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Tuning of the critical feedback level in 1.55-μm quantum dash semiconductor laser diodes

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Abstract: The onset of the coherence collapse (CC) regime, which is incompatible with data transmission, is investigated both theoretically and experimentally in a 1.55-μm InAs/InP quantum dash semiconductor laser. It is numerically shown that the filling from the excited state produces an additional term, which accelerates the route to chaos. This contribution can be seen as a perturbation that reduces the overall CC threshold.

1 Introduction

The performance of a semiconductor laser is usually strongly altered by any type of external optical feedback. Even small reflections in the percent range, which originate from fibre facets or any other optical elements introduced into the light path, can dramatically affect the laser stability. Five distinct regimes based on spectral observation were reported for 1.55-μm semiconductor distributed feedback lasers (DFB) [1]. At the lowest feedback levels, regime I, the laser operates on a single external cavity mode that emerges from the solitary laser mode. Depending on the phase of the feedback, the laser linewidth can be narrowed or broadened. Then, within regime II, the mode appears to split into two modes arising from rapid mode hopping. Noise-induced hopping between two external cavity modes is the underlying reason for this behaviour. The transition to regime II was found to correspond to multiple solutions of the steady-state equations that determine the frequency of the laser. In regime III, the laser re-stabilises in a single external cavity modes (the lowest linewidth mode) with constant power. As the level of feedback is increased, and independently of the length of the external cavity, the laser system undergoes a transition to a chaotic state named coherence collapse (CC) and enters regime IV [2]. The CC is the common name given to describe the complicated irregular dynamics that occurs when the laser is operating above and not too close to threshold. The CC has been extensively studied over the last 20 years. A lot of papers describe this regime as coexisting chaotic attractors [3] whereas others explain it as an important source of noise [4, 5]. The main consequence of the critical feedback regime is a drastic collapse of the laser's coherence time leading to a strong enhancement of the laser linewidth. In the important case of optical transmission, the CC leads to a strong degradation in the bit error rate when the laser is used as a transmitter, as theoretically [6] and experimentally [7] demonstrated. Further increase in the feedback level, the laser transits to regime V, which is another single mode, constant intensity and narrow linewidth regime when the diode laser's facet has been anti-reflection coated. This regime cannot be reached when laser diodes with uncoated facets are used. The purpose of this article is to show both theoretically and experimentally that the variations of the above-threshold linewidth enhancement factor (α_H-factor) significantly impact the onset of the CC. Thus, this article aims to demonstrate that large values in the above-threshold α_H-factor, as previously observed in quantum dash (QDash) semiconductor lasers [8], provoke a rapid collapse of the laser's coherence time. When considering the contribution of the ground state (GS) and the one from the excited state (ES), it is shown that the analytical relation giving the onset of the critical feedback level can be analytically extended. The carrier filling from the ES is found to produce an additional term, which accelerates the route to chaos. Also depending on how the above-threshold α_H-factor behaves, this paper shows that the critical feedback level can exhibit two different trends with output power. These different behaviours are very specific to QDash lasers in which the influence of the ES coupled to the non-linear effects is emphasised. This bottleneck makes QDash lasers more sensitive to optical feedback causing larger variations in the onset of the CC compared to QW devices.

2 Role of the ES in the critical feedback level

In QDash lasers, the lasing wavelength can switch from the GS to the ES as the injected current increases meaning that a carrier accumulation occurs in the ES even though lasing in the GS is still occurring. As a result, the filling of the ES inevitably enhances the above-threshold α_H-factor of the GS transition introducing an additional dependence with the injected current. Thus, taking into account the gain variation at the GS and at the ES, the above-threshold α_H-factor of the GS transition can be written as [9]

$$\alpha_H(P) = \alpha_{GS}(P, P_{sat}) + \alpha_{ES}(P, P_{sat}) \qquad (1)$$

In (1), α_H is the so-called linewidth enhancement factor evaluated at the GS-wavelength, which includes the gain compression effect at the GS denoted $\alpha_{GS}(P, P_{sat})$ as well as the carrier filling from the ES $\alpha_{ES}(P, P_{sat})$. The saturation power is P_{sat} such that $\varepsilon_P P = P/P_{sat}$ with ε_P the gain compression coefficient related to the output power P. The value of P_{sat} means that at this level of output power, non-linear effects start to be significant. Measuring the frequency response as a function of the output power is a common method to evaluate gain compression in semiconductor lasers [10]. The experimental dependence of the relaxation oscillation frequency shows a deviation from the expected proportionality (case with $\varepsilon_P = 0$) on the square root of the optical output power, which can be curve-fitted to express the gain compression in terms of a saturation power. In quantum dot (QD) and QDash lasers, the order of magnitude for the gain compression factor related to the photon density S such that $\varepsilon_S S = \varepsilon_P P$ ranges from 5×10^{-15} cm^3 to 1×10^{-16} cm^3 [9, 11] whereas for conventional QW lasers, it remains typically around 10^{-17} cm^3 [12].

As shown in [9], the contributions of the GS (α_{GS}) and the ES (α_{ES}) can be expressed such as

$$\alpha_{GS}(P, P_{sat}) = \alpha_0\left(1 + \frac{P}{P_{sat}}\right) \qquad (2)$$

and

$$\alpha_{ES}(P, P_{sat}) = \frac{\alpha_1}{1 - (g_{th}/(g_{max} - g_{th}))(P/P_{sat})} \qquad (3)$$

with α_0 and α_1 coefficients linked to the GS and ES, respectively, g_{th} the gain at threshold and g_{max} the maximum gain for the GS-lasing. If strong gain compression occurs or $g_{max} \sim g_{th}$, the second term in (1) dominates, and the α_H-factor follows a non-linear trend above the laser threshold as previously shown [9]. Expressions (2) and (3) show that the α_H-factor is mostly driven by non-linear effects as well as by the ratio g_{max}/g_{th}. Fig. 1 shows the calculated GS α_H-factor based on (1) as well as the comparison with measured data (black squares) from [8]. The saturation power P_{sat} is close to 17 mW, the ratio g_{max}/g_{th} is about 1.5 while coefficients α_0 and α_1 are treated as fitting parameters and are such that $\alpha_0 \ll 1$ and $\alpha_1 \sim 2$. The GS α_H-factor drastically increases from ~1 to ~14 as the bias current is tuned up to the ES threshold. The curve-fitted dashed line is found to be in a relative good agreement with experimental data; the residual discrepancy is attributed to the experimental resolution induced by the injection-locking technique, which was used to extract the α_H-factor. The enhancement of the GS α_H-factor is due to the plasma effect as well as to the carrier filling of the non-lasing states, which results in a differential gain reduction above threshold [13]. As it will be shown later, this strong degradation of the α_H-factor with the bias current is expected to produce a significant variation in the feedback laser's sensitivity. Based on the Lang and Kobayashi rate equations [14] in the presence of optical feedback, a way to calculate the onset of the CC regime is given by the following relationship [3]

$$\Gamma_c = \left(2\pi f_r(P)\frac{\tau_i}{\sqrt{2}C}\right)^2\left(\frac{1}{1 + \alpha_H^2(P)}\right) \qquad (4)$$

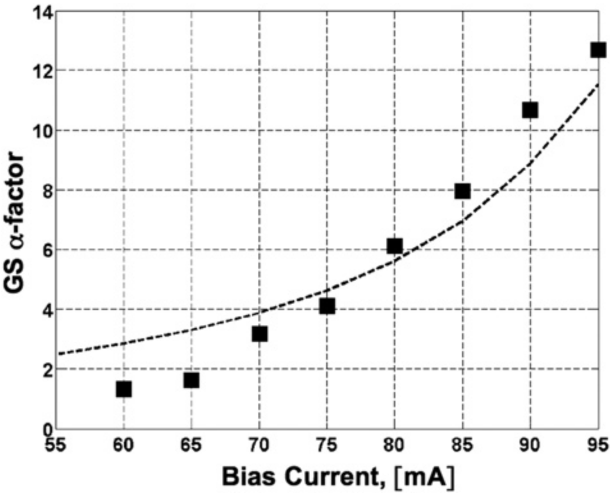

Figure 1 *Calculated GS α_H-factor as a function of the bias current and comparison with measured values (black squares)*

In (4), Γ_c represents the critical amount of injected feedback into the laser to observe the CC, C is the coupling coefficient from the laser's facet to an external cavity, f_r is the laser's relaxation frequency and τ_i is the internal roundtrip time. Expression (4) was derived by analysing the stability of the solutions of the oscillation condition for a laser with optical feedback [3]. The CC is seen as a chaotic attractor and that chaos is reached for increasing feedback level through a quasi-periodic route interrupted by frequency locking. For a long external cavity, for example, $f_r\ \tau_e \gg 1$ (with τ_e the external roundtrip time), this expression is supposed to provide a good approximation at which instability sets in. Based on expressions (1) and (4), the mutual contributions of the GS and the ES can be considered together so as to re-write the onset of the CC of a QDash semiconductor laser. Thus, the critical feedback level can be directly re-expressed in decibels as follows

$$\Gamma_{c_{\mathrm{dB}}} = 10\log_{10}(\Gamma_c) = \Gamma_{c0}(\mathrm{dB}) + 10\log\left(\frac{1}{1+(\alpha_{\mathrm{ES}}(P,P_{\mathrm{sat}})[\alpha_{\mathrm{ES}}(P,P_{\mathrm{sat}}) + 2\alpha_{\mathrm{GS}}(P,P_{\mathrm{sat}})]])/(1+\alpha_{\mathrm{GS}}^2(P,P_{\mathrm{sat}}))}\right) \tag{5}$$

with

$$\Gamma_{c0} = \left(2\pi f_r(P,P_{\mathrm{sat}})\frac{\tau_i}{\sqrt{2}C}\right)^2 \frac{1}{1+\alpha_{\mathrm{GS}}^2(P,P_{\mathrm{sat}})} \tag{6}$$

The amount Γ_{c0} denotes the contribution of the GS only towards the change in the onset of the CC. The second term in (5) occurs when the contribution from the ES is considered and strongly depends on the above-threshold α_{H}-factor that includes the contributions of the GS (α_{GS}) and the ES (α_{ES}), respectively. Expression (5) goes a step further in the analytical description of the onset of the critical feedback level since it includes the additional dependence related to the ES itself. In what follows, the sensitivity to optical feedback of 1.5-μm InAs/InP QDash semiconductor lasers is investigated. Based on this analysis, it is shown that the contribution of the ES filling impacts the route to chaos that results in a shift in the overall CC threshold.

3 Results and discussion

The experimental apparatus to measure the CC threshold is depicted in Fig. 2. It is based on a 50/50 four-port optical fibre coupler. Emitted light was injected into port 1 using a single-mode lensed fibre in order to avoid excess uncontrolled feedback. The optical feedback was created with a high-reflectivity dielectric-coated fibre ($R > 95\%$) located at port 2. The feedback level was controlled via a variable attenuator and its value was determined by measuring the optical power at port 4 (back reflection monitoring). The effect of the optical feedback was analysed at port 3 via a 10 pm resolution optical spectrum analyser (OSA). A polarisation controller was used to make the feedback beam's polarisation identical to that of the emitted wave in order to maximise the feedback effects. The roundtrip time between the laser and the external reflector is ~30 ns. As a consequence, the long external cavity condition mentioned in the previous section $f_r\ \tau_e \gg 1$ is fulfilled. This means that the CC regime does not depend on the feedback phase or on the external cavity length. The amount of injected feedback into the laser is defined as the ratio $\Gamma = P_1/P_0$, where P_1 is the power returned to the facet and P_0 the emitted one. The amount of reflected light that effectively returns into the laser can then be expressed as follows [15]

$$\Gamma_{\mathrm{dB}} = P_{\mathrm{BRM}} - P_0 + C \tag{7}$$

where P_{BRM} is the optical power measured at port 4, C is the optical coupling loss of the device to the fibre which was estimated to be about −4 dB and kept constant during the whole experiment. The device is epoxy-mounted on a heat sink and the temperature is controlled at 20°C. The determination of the onset of the CC was done using a technique based on spectral observation when the laser linewidth begins to significantly broaden as shown in [1, 7].

The device was grown on an InP substrate and its structure is described as a 500-μm Fabry–Perot (FP) long cleaved-cavity ridge waveguide (RWG) with a 4-μm wide stripe.

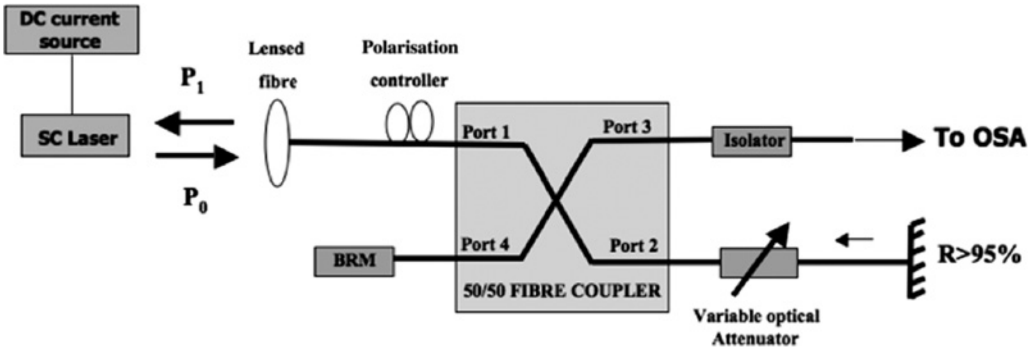

Figure 2 *Schematics of the experimental apparatus for the feedback measurements*

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Details of the structure have already been published elsewhere [16]. The threshold current leading to a GS-emission is ~45 mA and the external differential efficiency is about 0.2 W/A. Beyond a pump current of ~100 mA, ES lasing emission occurs. In Fig. 3, the measured onset of the CC is reported as a function of the bias current (black squares). The feedback sensitivity of the laser was found to vary by more than 15-dB over the range of current investigated. The sensitivity to optical feedback is altered when the α_H-factor gets higher (high bias current region) according to the effects reported in [8]. This QDash FP laser exhibits an improved resistance to optical feedback when decreasing the bias current. This large change in the laser's feedback sensitivity is induced from the α_H-factor variations which are much more significant over the whole range of current. This experimental result is in good agreement with [17] in which it has been shown that when the α_H-factor tends to zero, the critical feedback level is up-shifted but should remain finite. Experimental results indicate that this saturation certainly occurs at a feedback level larger than 18-dB. In order to explain this phenomenon, the contributions of gain compression at the GS as well as the carrier filling from the ES have to be considered simultaneously. Fig. 3 shows the calculated CC thresholds as a function of the bias current assuming gain compression at the GS only and the additional term related to the carrier filling from the ES. In the calculations, an internal roundtrip time of 10 ps and a coupling coefficient $C = (1 - R)/2\sqrt{R} \sim 0.6$ (for an as-cleaved laser) is considered. All other values such as the saturation power P_{sat}, the ratio g_{max}/g_{th} as well as fitting parameters α_0 and α_1 are similar to those mentioned in the previous section. On one hand, when plotting only the contribution related to the gain compression at the GS (labelled 1) given by (6), the critical feedback level is found to increase with the bias current. As the laser's relaxation frequency is power dependent, such a variation is naturally expected. On the other hand, when considering only the contribution taking into account the carrier filling from the ES (labelled 2) in (5), an opposite trend is observed. This contribution can be seen as a significant perturbation that results in a shift in the overall CC threshold. Thus, when both contributions are considered in the overall CC threshold, the calculated CC threshold is found to decrease with bias current (black solid line). The calculated values are found in a pretty good agreement with experimental ones except at low bias current for which the calculated trend stops increasing and shows a clamping roughly around −23 dB. Such discrepancy can be attributed to the fact that the amplitude of the optical feedback gets too large and does not match the low feedback assumption. As a conclusion, the overall experimental trend depicted in Fig. 3 appears unconventional since it does not follow the relaxation frequency variations even at low bias current levels for which the CC is up-shifted. This different behaviour is specific to QDash structures in which the non-linear effects associated with the ES can be much more emphasised. This phenomenon can make QDash lasers more sensitive to optical feedback, which results in larger variations in the onset of the CC compared to that of the quantum well (QW) devices.

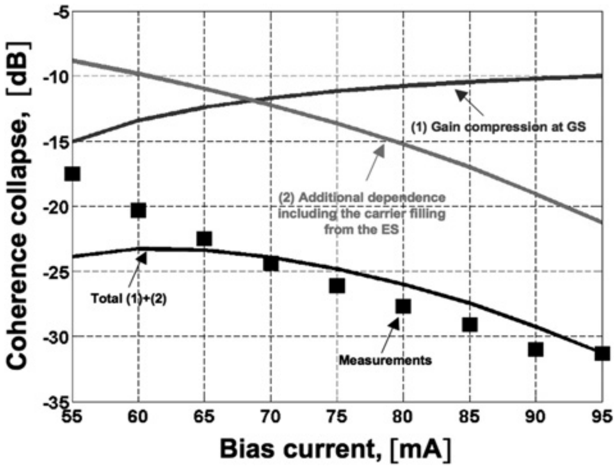

Figure 3 *Calculated CC thresholds as a function of the bias current including the gain compression at the GS only (labelled 1), the additional term related to the carrier filling from the ES (labelled 2), both contributions and a comparison with the measured data (black squares)*

In QW lasers, which are made from a nearly homogeneously broadened gain medium, the carrier density and distribution are clamped at threshold. Since the carrier distribution is clamped, α_0 itself in (2) does not change significantly as the output power increases. As an example let us assume the case of a 300-µm-long AR/HR QW DFB made with six compressively strained QW layers. The threshold current is about ~8 mA at room temperature. When measuring the α_H-factor above the laser threshold, it was found to linearly increase with the output power from about ~3.5 to ~6. These small variations have few consequences in the feedback sensitivity. Fig. 4 shows the measured CC threshold as a function of the bias current. An increase in the critical feedback level is found from −36 to −27 dB when the current increases from 12 to 70 mA. The onset of the CC follows the variations of the relaxation frequency. This conventional trend was previously observed in Fig. 3 when considering the GS contribution as a function of the bias current. Fig. 5 shows the measured CC thresholds as a function of the α_H-factor for both the QDash FP laser (circles) and the QW DFB (squares). This figure illustrates how the route to chaos may be accelerated in a semiconductor laser; indeed depending on how the above-threshold α_H-factor behaves, the sensitivity to the CC is tuned and may be improved or degraded. As regards the QW device, the sensitivity to optical feedback is improved when increasing the current. This conventional behaviour, which has already been observed many times [18], is attributed to the α_H-factor whose variations cannot encompass those related to the relaxation frequency. Thus, the α_H-factor increases quite linearly above the laser's threshold and it remains mostly

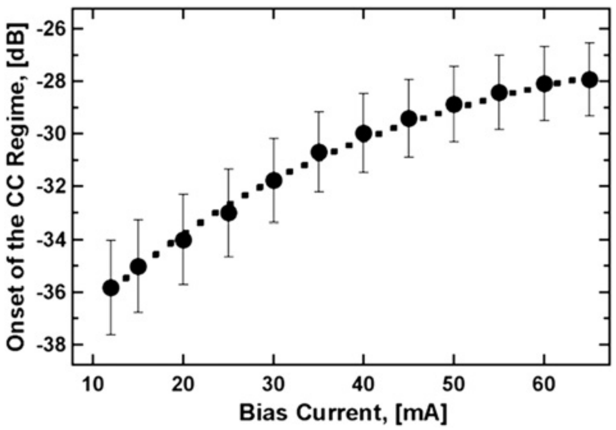

Figure 4 *CC threshold as a function of the bias current for the QW DFB laser*

Dashed line is added for visual help only

driven by the first term of (1) such as $\alpha_{\rm GS} \gg \alpha_{\rm ES}$. It is important to note that a similar expression was derived in earlier studies [19]. Expression (52) in [19] already shows that the $\alpha_{\rm H}$-factor increases in a semiconductor laser when intraband relaxation mechanisms are taken into account. However, these predicted variations are not as important as in the case of QDash semiconductor lasers in which gain compression effects are strengthened. As regards this QDash device, the result shows a different situation: the resistance to optical feedback is altered when increasing bias current. This effect is produced because the $\alpha_{\rm H}$-factor variations of the QDash FP laser are now much more important such that $\alpha_{\rm GS} \sim \alpha_{\rm ES}$ or $\alpha_{\rm GS} < \alpha_{\rm ES}$. This means that the carrier filling from the ES has to be considered in order to explain the non-linear increase in the GS above-threshold $\alpha_{\rm H}$-factor. As a consequence, the critical feedback level does not follow the relaxation frequency variations since the CC is found to be up-shifted when decreasing the bias current level. Such behaviours can mostly occur in QD and QDash lasers in which the influence of the ES coupled to the non-linear effects is emphasised. Finally, let us stress that making such a comparison with a QW FP laser instead of a QW DFB would not change the conclusion since on QW-based structures the increase in the $\alpha_{\rm H}$-factor with current is limited as compared to QDash devices.

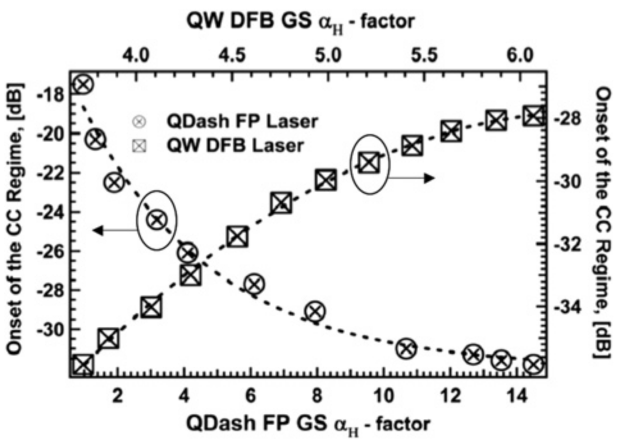

Figure 5 *CC thresholds as a function of the α_H-factor for the quantum well DFB laser (squared markers) and for the QDash FP laser (circled markers) under study*

Dashed lines are added for visual help

4 Conclusions

The onset of the CC regime has been investigated in a 1.55-μm QDash semiconductor laser both experimentally and theoretically. Calculations are in agreement with the experiments that demonstrate that the filling from the ES produces an additional term, which accelerates the route to chaos. This contribution can be seen as a perturbation that reduces the overall CC threshold. Depending on the variations of the $\alpha_{\rm H}$-factor above threshold, the feedback resistance can be improved or deteriorated from one laser to another. The design of QDash lasers with no ES, reduced gain compression effects, lower and quasi-constant $\alpha_{\rm H}$-factor remains a big challenge. Recently, an interesting result was achieved considering a 1.55-μm InAs/InP(311B) semiconductor laser with truly 3D-confined quantum dots [20]. The laser characteristics published exhibited a relatively constant $\alpha_{\rm H}$-factor as well as no ES over a wide range of current. These results highlight that the control of the $\alpha_{\rm H}$-factor has to be considered as a significant input for the realisation of feedback-resistant lasers. It is also pointed out that the prediction of the onset of the CC remains an important feature for all applications requiring a low noise level or a proper control of the laser coherence.

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