Optical Feedback Dynamics in Dual-state Quantum Dot Lasers

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***Abstract*—In this paper, the dynamics of dual-state quantum dot (QD) lasers under external optical feedback are investigated by solving the three-level rate equations in the time domain. The results show that the high excited-to-ground-state (ES-GS) energy separation in QD lasers leads to a high ES-GS threshold ratio hence strengthening the feedback resistance. These findings shed new light on the fabrication of feedback-resistant dual-state QD lasers for isolator-free photonic integrated circuits.**

Keywords-component; quantum dot lasers; external optical feedback; critical feedback level

I. Introduction

Photonic integrated circuits (PICs) have a very broad application prospect in various fields of next-generation data centers, high-performance computing, and LiDAR for self-driving vehicles [1]. However, the external optical feedback induced between the on-chip laser and other optical components can lead the laser to operate in a chaotic state, which becomes one of the major challenges in PICs. In this context, epitaxial quantum dot (QD) lasers on silicon with large damping factor, low linewidth enhancement factor (α-factor), and operating in sole ground state (GS) have shown remarkable feedback insensitivity [2].

For QD lasers, it is difficult to maintain the sole GS operation along with the increase of the bias current because of the mode competition between GS and excited state (ES). Due to the unclamped gain, the QD lasers trend to operate in the dual-state at high output power where simultaneous GS and ES lasing are obtained. The dual-state emission in QD lasers results from the cascade-like carrier relaxation process and leads to bistabilities and Q-switching mechanisms which are useful for optical information processing [3].

When the laser is experiencing external optical feedback, the critical feedback level is an important criterion to evaluate the feedback resistance which refers to the maximum feedback ratio making the laser entering within the coherence collapse regime. Prior works have shown that the onset of critical feedback level strongly depends on the excited-to-ground-state (ES-GS) threshold ratio, hence a robust GS emission without switching to higher energy states usually confers a higher degree of stability subject to optical feedback [4]. This effect can be partly explained by the larger damping factor and lower α-factor at the ES lasing threshold [5].

The purpose of the current work is to further investigate the complete optical feedback dynamics in dual-state QD lasers through the analysis of the three-level rate equations taking into account the effect of optical feedback. The critical feedback level extracted from the bifurcation diagram is used to characterize the feedback resistance of the QD lasers. The ES-GS energy level separation associated with the threshold ratio determines the stable operation range of the laser under external optical feedback. These results show that the optimized higher ES-GS energy separation leads to a relative high feedback tolerance, which provides new insight for isolator-free applications.

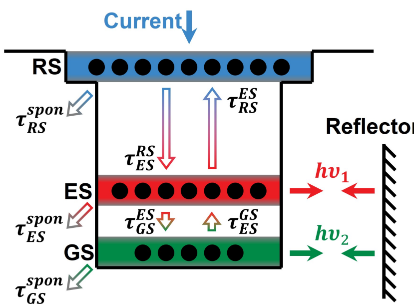

Figure 1. Schematic of carrier dynamic in dual-state QD lasers under optical feedback.

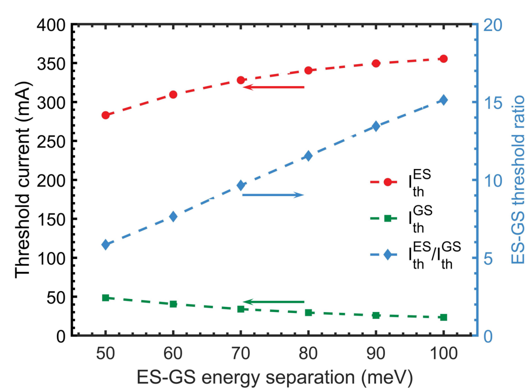

Figure 2. GS threshold current, ES threshold current and corresponding ES-GS threshold ratio as a function of ES-GS energy separation.

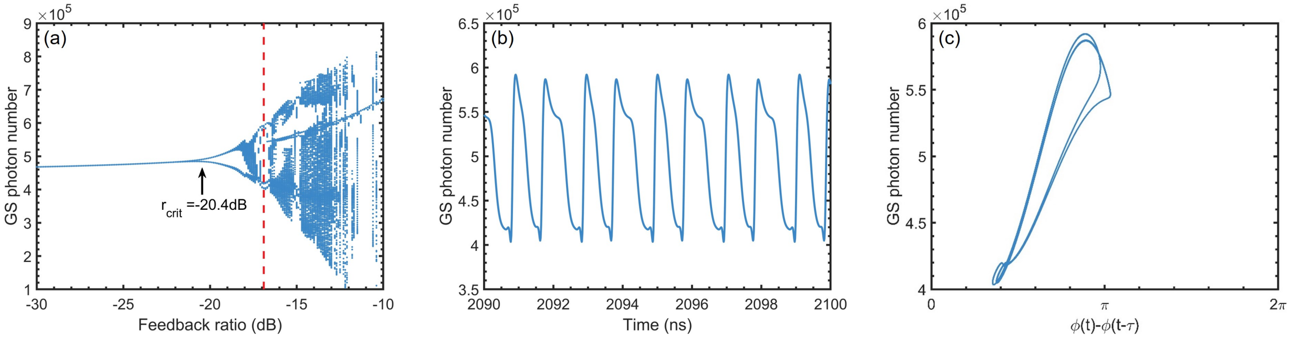

Figure 3. (a) Bifurcation diagram, (b) time series, and (c) phase portrait at I/I_{th}^{ES} of 0.82. The time series and phase portrait are taken from the feedback ratio of -16.9. dB (red vertical dotted lines in bifurcation diagram).

II. Three-Level Model of Quantum Dot Laser under Feedback

A schematic of carrier dynamic describing the three-level model of dual-state QD lasers under optical feedback is shown in Fig. 1. It is assumed that electrons and holes can be considered as neutral excitons and the active region has only one QD ensemble, which means that the size distribution of the QD is not considered in this model. Carriers are captured from a two-dimension carrier reservoir (RS) to a four-fold degenerate of ES after they were directly injected from the electrode to RS. Then a relaxation process occurs from the ES to a two-fold degenerate of GS. Also, some carriers are thermally excited from GS to ES and from ES to RS. On the other hand, some carriers in RS, ES, and GS recombine spontaneously. These processes can be expressed by capture time (τ_{ES}^{RS}), relaxation time (τ_{GS}^{ES}), escape time (τ_{RS}^{GS}, τ_{RS}^{ES}), and spontaneous emission time ($\tau_{RS,ES,GS}^{spon}$), respectively. Both the GS and the ES exhibit stimulated emission and suffer from the external optical feedback simultaneously.

$$\frac{dN_{RS}}{dt}=\frac{I}{q}+\frac{N_{ES}}{\tau_{RS}^{ES}}-\frac{N_{RS}}{\tau_{ES}^{RS}}\left(1-\rho_{ES}\right)-\frac{N_{RS}}{\tau_{RS}^{spon}} \tag{1}$$

$$\begin{aligned}\frac{dN_{ES}}{dt}=&\left(\frac{N_{RS}}{\tau_{ES}^{RS}}+\frac{N_{GS}}{\tau_{ES}^{GS}}\right)\left(1-\rho_{ES}\right)-\frac{N_{ES}}{\tau_{GS}^{ES}}\left(1-\rho_{GS}\right)-\frac{N_{ES}}{\tau_{RS}^{ES}}\\&-\frac{N_{ES}}{\tau_{ES}^{spon}}-\Gamma_p v_g g_{ES}S_{ES}\end{aligned} \tag{2}$$

$$\begin{aligned}\frac{dN_{GS}}{dt}=&\frac{N_{ES}}{\tau_{GS}^{ES}}\left(1-\rho_{GS}\right)-\frac{N_{GS}}{\tau_{ES}^{GS}}\left(1-\rho_{ES}\right)-\frac{N_{GS}}{\tau_{GS}^{spon}}\\&-\Gamma_p v_g g_{GS}S_{GS}\end{aligned} \tag{3}$$

$$\begin{aligned}\frac{dS_{ES}}{dt}=&\left(\Gamma_p v_g g_{ES}-\frac{1}{\tau_p}\right)S_{ES}+\beta_{sp}\frac{N_{ES}}{\tau_{ES}^{spon}}\\&+2\frac{k}{\tau_{in}}\sqrt{S_{ES}(t)S_{ES}(t-\tau)}\cos\left(\Delta\phi_{ES}\right)\end{aligned} \tag{4}$$

$$\begin{aligned}\frac{dS_{GS}}{dt}=&\left(\Gamma_p v_g g_{GS}-\frac{1}{\tau_p}\right)S_{GS}+\beta_{sp}\frac{N_{GS}}{\tau_{GS}^{spon}}\\&+2\frac{k}{\tau_{in}}\sqrt{S_{GS}(t)S_{GS}(t-\tau)}\cos\left(\Delta\phi_{GS}\right)\end{aligned} \tag{5}$$

$$\begin{aligned}\frac{d\phi_{ES}}{dt}=&\frac{1}{2}\Gamma_p v_g\left(g_{GS}\kappa_{ES}^{GS}+g_{ES}\alpha_{ES}+g_{RS}\kappa_{ES}^{RS}\right)\\&-\frac{k}{\tau_{in}}\sqrt{\frac{S_{ES}(t-\tau)}{S_{ES}(t)}}\sin\left(\Delta\phi_{ES}\right)\end{aligned} \tag{6}$$

$$\begin{aligned}\frac{d\phi_{GS}}{dt}=&\frac{1}{2}\Gamma_p v_g\left(g_{GS}\alpha_{GS}+g_{ES}\kappa_{GS}^{ES}+g_{RS}\kappa_{GS}^{RS}\right)\\&-\frac{k}{\tau_{in}}\sqrt{\frac{S_{GS}(t-\tau)}{S_{GS}(t)}}\sin\left(\Delta\phi_{GS}\right)\end{aligned} \tag{7}$$

Equations (1-7) are corpuscular rate equations describing the dynamics of carrier number ($N_{RS,\ ES,\ GS}$), photon number ($S_{ES,\ GS}$), and optical field phase ($\phi_{ES,\ GS}$). The injected current is expressed by I, the photon lifetime is expressed by τ_p, the internal round-trip time is expressed by τ_{in}, and the external round-trip time is expressed by τ. The feedback term is characterized by:

$$k=\frac{1-R}{\sqrt{R}}\sqrt{f_{ext}} \tag{8}$$

where f_{ext} is the feedback ratio of the external cavity, and the feedback phase variation written as:

$$\Delta\phi_{ES}=\phi_{ES}(t)-\phi_{ES}(t-\tau) \tag{9}$$

$$\Delta\phi_{GS}=\phi_{GS}(t)-\phi_{GS}(t-\tau) \tag{10}$$

Material and optical parameters of the dual-state QD laser are the same as those given in [6] when they are not otherwise determined. The intrinsic α-factor is 1.0 in this work.

III. Results and Discussion

Based on this three-level model, the GS threshold current (I_{th}^{GS}), ES threshold current (I_{th}^{ES}), and ES-GS threshold ratio are plotted in Fig. 2 as a function of ES-GS energy level separation. I_{th}^{ES} increases from 283 mA at ΔE_{GS}^{ES} = 50 meV to 355.5 mA at ΔE_{GS}^{ES} = 100 meV, while I_{th}^{GS} decreases from 48.5 mA to 23.5 mA hence the ES-GS threshold ratio increases from 5.84 to 15.1. This trend indicates that the ES-GS energy separation enlarges the ES-GS threshold ratio. It is noted that a QD laser with the ES-GS energy separation of 108 meV has been demonstrated [7] and the energy separation is theoretically achievable up to 126 meV [8].

Fig. 3(a) shows the bifurcation diagram, time series, and phase portrait plotted at bias current normalized to the ES threshold current (I/I_{th}^{ES}) of 0.82 when ΔE_{GS}^{ES} is fixed at 50 meV, corresponding to an ES-GS threshold ratio of 5.84. The QD laser shows the clear route to chaotic state with the increase of feedback ratio through the steady-state, single-period, double-period, and multi-period states. Fig. 3(b) gives an example of double-period state in the time series when f_{ext} = –16.9 dB with the corresponding phase portrait shown in Fig. 3(c).

The critical feedback level can be obtained from the first Hopf bifurcation, which is shown by the arrow in Fig. 3(a). In order to investigate the effect of energy level separation on the feedback resistance, the critical feedback level versus I/I_{th}^{ES} is plotted in Fig. 4 for ΔE_{GS}^{ES} = 50 meV and ΔE_{GS}^{ES} = 100 meV, respectively. For comparison, the red dotted curve also gives the measurement data from [4]. The simulation in the case of $\Delta E_{GS}^{ES} = 50\ meV$ qualitatively agrees with the measurements. The laser shows relatively high feedback stability in the regime before and after I_{th}^{ES}. Once the laser operates at the ES threshold, the critical feedback level is degraded due to the larger damping factor and lower α-factor [4].

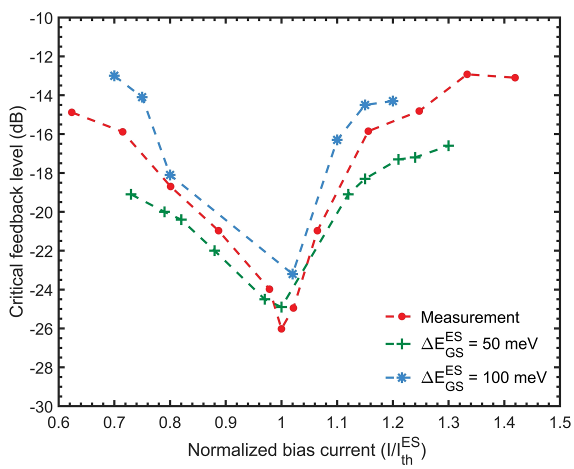

Figure 4. Critical feedback levels versus normalized bias current I/I_{th}^{ES} for the cases of measurement, simulation at $\Delta E_{GS}^{ES} = 50\ meV$ and simulation at $\Delta E_{GS}^{ES} = 100\ meV$, respectively.

When the ES-GS energy level separation increases to 100 meV, the entire critical feedback level versus the bias current is up-shifted to a higher level suggesting a better feedback insensitivity. Experiments in [4] have demonstrated that dual-state QD lasers with large ES-GS threshold ratios are more stable for external optical feedback. The simulation in this work shows that the ES-GS threshold ratios depend on ES-GS energy separation. These results validate the experimental observation and further show a possible path to fabricate the feedback-insensitive dual-state QD laser by increasing the ES-GS energy separation through the use of smaller dots, and more QD layers in the active region.

IV. Conclusion

In summary, the three-level model of dual-state QD lasers under external optical feedback is developed. The critical feedback level is extracted from the bifurcation diagram with times series and phase portrait. The results show that the higher ES-GS energy level separation, which is positively correlated with the ES-GS threshold ratio, can improve feedback insensitivity. These results provide an attractive explanation for the previously discovered phenomenon and highlight the importance of energy level engineering for designing the feedback-insensitive dual-state QD laser for isolator-free PICs.

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