Effects of carrier relaxation processes on quantum dot laser properties

A. Tohyama, R. Lang, K. Misawa, H. Saito*, and K. Nishi*

*Applied Physics Department, Tokyo University of Agriculture and Technology, and *Photonic and Wireless Devices Research Labs., NEC Corporation*

The lasing properties of the quantum dot (QD) lasers are critically dependent on the carrier relaxation processes that redistribute carriers among different confined states and dots. For example, they are essential in reducing the *spectral* and *spatial* hole-burnings which would otherwise cause multi-mode lasing [1]. In turn, lasing characteristics are sensitive indicators of the various relaxation rates in QDs. Much attention is being focused on the direct modulation properties of QD lasers. In this report, effects of the inter-confined levels relaxation and Pauli blocking on modulation properties are analyzed. The down- and up-ward relaxation flows between the ground confined (denoted as 1) and the first excited (2) levels can be expressed as $\gamma_{21} p_2(1-p_1)$ and $\gamma_{12} p_1(1-p_2)$, respectively, where p_1 and p_2 are the occupation probabilities of the relevant states. It has been pointed out that the inter-confined level relaxation may be affected by so called phonon bottleneck. Experimental and theoretical values reported for γ_{21} vary widely around from 10^{12} to 10^{10} s^{-1}, which very likely results from the dependence of the coefficient on device parameters such as the level separations determined by the dot size and carrier densities in QDs and confining layers.

Fig.1(a-c) depict calculated transient response of the laser output to a stepwise increase at time t=0 of the injection current density from zero to 3.0 times the threshold value J_{th}. It is apparent that the familiar relaxation oscillations in the laser output is strongly damped as inter-level relaxation coefficient γ_{21} is reduced from 10^{12} (observed in some QD lasers at room temperature) to $10^{10}s^{-1}$. The reason can be deduced from the associated wave form of level occupancies depicted in Fig.1(d-f). Slow bilateral carrier flows between the two levels result in phase difference in the oscillation of the level occupancies, which causes the damping, leading to severe reduction in effective modulation bandwidth for digital signals.

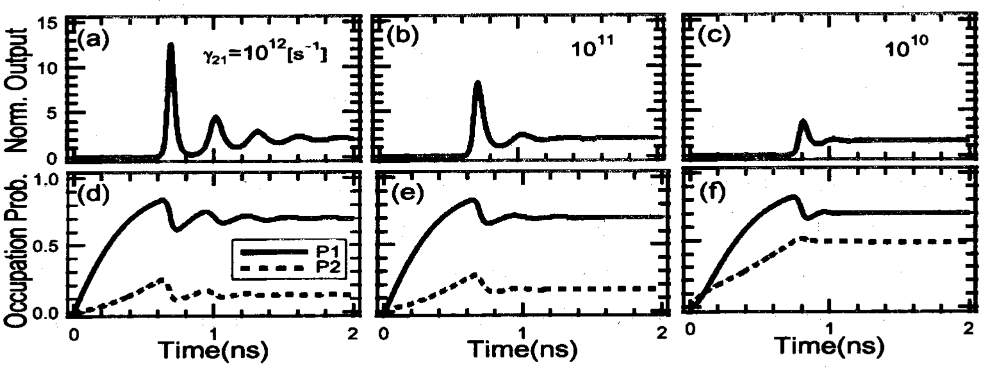

Fig1. Transient responses of output(a-c) and occupation(d-f) to a stepwise increase of current.

The Pauli blocking factor $(1-p_1)$ shows up as a multiplicative factor in the transition flow. It has been found that increase in the threshold (or steady state) value of p_1 does not just reduce the downward transition flow, but markedly lower the relaxation oscillation frequency f_R, resulting also in narrowing of the modulation bandwidth. These results indicate that the QD laser dynamic response bandwidth will be expanded substantially by device parameter optimization to increase the inter-level relaxations and to reduce the threshold occupation in the lasing level.

[1] R. Lang, H. Ito, and K. Misawa, Abstracts of the 7th International Workshop on Femtosecond Technology, p.83 (2000).

◎*List of publications and presentations(after last Symposium)*

(1) Pubulications

1) Kazuhiko Misawa, "Ultrafast exciton dynamics in molecular J-aggregates", Abstracts of International Workshop on Femtosecond Technology 2001, p.77 (2001).

2) Sayako Itoh, Kazuhiko Misawa, and Roy Lang, "Femtosecond Phase and Amplitude Distortion in Dielectric Materials Measured by Cross-Correlation Frequency Resolved Optical Gating", Abstracts of International Workshop on Femtosecond Technology 2001, p.185 (2001).

3) Isao Matsuda, Kazuhiko Misawa, and Roy Lang, "Phase-Programmable Femtosecond Optical Source for Wave Packet Engineering", Abstracts of International Workshop on Femtosecond Technology 2001, p.186 (2001).

4) Tsugumichi Nagana, K. Misawa, and R. Lang, "Time-resolved interferometry of porphyrin J-aggregates using femtosecond Sagnac interferometer", Abstracts of International Workshop on Femtosecond Technology 2001, p.184 (2001).

5) 松田功、三沢和彦、覧具博義「電子波束制御を目的としたフェムト秒位相制御光源」信学技報 LQE2001-13, vol.101 No.65 (2001)

6) A. V. Uskov, I. Magnusdottir, B. Tromborg, and J. Mork, and R. Lang, "Line broadening caused by Coulomb carrier-carrier correlations and dynamics of carrier capture and emission in quantum dots", Applied Physics Letters, 79(11) 1679-1681 (2001)

7) K. Ohmori, M. Nakamura, H. Chiba, K. Amano, M. Okunishi, and T. Sato, "Development of Attosecond Optical-Phase Manipulation for the Wave-Packet Engineering", J. Photochemistry Photobiology A: Chemistry, accepted (2001).

8) Y. Sato, H. Chiba, M. Nakamura, and K. Ohmori, "Double-Pulse Manipulation of Vibrational Wavepackets in HgAr van der Waals Complex", American Chemical Society Book on "Laser Control and Manipulation of Molecules" ed. by A. Bandrauk, Y. Fujimura, and R. J. Gordon (ACS Press, 2001) , invited paper, in press.

9) Y. Sato, K. Ohmori, K. Amano, H. Chiba, and M. Nakamura, ﾒSub-femtosecond Coherent Control of Vibrational Wavepacket in the van der Waals Interactions ﾓ, Proceedings of the 21st International Conference on Photonic, Electronic, and Atomic Collisions, (Rinton Press, 2001).

10) K.Ohmori, K.Amano, H.Chiba, M.Nakamura, M.Okunishi, and Y.Sato, "Attosecond coherent control of the wave packet dynamics in the Hg-X van der Waals interaction", in Spectral Line Shapes, Vol. 11, edited by J. Seidel (AIP Press, 2001), pp.284-286.

11) Kenji Ohmori, ``Using optical collision to control the transition-region dynamics", in Multiphoton Processes and Spectroscopy, Vol.14, edited by R.J.Gordon and Y.Fujimura (World Scientific, 2001), invited paper, pp.80-96.

(2) Presentations

1) Kazuhiko Misawa, "Ultrafast exciton dynamics in molecular J-aggregates", International Workshop on Femtosecond Technology 2001, Tsukuba (June 29-30,2001).

2) Sayako Itoh, Kazuhiko Misawa, and Roy Lang, "Femtosecond Phase and Amplitude Distortion in Dielectric Materials Measured by Cross-Correlation Frequency Resolved Optical Gating", International Workshop on Femtosecond Technology 2001, Tsukuba (June 29-30,2001).

3) Isao Matsuda, Kazuhiko Misawa, and Roy Lang, "Phase-Programmable Femtosecond Optical Source for Wave Packet Engineering", International Workshop on Femtosecond Technology 2001, Tsukuba (June 29-30,2001).

4) Tsugumichi Nagana, Kazuhiko Misawa, and Roy Lang, "Time-resolved interferometry of porphyrin J-aggregates using femtosecond Sagnac interferometer", International Workshop on Femtosecond Technology 2001, Tsukuba (June 29-30,2001).
5) 松田功、三沢和彦、覧具博義「電子波束制御を目的としたフェムト秒位相制御光源の開発」応用物理学会、2001 年 3 月（東京）
6) 松田功、三沢和彦、覧具博義「電子波束制御を目的としたフェムト秒位相制御光源」電子情報通信学会 LQE 研究会、2001 年 5 月（金沢）
7) 永名継道、三沢和彦、覧具博義「Sagnac 干渉計を用いたフェムト秒時間分解干渉測定」応用物理学会、2001 年 9 月（名古屋）
8) 松田功、三沢和彦、覧具博義「フェムト秒位相制御光源を用いたシアニン色素の分子振動波束制御」応用物理学会、2001 年 9 月（名古屋）
9) 松田功、三沢和彦、覧具博義「フェムト秒位相制御光源を用いた分子核波束の制御」日本物理学会、2001 年 9 月（徳島）
10) 三沢和彦「フェムト秒位相制御光源を用いた電子波束制御エンジニアリング」超高速光エレクトロニクス研究会、2001 年 10 月（横浜）
11) 大森賢治, ``アト秒量子波束エンジニアリングの開発", 高輝度光源長尺アンジュレーター利用研究ワークショップ, 2001 年 8 月 24 日, 柏, 招待講演
12) 大森賢治, ``アト秒量子波束エンジニアリングの開発", 第 41 回 分子科学若手の会 夏の学校, 2001 年 8 月 7-11 日, 箱根, 招待講演
13) 大森賢治, ``アト秒量子波束エンジニアリングの開発", レーザー光子場による分子制御研究会, 2001 年 6 月 30 日, 仙台, 招待講演
14) Y. Sato, K. Ohmori, K. Amano, H. Chiba, and M. Nakamura, Sub-femtosecond Coherent Control of Vibrational Wavepacket in the van der Waals Interactions t, 21st International Conference on Photonic, Electronic, and Atomic Collisions, Santa Fe, New Mexico, (July 18-24, 2001)
15) 中村美香、大森賢治、千葉　寿、奥西みさき、佐藤幸紀「アト秒量子波束エンジニアリング…アト秒波束干渉制御法の開発」分子構造総合討論会、2001 年９月、札幌；及び、化学系７学協会連合東北地方大会、2001 年９月、鶴岡
16) 佐藤幸紀、大森賢治、千葉　寿、中村美香、奥西みさき「アト秒量子波束エンジニアリング…分子波束エンコーディングのモデル計算」分子構造総合討論会、2001 年９月、札幌；及び、化学系７学協会連合東北地方大会、2001 年９月、鶴岡
17) 大森賢治、千葉　寿、中村美香、奥西みさき、佐藤幸紀「アト秒量子波束エンジニアリング…強レーザー場での量子位相制御を目指して」分子構造総合討論会、2001 年９月、札幌；及び、化学系７学協会連合東北地方大会、2001 年９月、鶴岡
18) 千葉　寿、中村美香、大森賢治、奥西みさき、佐藤幸紀「アト秒量子波束エンジニアリング…アト秒位相変調器の試作」化学系７学協会連合東北地方大会、2001 年９月、鶴岡
19) H. Saito, "Uniform InAs quantum dot formation by MBE and its laser application", International Symposium on Advanced Physical Fields, Tsukuba (March 6–9, 2001)

<u>(3) Patent applications(total)</u>

1) 三沢 和彦、覧具 博義「光多重送信装置、光多重受信装置、光多重送受信装置、光多重通信装置」、2001 年 9 月 5 日、特願 2001-268846