Feedback induced instabilities in a quantum dot semiconductor laser

Olwen Carroll, Ian O'Driscoll, Stephen P. Hegarty and Guillaume Huyet

Tyndall National Institute and Physics Department, University College Cork, Lee Maltings, Cork, Ireland

carroll@tyndall.ie

John Houlihan

Department of Computing, Maths and Physics, Waterford Institute of Technology, Waterford, Ireland

jhoulihan@wit.ie

Evgeny A. Viktorov and Paul Mandel

Optique Nonlineaire Theorique, Universit Libre de Bruxelles, Campus Plaine CP 231, B-1050 Bruxelles, Belgium

Abstract: We analyse the properties of GaAs based quantum dot semiconductor lasers emitting near 1310 nm. The line-width enhancement factor is shown to depend strongly on device temperature, ranging from 1.5 at 20° C to 5 at 50° C. With optical feedback from a distant reflector, devices remained stable at 20° C but displayed a range of instabilities at 50° C, including irregular power drop–outs and periodic pulsations, before entering a chaotic regime. Such dynamical features are unique to quantum dot lasers – quantum well lasers are significantly more unstable under optical feedback making such a clear route to chaos difficult to observe.

OCIS codes: (250.0250) Optoelectronics; (140.0140) Lasers and laser optics; (140.5960) Semiconductor lasers

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1. Introduction

Quantum dot (QD) semiconductor lasers display an interesting hybrid of atomic laser and standard quantum-well (QW) semiconductor laser properties. Single isolated quantum-dots display linewidths at room-temperature limited only by optical phonon lifetimes [1], but quantum-dot ensembles display linewidths on the order of several 10s of meV, very similar to those of QW lasers. An area where atomic lasers and QW lasers differ greatly is that of the phase-amplitude coupling, or α–factor [2]. Atomic lasers posess values near zero at gain peak, while QW lasers have substantial values that dictate significant characteristics of the laser. The nature and magnitude of the α–factor in QD devices is a current topic of discussion in the literature. A range of values has been reported, ranging from very small [3] to "giant" [4], and this has been attributed in part or whole to plasma effects [5] or excited state population [4].

Two technologically important shortcomings of QW lasers governed by their finite α–factors are the spatial instability of filamentation and the temporal instability of coherence collapse. QD lasers have demonstrated reduced filamentation [6] and low sensitivity to optical feedback [7]. This latter property allows QD laser transmitters to operate without the presence of optical isolators. The improved performance of QDs under optical feedback has been linked to an increased damping of the relaxation oscillations and a reduction in the α–factor [8] that can be explained by conventional rate equations [9]. It has also recently been shown that short cavity quantum dot semiconductor lasers that emit from both ground and excited states, can exhibit antiphase low frequency power drop-outs under the influence of optical feedback [10]. This paper will detail the effect of temperature on the α–factor and feedback stability of QDs from 20° C to 50° C. The devices studied in this article lase only in the ground state. We observe that higher temperature increased both the line-width enhancement factor and the feedback sensitivity of the QD devices. In this regime, the laser remained more stable under optical feedback than conventional QWs as it only displayed instabilities at high levels of injection current. In particular noise induced power drop–out events followed by an oscillatory transient whose duration increased with feedback level were observed. As the feedback level increased, a sequence of periodic oscillations at increasing multiples of the round-trip frequency was observed until chaotic behaviour appeared.

2. Device properties

The devices used in this paper were fabricated from a single quantum dot wafer, its active region consisting of a six–fold stack of InAs QDs in a GaAs waveguide, emitting at 1.3 µm. The QD layers were embedded in a strained InGaAs QW (DWELL structure) to improve carrier capture,

with optical confinement provided separately by AlGaAs cladding regions. The growth and fabrication techniques are detailed elsewhere [11]. Alpha–factor measurements were performed on 1.5 mm long, 35 μm stripe, gain guided broad-area lasers (BAL) with uncoated facets. The feedback measurements were carried out using uncoated ridge waveguide lasers (RWGL), with ridge widths of 3 μm and cavity lengths of 1.5 mm.

3. Temperature dependence of α

The α–factor was measured using the Hakki-Paoli technique [12], where amplified spontaneous emission (ASE) spectra are recorded as a function of bias below threshold. The BAL were mounted p–side up on a temperature–controlled copper mount and the devices biased in pulsed mode and at low duty cycles to avoid self–heating. The laser output was coupled via an optical isolator to a single mode fibre, which acted as a spatial filter. It has been previously reported for similar devices that α decreased from 3 to 1 as cavity lengths increased from 1 mm to 2 mm [13]. The results obtained for these 1.5 mm long devices are shown on Fig. 1. α is <2 at 20° C and shows a pronounced increase with temperature to exceed 5 at 50° C. This result is not unexpected, as increasing the temperature decreases the differential gain, in this case by 50%. The differential index increases by about 60%, possibly due to increased non-resonant carrier populations in excited and wetting layer states.

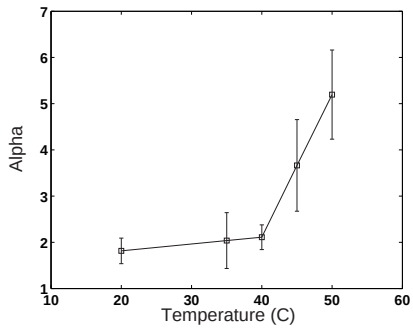


Fig. 1. Measurement of the α–factor at different operating temperatures. There is a sharp increase in the slope at 40° C, and the major part of the change from 2 to 5 occurs between 40° C and 50° C.

4. Room temperature stability with optical feedback

The QD RWG lasers were mounted p-side up on a copper mount giving optical access to both facets. Through this means, the largest range of the feedback parameter may be explored without compromising the detection sensitivity. The external cavity arm comprised a high numerical aperture lens, a high reflectivity mirror and a neutral density filter to control the feedback level. Optimum coupling of light back into the QD laser is achieved by adjusting the lens and mirror so as to minimise laser threshold. Light in the diagnostic arm was coupled through a focussing lens to a multi mode fiber (MMF) via an optical isolator to eliminate spurious feedback effects. The MMF was coupled to a Newport D–30 fast detector and a Newport AD–300 amplified detector to monitor the power spectrum and the time series simultaneously. The D–30 photodiode signal was amplified using a Miteq high gain amplifier. The D–30 had a bandwidth of 14 GHz, the AD–300 a bandwidth of 1 GHz and the Miteq amplifier a bandwidth of 20 GHz and a noise figure of 3.5 dB. The electronic spectrum and time series were analysed with a 26 GHz Advantest R3172 electronic spectrum analyser (ESA) and a 6 GHz LeCroy real–time oscilloscope

respectively. The length of the feedback arm was varied from 40 to 80 cm to obtain various external cavity round–trip times. The threshold current reduction of the device with feedback was measured using a linear gain approximation, similar to that used by Olsson, [14]. The feedback strength, f_{ext}, could then be calculated using a simple analytical expression relating f_{ext} to the effective reflectivity of the external cavity, R_{eff},

$$f_{ext} = \frac{R_{eff} - R_2}{1 - R_2} \tag{1}$$

where R_2 corresponds to the reflectivity of the solitary laser facet in the external cavity arm. A threshold current of 35 mA at room temperature was measured for the free–running laser (this reduced to 28 mA at maximum levels of feedback for all external cavity lengths). For a temperature of 50° C, the free–running threshold increased to 67 mA, with a corresponding threshold redction of 9 mA for maximum feedback. Over the entire feedback range accessed (-13 to -5 dB), and for all external cavity lengths, no fluctuations distinguishable from detector noise were visible on the 6 GHz oscilloscope. The ESA offers more sensitivity as it does not integrate the noise over the frequency spectrum. For very low feedback levels, the power spectra were similar to those obtained for the free–running laser. At higher levels of feedback, the power spectra exhibited a series of peaks corresponding to the external cavity modes. This indicates multiple external cavity mode operation, but the amplitude of the side modes remained smaller than the noise level of our oscilloscope as no periodic oscillations were detected in the time domain.

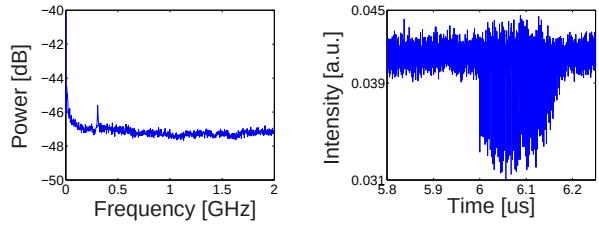
5. Instability with optical feedback at 50^oC

As the temperature of the device was increased from 20 to 50° C, the threshold for the onset of instabilities decreased, and more complex dynamical features were observed at high injection current, typically in the range 2–3I_{th}. Let us discuss the most typical dynamical regimes: power dropouts, hysteresis and bistability between periodic oscillations and steady state, and higher order instabilities which were observed in several devices.

Power dropouts were observed at a feedback level $f_{ext} = -13$ dB. The laser displayed infrequent, irregular dropouts, an example of which is shown in Fig. 2(b). Here the output power drops to the solitary laser power followed by a number of oscillations at the external cavity round–trip time. These drop-out events were extremely rare, with interburst intervals on the order of ms, a timescale which is much longer than any intrinsic timescale in the system. The power spectrum displayed a small peak at a frequency ν_1, slightly lower than the external cavity frequency $\nu_{ext} = c/(2L)$, Fig. 2(a). Experiments at different external cavity lengths (L) yielded different values for ν_1; $L = 40$, 60 and 80 cm resulted in $\nu_1 = 305$, 215 and 166 MHz respectively. The power spectrum did not exhibit fluctuations at multiples of the external cavity frequency (Fig. 2(a)) and there was no other manifestation of multiple external cavity modes. The origin of ν_1 could be related to the relaxation oscillation frequency of the compound cavity. The clarification of this question requires further experimental and theoretical work that will be reported later.

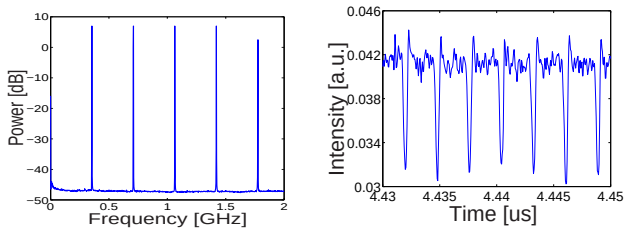
As the feedback level was increased at fixed current, the frequency and duration of these dropouts increased, leading to the appearance of frequencies at ν_{ext}, $2\nu_{ext}$... in the power spectrum together with ν_1. Each dropout was followed by an oscillatory transient whose duration increased with feedback level until it finally became a stable periodic oscillation. This occured at a feedback level $f_{ext} = -11$ dB. The frequency ν_1 was no longer present in the power spectrum which consisted of ν_{ext} and its harmonics, Fig. 3(a).

A hysteresis loop was observed when the current at this feedback level was varied, as shown on Figure 4. We found that there was a bistability between the stable steady state operation and



(a) (b)

Fig. 2. (a) Power spectrum for low feedback levels, $f_{ext} = -13$ dB, where a small peak at frequency ν_1 is observed and (b) the corresponding time series with a noise–induced dropout event for a pump current of 190 mA at 50°C and an external cavity of 40 cm



(a) (b)

Fig. 3. (a) Periodic features observed in the power spectrum for $f_{ext} = -11$ dB and (b) the corresponding time series with periodic oscillations at the round–trip frequency for I=190 mA, L=40 cm and T=50°C

the periodic oscillations at ν_{ext} as indicated in the figure.

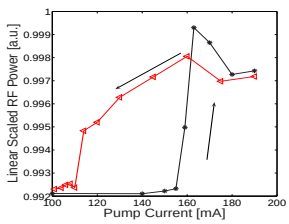


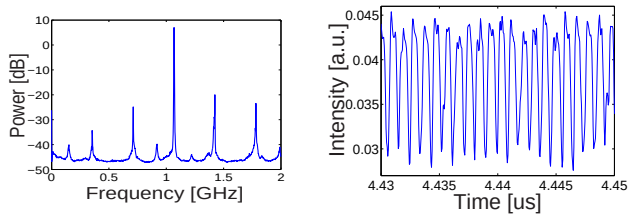
Fig. 4. Hysteresis loop observed at a fixed feedback level f_{ext}=-11 dB for an operating temperature of 50°

Higher order instabilities were observed for a feedback level above $f_{ext} = -11$ dB and for $L =$ 40 cm. The frequency of the regular oscillations changed abruptly from ν_{ext} to $2\nu_{ext}$. A similar transition to higher frequency ($3\nu_{ext}$) was observed at a higher feedback level, $f_{ext} = -10$ dB, (Fig. 5(a), 5(b)), before the laser exhibited chaotic behaviour for a maximum feedback level ($f_{ext} = -5$ dB), Fig. 6(a), 6(b).

Extending the external cavity length lead to a remarkable increase in the number of observable harmonics before the appearance of chaos. For an external cavity of 40 cm, ($\nu_{ext} = 355$ MHz), periodic oscillations up to $3\nu_{ext}$ ($\simeq 1$ GHz) were observed before the laser entered a chaotic regime. For a 60 cm cavity, periodic oscillations up to and including $5\nu_{ext}$ ($\simeq 1.2$ GHz) were observed, while for an 80 cm external cavity, periodic oscillations up to and including

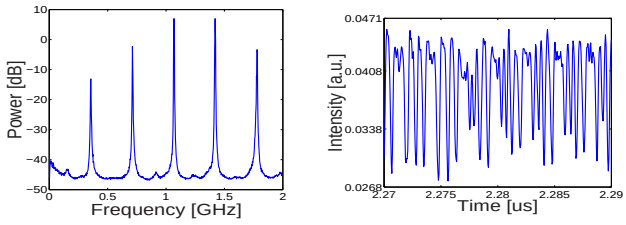
$7\nu_{ext}$ ($\simeq$ 1.3 GHz) were seen. The frequency ν_1 was not present in the sequence of higher harmonics $n\nu_{ext}$. The observation of the ordered sequence $3\nu_{ext}, 4\nu_{ext}, \ldots 7\nu_{ext}$ before chaos is a unique feature of QDs and has not been observed for QW devices subjected to optical feedback.

The feedback–induced instabilities presented here differ significantly from those ordinarily observed in QW semiconductor lasers. For these devices low frequency power drop–outs are commonly observed. In the case of the quantum dot devices investigated in this paper, such low frequency drop–out events were not present but instead the dynamical regimes described above were observed. The absence of low frequency fluctuations in our devices can be explained by strong damping of the relaxation oscillations preventing drift between the external cavity modes. For this reason quantum dot devices display different instabilities to those previously reported in quantum wells.



(a) (b)

Fig. 5. (a) Power spectrum showing the appearance of higher harmonics and (b) time series for $f_{ext} = -10$ dB, both at a pump current of 190 mA, temperature of 50°C and 40 cm external cavity



(a) (b)

Fig. 6. (a) Power spectrum showing broadened peaks and (b) time series exhibiting chaotic behaviour for maximum current (190 mA) at 50°C, and feedback levels ($f_{ext} = -5$ dB) for an external cavity length of 40 cm

6. Discussion

We have analysed the dynamics of a quantum dot semiconductor laser subjected to optical feedback as a function of operating temperature. We have shown that the α–factor increases with device temperature, most likely due to increased occupancy in non–resonant states. We have also seen that the device was more unstable at a temperature of 50° C, where it operated with a higher value for α. However, these dynamics were only observed for temperatures of 50° C and at high injection currents (typically 2–3I_{th}), so that the overall device stability remains very good. The specifics of the route to chaos are dependent on the external cavity length,

with longer external cavities introducing higher order dynamics into the laser system. Such behaviour has, to our knowledge, not been observed in QW lasers, most likely because these devices have a larger alpha–factor and a lower relaxation oscillation damping rate. The superior stability of QD lasers under optical feedback enables us to observe the progressive development of instabilities, thereby identifying distinctive operating regimes unseen in QWs.

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