Bistability and opto-thermal-pulsations in a quantum-dot edge-emitting laser diode

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Abstract. Self-sustained pulsations in the output of an InAs quantum dot laser diode in the MHz range are reported for the first time. The characteristics (shape, range and frequency) are presented for the free running laser and when optical feedback in the Littrow configuration is applied. The time scale suggest that these are opto-thermal pulsation similar to those reported in quantum well amplifiers. Bistability in the light-current characteristics is observed for wavelengths smaller the gain peak ($\lambda = 1225$ nm), but it is not present for wavelength above the gain peak and for the free running lasers.

1. Introduction
Quantum dots (QD) lasers and amplifiers are emerging as an attractive light source in the wavelength range between 1.2-1.3 $\mu$m and it is important to assess their performance and stability. One subject of interest are self-pulsing lasers where self-Q-switching due to saturable absorption was observed in many devices [1, 2]. Pulsations are in the GHz region as can be expected for passive Q-switching with the lifetime of the excited state in the nanosecond range. Self-pulsations in edge-emitting QD lasers without an intentionally introduced absorber section were also observed and explained in terms of the inhomogeneous nature of the QD gain, the existence of several confined QD states and the resulting saturable absorption by energy states lower than the laser photon energy [3]. Nevertheless, these oscillations are still in the GHz range.

Bistability is also reported in quantum dot lasers with saturable absorber [1], which is not surprising because saturable absorption is known to promote bistability and self-Q-switching.

We are reporting here on self-pulsations in QD edge-emitting lasers without a saturable absorber section taking place on the MHz scale. The oscillation frequency as well as the square-wave shape hint to a thermal origin of the dynamics. Indeed, opto-thermal pulsations with a very similar phenomenology were studied in quantum well amplifiers [4, 5] and are typical for a variety of other nonlinear optical systems [6, 7]. It was shown in [4] that the self-oscillations follow van der Pol-Fitzhugh-Nagumo dynamics, a fairly general scenario of relaxation oscillations, which are characterized by the competition of very different time scales (in [4, 5] for example carrier dynamics and thermal relaxation). Interestingly, the self-pulsing dynamics are found to persist if frequency-selective feedback is applied.

2. Devices and experimental setup
The laser is an edge-emitting diode (QDL) from Innolume GmbH with a length of $L = 3.5$ mm. It contains InAs QD in a GaAs matrix. It is designed to be single spatial mode with only a
shallow edged waveguide and a stripe width of $w = 5 \mu m$. One facet of the QDL diode is anti-reflection (AR) coated while the other is high-reflection (HR) coated. The laser is mounted on a C-mount and the temperature is controlled by a Peltier element. The emission wavelength is then centered at $\lambda = 1225 \text{ nm}$.

**Figure 1.** Experimental setup: mirror (M), diffraction grating (DG), aspheric collimator (C1) ($f = 3.1 \text{ mm}$), aspheric collimator (C) ($f = 8 \text{ mm}$), optical isolator (OI), L1 ($f = 30 \text{ mm}$), L2 ($f = 200 \text{ mm}$), L3 ($f = 50 \text{ mm}$), L4 ($f = 35 \text{ mm}$), Wollaston polarizer (P), filter (D), Photodiode (PD), Optical Spectrum Analyzer (OSA).

The experimental setup is illustrated in Fig. 1. The emission in the fast axis is nearly collimated using an aspherical lens (C1) of 3.1 mm focal length and numerical aperture NA = 0.68. Feedback is provided in a Littrow scheme with a diffraction grating with 1450 lines/mm arranged at an angle $\Theta = 75^\circ$ with respect to the incoming beam. The collimator is positioned in a way to optimize threshold reduction by focusing on the grating (external cavity length 123 mm). After the external cavity, there is a lens, L2, for beam shaping and an optical isolator (OI) to prevent feedback from the detection part. A Wollaston polarizer splits the beam in the two polarization components, horizontal and vertical and sent them to two InGaAs detector (Thorlabs PDA255, bandwidth of 50 MHz) to monitor the dynamics. The optical spectrum is also monitored from the HR facet of the diode by a fiber coupled optical spectrum analyzer with a nominal resolution of 0.07 nm. For the characterization of the free running laser we simply replace the grating by a high reflectivity mirror. The threshold current of the free running laser is $I = 760 - 800 \text{ mA}$ depending on temperature ($T = 6 - 10^\circ \text{ C}$). With feedback at the same wavelength ($\lambda = 1225 \text{ nm}$, gain peak) it is reduced to $I = 550 \text{ mA}$, a threshold reduction of about 27%.

### 3. Experimental results

The free running laser shows strong pulsations according to Fig. 2 in a wide range of drive currents. The main polarization component is the horizontal, which is the one shown in Fig. 2, while the vertical polarization has about 10 times lower intensity but exhibits qualitatively the same behavior. The pulsations start around the threshold of the laser. They are large amplitude pulses on a small background (Fig. 2(a)). With increasing drive current their frequency increases and reaches a maximum characterized by approximately 50% duty cycle (Fig. 2(b)). At higher currents, the on-state dominates (Fig. 2(c)) until the pulses are better described as short dropouts from a high-amplitude state (Fig. 2(d)). The pulsations disappear above $I = 850 \text{ mA}$ (Fig. 2(d)) and the laser emission is stable afterwards. Quantitatively, the frequency of this pulsations varies between 2.75 MHz and 5.1 MHz (Fig. 2(e)). It is evident from the figures that there is some variation in pulse duration (e.g. Fig. 2(c), (d)), i.e. there is a jitter in the width of the pulses present at all drive currents.
Figure 2. Behavior of the oscillation for the free running laser for increasing current: (a) 795 mA, (b) 810 mA, (c) 850 mA, (d) 870 mA. (e) Frequency behavior versus current in a different realization (laser threshold $I = 760$ mA).

Figure 3. Evolution of oscillations with feedback for increasing current (red curve vertical polarization, blue curve horizontal) at $\lambda = 1195$ nm: (a) 790 mA, (b) 810 mA, (c) 820 mA, and (d) 830 mA. (e) Oscillation range in dependence of wavelength.

The laser with feedback also shows oscillations as evidenced in Fig. 3. In this case the oscillations are more of a square-shape type. They appear at frequencies somewhat lower than the ones in the free running laser and are centered around 1 MHz. Figs. 3(a)-(d) illustrate the development of pulsing in dependence of current. It is taken for lower emission wavelengths ($\lambda = 1195$ nm) than the gain maximum but the qualitative behavior does not depend on wavelength and is quite the same as in the free-running laser.

Fig. 3(e) shows the range of the oscillation for different wavelengths available by tuning the diffraction grating from 1195 nm to 1250 nm. Between 1195 nm and 1220 nm, the range where the oscillation are present is quite small, around 40 mA, then it increases to around 100 mA.
around the central wavelength. This range is for both polarizations of the diode.

The time-averaged optical light output versus current characteristics (LI-curves) differ strongly below the wavelength of minimal threshold of 1230 nm and above. At $\lambda = 1195$ nm, Fig. 4(a), there is bistability at laser threshold with a pronounced hysteresis loop. Afterwards, the average intensity increases linearly. At a kink at about 780 mA the slope of the LI-curve changes and the laser becomes stable. Increasing the emission wavelength, the width of the hysteresis loop becomes smaller but an abrupt transition is still present up to $\lambda = 1221$ nm, Fig. 4(b). Fig. 4(c) refers to $\lambda = 1240$ nm where there is no sign of bistability and the laser threshold is continuous. Also the free running laser doesn’t present bistability. Frequency-selective feedback is known to support bistability at lasing onset in bulk and quantum well lasers [8]. The dependence on the sign of detuning might indicate a nonlinear index effect.

4. Conclusions

Self-sustained pulsations of the output have been observed in a InAs quantum dot laser diode in the MHz range for the first time. The time scale and other observations suggest that these are opto-thermal pulsations similar to the ones reported in quantum well amplifiers [4]. We are currently investigating the hypothesis of a dynamical change of thermal waveguiding properties. Bistability is present below the gain peak.

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References

[1] Qasaimeh O, Zhou W D, Phillips J, Krishna S, Bhattacharyaa P and Dutta M 1999 Appl. Phys. Lett. 74 1654–1657
[2] Summers H D, Matthews D R, Smowton P M, Rees P and Hopkinson M 2004 J. Appl. Phys. 95 1036–1042
[3] Mokkapati S, Tan H H, Jagadish C and Buda M 2008 Appl. Phys. Lett. 92 021104
[4] Barland S, Piro O, Giudici M, Tredicce J R and Balle S 2003 Phys. Rev. E 68 036209
[5] Marino F, Catalán G, Sánchez P, Balle S and Piro O 2004 Phys. Rev. Lett. 92 073901
[6] Rzhanov Y A, Richardson H, Hagberg A A and Moloney J V 1993 Phys. Rev. A 47 1480–1491
[7] Suret P, Derozier D, Lefranc M, Zemmouri J and Bielawski S 2000 Phys. Rev. A 61 021805(R)
[8] Giudici M, Giuggioli L, Green C and Tredicce J R 1999 Chaos, Solitons & Fractals 10 811–818