Lasing state hysteresis in a two-state quantum dot laser via optical injection

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ABSTRACT

Quantum dot lasers readily lase from multiple distinct energy states. We examine the influence of optical injection into the ground state (GS) when the free-running operation is the first excited state (ES) only and demonstrate the existence of an injection-induced bistability between GS emission and ES emission. There is a consequent hysteresis loop in the lasing output. Experimental and numerical investigations are in excellent agreement.

1. INTRODUCTION

Quantum dot (QD) lasers based on InAs readily lase from multiple distinct energy states. As with conventional semiconductor lasers these devices can emit from the ground state (GS).\textsuperscript{1} However, single state lasing from the first excited state (ES) and the second excited state can also be obtained as well as simultaneous two-state lasing from the GS and first ES.\textsuperscript{2} The behavior of these devices under optical injection into the GS when the free-running operation is GS lasing only has been well studied in recent years.\textsuperscript{3–5} However, their behavior when undergoing optical injection into the GS when the free-running operation is single-state lasing from the first ES has only recently begun to be examined. Optical injection into the GS can suppress the ES emission and cause the device to lase from the GS only, even with relatively weak injection strengths. We demonstrate the existence of an injection-induced bistability between the GS emission and ES emission and a consequent hysteresis loop in the output lasing state, revealed by sweeping the power of the master laser up and down close to the lasing wavelength of the GS. We investigate the size of the loop as the operating point of the laser is varied. We also investigate the influence of the wavelength of the master laser and identify several new dynamic two-state pulsing regimes. We analyze the system numerically using a detailed model designed specifically for quantum dot lasers and show excellent agreement with the experimental results.

2. FREE RUNNING QD LASER

Experimentally, the studied slave laser (SL) was a 0.6 mm long InAs QD laser similar to that used in\textsuperscript{6} and lased either at the GS (around 1300 nm) or simultaneously at the GS and ES (around 1215 nm) or solely at the ES. The threshold currents of the laser were 34 mA for GS lasing and 60 mA for simultaneous GS and ES lasing at room temperature. Above 80 mA, the device lased from the ES only. Three modes of operation - GS, GS+ES, ES - for the output are typical for short cavity QD lasers with increasing pump current and their study has previously attracted significant attention.\textsuperscript{6–11} The emission from the GS was strictly from a single (longitudinal) mode which we label the preferential mode. The emission from the ES was multimode with about 10 nm spectral

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width. We studied the SL operating current was over the range 84-92 mA. At these currents the device lased from the ES only with an ES to GS suppression ratio in excess of 30 dB with a wavelength separation between the two states of about 85 nm.

3. MASTER LASER (ML) AND EXPERIMENTAL SETUP

The experimental setup is presented in Fig. 1. The ML was a commercially available tunable (in 0.1 pm steps) laser with a low 100 kHz linewidth. An optical circulator was used to inject light from the ML to the SL through lensed fiber via a polarization controller to ensure that the polarization states of the ML and SL were identical. The output from the SL was collected at port 3 of the circulator and connected to a 50/50 fiber beam splitter. In order to analyze the GS and the ES signals independently two optical band pass filters were used, one in each output arm of the splitter. The outputs of both optical filters were then connected to fast photodiodes and a high speed, real-time oscilloscope.

4. EXPERIMENTAL OPTICAL INJECTION

The wavelength of the master laser was set so that it was close to the preferential mode of the GS. The operating wavelength for the ML was then chosen so that the output intensity of the SL device was both constant and maximal. Injection of sufficient strength into the GS induced suppression of the ES by ~ 40 dB in comparison to the free-running emission. Sweeping the injection power of the ML up and down with a step size of 100 µW we found switching boundaries between the GS and the ES. The average intensities of both the GS and the ES after each step in both directions are shown in Fig. 2 for the full range of currents where injection induced suppression was possible. Solid lines represent the direction of increasing ML power while dashed lines represent the direction of decreasing ML power. There is an abrupt switch between the lasing states at different ML powers depending on the direction of the ML sweep. The switching boundaries form an injection induced hysteresis loop. The hysteresis loop area versus the pump current increased as shown in the onset to Fig. 2. At the chosen operating point dynamical instabilities were not observed apart from very small pockets of bursts in intensity, but various dynamical regimes were observed for other values of the ML wavelength, including excitability, large amplitude pulsations and chaos.

5. NUMERICAL SIMULATION

We consider a rate equation model customized explicitly for QD lasers, consisting of five equations for the complex electric field of the GS \(E_g\), the intensity of the ES \(I_E\), the occupation probabilities of the GS \(n^g\) and ES \(n^e\) and the carrier density in the wetting layer \(n^w\). The phase of the ES is not included since the ES is not considered. \(\epsilon\) is coupled neither to the injection nor the GS.

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\begin{align*}
\dot{E}_g &= \frac{1}{2}((1 + i\alpha)(n_e^g + n_h^g - 1) - 1) + i4\beta g_0^g(n_e^g + n_h^g - 1)E_g + i\Delta E_g + \epsilon, \\
\dot{I}_e &= [4g_0^e(n_e^e + n_h^e - 1) - 1]I_e, \\
\dot{n}_{e,h}^g &= \eta[2B_{e,h}n_{e,h}^g(1 - n_{e,h}^g) - 2C_{e,h}n_{e,h}^g(1 - n_{e,h}^e) - n_{e,h}^g - g_0^g(n_e^g + n_h^g - 1)I_g], \\
\dot{n}_{e,h}^e &= \eta[-2B_{e,h}n_{e,h}^e(1 - n_{e,h}^e) + C_{e,h}n_{e,h}^e(1 - n_{e,h}^e) + B_{e,h}n_{e,h}^w(1 - n_{e,h}^e) + B_{e,h}n_{e,h}^w - C_{e,h}n_{e,h}^e], \\
\dot{n}_{e,h}^w &= \eta[J - n_e^w n_h^w - 4B_{e,h}n_{e,h}^w(1 - n_{e,h}^e) + 4C_{e,h}n_{e,h}^w].
\end{align*}
\]
Figure 2. Experimental results showing hysteresis over a range of currents: (a) 84mA, (b) 88mA, (c) 92mA. The inset shows that the hysteresis loop area versus the slave laser pump current increases approximately linearly over the full range of currents tested.

The subscripts $e$ and $h$ stand for electron and hole respectively, dot means differentiation with respect to $t \equiv t'/\tau_{ph}$ where $t'$ is time and $\tau_{ph}$ is the photon lifetime. $\eta \equiv \tau_{ph}/\tau^{-1} \ll 1$, where $\tau$ denotes the carrier recombination time. The factors 2 and 4 account for the spin degeneracy in the quantum dot energy levels. We define $g_0^e = g_0^h = g$ as the effective gain factor scaled to the cavity losses, and assume the gain factors and the cavity losses to be identical for both GS and ES. The terms $(1 - n_{c,e,h})$ describe Pauli blocking. $B_{e,h}$ and $B_{c,h}$ describe the capture rates to the GS and ES correspondingly. To determine the escape rates $C_{c,h}$, we use the Kramers relation\textsuperscript{10} linking the capture $B_{e,h}$ and the escape $C_{c,h}$ rates

$$C_{c,h} = B_{c,h} \exp\left(-\Delta E_{c,h}/k_B T\right),$$

where $k_B$ is Boltzmann’s constant and $T$ the plasma temperature. We assume the GS and ES spacing to be $\Delta E_e \simeq 50$ meV and $\Delta E_h \simeq 0$ meV. At room temperature $k_B T = 25$ meV. $J$ is the pump current and $\alpha$ is the standard phase-amplitude coupling (the linewidth enhancement factor) in the GS. $\beta$ describes a phase-amplitude coupling from the GS to the ES and phenomenologically models inhomogeneous broadening. $\epsilon$ is the injection strength and $\Delta$ is the detuning between the injected light and the GS emission.

For zero detuning only ($\Delta = 0$) we clearly reconstruct the experimentally observed hysteresis as shown in Fig. 3. As with the experiment, the injection strength $\epsilon$ is swept both up and down. For each value of $\epsilon$ the output from each state is constant, but the injection induces a bistability in the system. The predominant emission can be from the GS or from the ES depending on the initial conditions. Hysteresis exists for $\beta \gtrsim 2$, but the hysteresis loop area progressively decreases with decreasing $\beta$ and does not exist for small but still non-zero values such as $\beta = 1.8$ and $\beta = 1$ (Fig. 3 (d,e)). The parameter $\beta$ accounts for ES-induced phase amplitude coupling. It is introduced in a somewhat phenomenological fashion but the physical origin can be addressed to the inhomogeneously broadened QD medium.
Figure 3. Numerical simulations for different amplitudes of the ES-induced phase amplitude coupling (a) $\beta = 3.5$, (b) $\beta = 3$, (c) $\beta = 2.5$ and (d) $\beta = 1$. Each panel shows the GS (blue) and ES (red) intensities versus increasing injection strength (continuous line) and decreasing injection strength (dashed line). The other parameters are: $\Delta = 0; \eta = 0.01; \alpha = 3; g_0^g = g_0^e = 0.55; J = 20; B_c = B_h = B_e^w = C_h = C_e^w = 100; C_w^v = 10$.

Figure 4. Numerical simulations for different injection strengths: (a) $\varepsilon = 2$ and (b) $\varepsilon = 3$. The panels show the GS (blue) and ES (red) intensities versus increasing injection strength (continuous line) and decreasing injection strength (dashed line). The other parameters are: $\eta = 0.01; \alpha = 3; \beta = 3; g_0^g = g_0^e = 0.55; J = 20; B_c = B_h = B_e^w = C_h = C_e^w = 100; C_w^v = 10$.

The introduction of non-zero detuning maintains the hysteretic behavior but the boundaries are different. For large positive and negative $\Delta$, the operation is predominantly ES. Variation of the detuning in the positive side leads to a hysteresis which is similar to the hysteresis obtained by sweeping the injection power $\varepsilon$. However, the hysteresis loop does not exist for the negative side of the detuning as $\Delta$ increase leads to a gradual increase of the ES intensity while the GS output correspondingly decreases similar to the case of small $\beta$ in Fig. 3 (d,e).
This preserves the asymmetry in the phase amplitude coupling well known for optically injected conventional semiconductor lasers.

6. CONCLUSION

In this paper, we considered the impact of ground state optical injection on a QD laser operating at the first excited states. We have shown that depending on the initial conditions, one can obtain emission from the GS or emission from the GS and ES simultaneously so the system demonstrates a bistability and a resulting hysteresis cycle which can be very large. The numerical hysteretic behavior is in excellent qualitative agreement with the experimental observations.

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