Feedback-generated periodic pulse trains in quantum dot lasers

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ABSTRACT

Quantum dot lasers have been shown to have greatly enhanced stability in the feedback configuration thanks to a high damping of the relaxation oscillations and they display different dynamics to those of conventional semiconductor lasers. For high feedback levels in conventional devices one obtains Low Frequency Fluctuations: sharp dropouts in intensity and subsequent gradual build-ups. Standard low frequency fluctuation-like traces are conspicuous by their absence in studies of feedback with quantum dot devices. We experimentally examine single mode quantum dot lasers at high feedback levels with a long delay and observe regular pulse-trains with a period equaling the external cavity round-trip time where each pulse features a distinctive broad trailing edge plateau. The distinctive pulse shape is very similar to the recently published strong pulse-asymmetry in two-section, passively mode-locked quantum dot lasers where this asymmetry was shown to result from the creation of different modal groups. We attribute the pulses in our experiment to the same phenomenon: each pulse corresponds to a simultaneous excitation of a number of the external cavity modes. We consider a model tailored specifically for quantum dot lasers with strong optical feedback and find it reproduces the experimentally observed trains extremely well.

Keywords: Optical Feedback, Quantum dot devices, Mode-locking

Introduction

The influence of delayed optical feedback on conventional semiconductor laser emission is a well-known and well-studied field. A schematic of an experimental set-up is shown in Fig. 1. The geometry of the configuration results in the creation of external cavity modes (ECMs) defined by the round trip time of the external cavity. When subject to very low feedback levels a semiconductor laser emits on one of the ECMs with constant frequency and constant intensity. As the feedback level is increased the behaviour changes and several distinct regimes can be observed including linewidth narrowing, mode hopping and linewidth broadening.\textsuperscript{1} At moderate to high feedback levels in conventional semiconductor lasers a regime of particular interest emerges where the coherence of the laser undergoes a large degradation known as coherence collapse (CC).\textsuperscript{2} In this regime the intensity displays large fluctuations and the linewidth can broaden to some 10s of Gigahertz. Of most interest to this work is a regime within the CC regime where the laser displays power dropouts with a staircase recovery. The rate of these dropouts is much lower than any natural frequency of the system leading to the description of the behaviour as low-frequency fluctuations (LFF).\textsuperscript{3} This behaviour has been recognised as a chaotic itinerancy of the ECMs\textsuperscript{4} and has spawned a very large number of studies and a consequent vast literature, both experimental and theoretical.

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Lasers based on quantum dot (QD) material emitting around 1300 nm have been shown to have greatly enhanced stability in the feedback configuration relative to conventional semiconductor devices. While conventional devices become unstable even at levels as low as -30 or -40 dB, quantum dot devices can remain stable at feedback levels even greater than -10 dB. This is mostly due to a high damping of the relaxation oscillations which has also been shown to greatly improve the behaviour in both optically injected and mutually coupled configurations. Thus far experimental studies have been restricted to multimode devices and these display very different dynamics to those displayed by conventional semiconductor lasers. The most striking differences are the high feedback levels required to obtain chaotic behaviour and the absence of low frequency fluctuations.

Experiment

In this work we experimentally examine single mode QD devices at high feedback levels (50% - 80%) with a long delay (approximately 1 m). We observe regular pulse trains with a period equaling the external cavity round-trip where each pulse features a distinctive broad trailing edge plateau (TEP). The formation of the sharp
peak pulses with TEP is very similar to the recently published strong pulse asymmetry in passively mode-locked QD lasers where a mode decomposition technique revealed the superposition of different modal groups.\textsuperscript{12} This suggests the possibility of stable multi-ECM operation of the device, a phenomenon unobserved with conventional devices. The laser used is a distributed feedback (DFB) single mode QD device with a strong damping rate of the relaxation oscillations, similar to that used in the study of optically injected single mode QD lasers.\textsuperscript{6} The experimental set-up is shown in Fig. 2. For low feedback levels the output has constant intensity and constant frequency as expected. As the feedback level is increased a dynamical regime emerges with a pulse train consisting of short pulses featured by broad trailing edge plateaux and a subsequent dropout as shown as shown in Fig. 3.

Theory

While the famous Lang-Kobayashi model explains the observations with conventional semiconductors very well it is unsuitable for the QD case, principally because of the high feedback levels and long external cavities typically required for instabilities. We consider here a model for a QD laser with strong optical feedback,\textsuperscript{11} relevant for the qualitative explanation of the experimental results (Fig.2). Similar to case of the optically injected QD laser, this configuration allows a class A approximation.\textsuperscript{9,10}

As with the experiment, for very low feedback levels the operation is standard continuous wave. As the level is increased a periodic pulse train emerges which is qualitatively identical to the experimental case. An example is shown in Fig. 4. The similarity to the experimental trace is very clear. Further, the similarity to the aforementioned asymmetric pulse trains obtained in passively mode locked QD lasers\textsuperscript{12} is remarkable leading to the strong suggestion that different modal groups have formed. This in turn requires a dynamical phase-locking of ECMs, a phenomenon heretofore unobserved with semiconductor lasers.
Figure 4. Numerically obtained periodic pulse train. Again, the trailing edge plateau followed by a dropout is clear in each case.

Conclusions

A single mode quantum dot laser was studied when undergoing delayed external optical feedback with a long external cavity. For low values of feedback the behaviour was typical with constant frequency and constant intensity output. For large levels of feedback a periodic trace was observed. Numerical modelling agreed extremely well with experiment and suggested the behaviour was the result of a dynamic synchronisation between several ECMs, a phenomenon very different to the well-known chaotic low frequency fluctuation behaviour associated with conventional devices.

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REFERENCES


