] G.S.Sokolovskii, M.AbuSaa, J.Danckaert, V.V.Dudelev, A.G.Deryagin, I.I.Novikov, M.V.Maximov, A.E. Zhukov, V.M.Ustinov, V.I.Kuchinskii, W.Sibbett, E.U.Rafailov, E.A.Viktorov, T.Erneux, “The effect of slow passage in the pulse-pumped quantum dot laser” Proc. SPIE 9134, 9134-4 (2014).

[11] T. Erneux, E.A. Viktorov, P. Mandel, “Time scales and relaxation dynamics in duantum-dot lasers,” Phys. Rev. A 76, 023819 (2007).

[12] M. Abusaa, J. Danckaert, E. A. Viktorov, and T. Erneux, “Intradot time scales strongly affect the relaxation dynamics in quantum dot lasers,” Phys. Rev. A 87, 063827 (2013).