Dynamic properties of two-state lasing quantum dot laser for external optical feedback resistant applications

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Abstract—This work investigates the dynamics of two-state quantum dot lasers through semi-analytically solving a set of rate equations. Simulations reveal that the occurrence of excited state lasing reduces the damping factor and relaxation oscillation frequency of the laser while increases the linewidth enhancement factor associated to the ground state transition. These results are in good agreement with the experimental observation showing that the quantum dot laser becomes more sensitive to external optical feedback at excited state lasing threshold. This work brings novel insights in the understanding of quantum dot laser physics that are useful for designing feedback resistant lasers in photonic integrated technologies.

Index Terms—Semiconductor lasers, quantum dots, linewidth enhancement factor, external optical feedback.

I. INTRODUCTION

Silicon photonics has been introduced to achieve high performance and low cost photonic integrated circuits (PICs) [1]. However, the challenge in PICs is the parasitic reflections from on-chip components that feed light back into the laser source and cause strong laser destabilization. As on-chip optical isolators are complicated to fabricate, the development of highly optical feedback resistant laser sources is important. Quantum dot (QD) lasers directly grown on silicon have been shown much higher tolerance to external optical feedback than quantum well lasers, mostly attributing to the small linewidth enhancement factor ($\alpha_H$-factor) and the high damping factor [2]. However, owing to the slow carrier scattering rate and the unclamped gain dynamics, QD lasers can simultaneously emit on both ground state (GS) and excited state (ES) transitions. The critical feedback level ($r_{crit}$) is an important criterion, corresponding to the maximum feedback ratio that can be tolerated into a communication system for maintaining an error-free operation. Above $r_{crit}$, the laser enters the coherence collapse regime which is typically determined at the point where the laser linewidth is significantly broadened. We experimentally found that the $r_{crit}$ of the QD laser strongly depends on the occurrence of the ES, demonstrating that the reflection tolerance is greatly degraded at ES lasing threshold of $I_{ES}^{th}$ [3]. This work is therefore motivated by theoretically explaining this phenomenon. Simulations are in good agreement with the experiments, showing that the damping factor and relaxation oscillation frequency (ROF) significantly decrease while the $\alpha_H$ substantially increases at the ES lasing threshold, which finally affects the laser’s resistance against external optical feedback.

II. RATE EQUATION MODEL OF QUANTUM DOT LASER

Fig. 1(a) illustrates the schematic of the carrier dynamics of the QD laser, where both electrons and holes are treated as neutral excitons. The QD model consists of a two dimension carrier reservoir RS, a four-fold degenerate ES and a two-fold degenerate GS. The dynamics among the three levels is characterised by capture time $\tau_{ES}^{opt}$, relaxation time $\tau_{ES}^{opt}$ and escape time $\tau_{GS}^{opt}$ and $\tau_{ES}^{opt}$. In addition, carriers in RS, ES and GS are also recombined spontaneously within spontaneous time $\tau_{RS,ES,GS}^{opt}$ respectively. The stimulated emissions are considered to occur in both ES and GS. The dynamics of carrier number $N_{RS,ES,GS}$, the photon number $S_{ES,GS}$, and the phase of the light $\phi_{ES,GS}$ are described by a coupled rate equation model as shown in Fig. 1(b) [4]. Where $I$ is the injected current, $q$ is the elementary charge, $\rho_{RS,ES,GS}$ are the corresponding carrier occupation probabilities in RS, ES, and GS, $\Gamma_p$ is the optical confinement factor, $\tau_p$ is the photon lifetime, $\beta_{sp}$ is the spontaneous emission factor, and $v_g$ is the group velocity of the light. $\alpha_{ES,GS}$ are the intrinsic $\alpha_H$-factor of ES and GS, $k_{RS,ES}$ are the contributions of carrier variation in RS and ES to the $\alpha_H$ of GS, $g_{RS,ES,GS}$ represent material gain of each state. $F_{RS,ES,GS}$ are carrier noise sources in RS, ES and GS, respectively. $F_{ES,GS}$ and $F_{ES,GS}$ are the corresponding photon and phase noise sources in ES and GS. The damping factor and ROF are extracted from the laser system modulation transfer function, while the $\alpha_H$ is obtained from the frequency noise spectrum [4].

III. RESULTS AND DISCUSSION

Fig.2 shows the bias current dependence of the damping and relaxation oscillation dynamics of the QD laser. At about $0.8 \times I_{ES}^{th}$, the laser is overdamped with a damping factor as...
large as 170 GHz and a ROF of 1.23 GHz. However, along with the increase of the bias current, the damping factor dramatically decreases down to a minimal level at 9 GHz with a ROF of 0.6 GHz at the ES lasing threshold. This large collapse of the damping factor is attributed to the dominant contribution of the spontaneous emission of ES. After the ES lasing threshold, the stimulated emission of ES prevails over the spontaneous emission, which increases the damping factor as well as the ROF. Fig. 3 demonstrates the $\alpha_H$ originates from the GS lasing and ES lasing as a function of the bias current. As shown, the GS $\alpha_H$ increases from 0.7 at $0.2\times I_{th}^{ES}$ to 1.1 at $0.9\times I_{th}^{ES}$, resulting from the increased contribution of carrier variation from ES and RS. Near the ES lasing, the GS $\alpha_H$ dramatically increases to 2.9, which is attributed to the enhanced carrier variation strength in ES associated with the collapsed damping factor [5]. While after ES lasing, the carriers in ES are clamped, thus the carrier variation in ES is suppressed and the damping factor increases again, hence the GS $\alpha_H$ decreases and finally gets saturated around 0.6. By comparison, the ES $\alpha_H$ increases from 0.33 at ES threshold to 0.5 at $1.5\times I_{th}^{ES}$. The $r_{crit}$ can be expressed by the relationship

$$ r_{crit} = \omega_{ROF}^2 R/(1 - R)^2 (1 + \alpha_H^2) \Delta \nu^2 $$

with $\omega_{ROF}$ the angular ROF, $R$ the facet reflectivity coupled to the external cavity, $\Delta \nu$ the free spectral range of the laser. Fig. 4 compares the $r_{crit}$ as a function of the bias current normalized to the ES threshold current ($I/I_{th}^{ES}$) between the simulation and the measurement. The simulation results qualitatively agree with the measurements, indicating that the QD lasers show strong stability against optical feedback with relative high $r_{crit}$ before the ES lasing occurs. As the bias current increases, the $r_{crit}$ decreases due to the progressive occurrence of the ES and reaches the lowest level at ES threshold. Once the ES lasing occurs, the $r_{crit}$ re-increases with the bias current and the laser returns to the high $r_{crit}$. However, the simulations do not quantitatively agree with the experiment. This discrepancy can be mostly explained by the model itself, which does not take into account all the peculiar properties of the QD and the lasers have different ES-to-GS ratio. These results demonstrate that the $\alpha_H$ (damping factor respectively) exhibits a local maximum (minimum respectively) value at the onset of the ES lasing which transforms into a local minimum value of the critical feedback level at $I_{th}^{ES}$. This theoretical analysis is in a good agreement with the experimental observation and tends to prove that QD lasers exhibiting a two-state lasing operation are more sensitive to external optical feedback.

**IV. CONCLUSION**

In summary, we theoretically demonstrate that the two-state lasing QD laser exhibits local extrema for the damping, ROF and $\alpha_H$ at the ES lasing threshold. Together, these contributions make the QD laser more sensitive to external optical feedback, which is in good agreement with the prior experimental observation. Overall, this work brings new insights for understanding the physical mechanisms in QD lasers and is useful for designing feedback-insensitive lasers in PICs.

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**REFERENCES**


