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Tuning of the Critical Feedback Level in 1.5- μm Quantum Dash Semiconductor Laser Diodes

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Abstract: The onset of the coherence collapse regime, which is incompatible with data transmission, is investigated both theoretically and experimentally in a 1.5- μm InAs/InP quantum dash semiconductor laser. It is numerically shown that the excited state filling produces an additional term, which accelerates the route to chaos. The paper also experimentally shows that the linewidth enhancement factor can lead to different feedback variations above threshold with the bias current. These results point out that the prediction of the onset of the coherence collapse remains an important feature for all applications requiring a low noise level or a proper control of the laser's coherence.

Key-words: optical feedback, coherence collapse, quantum wells, quantum dashes, linewidth enhancement factor, chaos, semiconductor lasers

I. 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 fiber 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 behavior. The transition to regime II was found to correspond to multiple solutions of the steady state equations that determines the frequency of the laser. In regime III the laser re-stabilizes 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 coherence collapse 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 coherence collapse has been extensively studied over the last twenty 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 coherence collapse 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) hardly impact the onset of the coherence collapse. 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], are not beneficial in practice because this phenomenon provokes a rapid collapse of the laser's coherence time. When considering the contributions of both the ground state (GS) and the excited state (ES), it is shown that the analytical relation giving the onset of the critical feedback level can be rewritten. The ES filling 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 behaviors are very specific to QDash lasers in which the influence of the ES coupled to the non-linear effects are emphasized. This bottleneck makes QDash lasers more sensitive to optical feedback causing larger

variations in the onset of the coherence collapse compare to QW devices.

II. 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 introducing an additional dependence with the injected current. Thus, taking into account the gain variation at the GS and at the ES, the α_H -factor can be written as [9]:

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

In (1) P_{sat} is the saturation power such that $\epsilon_P P = P/P_{sat}$ 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. As shown in [8], the contributions of the GS (α_{GS}) and the ES (α_{ES}) can be expressed such as:

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

and,

$$\alpha_{ES}(P, P_{sat}) = \alpha_1 g \left(P, P_{sat}, g_{max} / g_{th} \right) \quad (3)$$

with α_0 and α_1 coefficients linked to the GS and ES respectively and g an analytical function related to g_{th} the gain at threshold and g_{max} the maximum gain for the GS-lasing. The analytical expression of g depends on the gain model used in the calculations. The first term in (1) denotes the gain compression effect at the GS while the second one is the contribution from the carrier filling in the ES. If strong gain compression is present or $g_{max} \approx g_{th}$, 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} . Based on the Lang and

Kobayashi rate equations [10] in the presence of optical feedback, a way to calculate the onset of the coherence collapse regime is given by the following relationship [3]:

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

with C the coupling coefficient from the laser's facet to an external cavity, f_r the laser's relaxation frequency and the τ_i the internal roundtrip time. Expression (4) was derived by analyzing the stability of the solutions of the oscillation condition for a laser with optical feedback [3]. The coherence collapse 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 e.g. $f_r \tau_e \gg 1$ (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 coherence collapse of a QDash semiconductor laser as follows:

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

with,

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

The amount Γ_{c0} denotes the contribution of the GS only towards the change in the onset of the coherence collapse. The second term in (5) occurs when the contribution of 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 coherence collapse threshold.

III. Results and discussion

The experimental apparatus to measure the coherence collapse threshold is depicted in fig. 1. It is based on a 50/50 4-port optical fiber coupler. Emitted light was injected into port 1 using a single-mode lensed fiber 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 analyzed at port 3 via a 10pm resolution optical spectrum analyzer (OSA). A polarization controller was used to make the feedback beam's polarization identical to that of the emitted wave in order to maximize the feedback effects. The roundtrip time between the laser and the external reflector is $\sim 30\text{ns}$. 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 coherence collapse regime does not depend on the feedback phase nor the external cavity length. Thus, in order to improve the accuracy of the measurements at low output powers, an erbium-doped-fibre-amplifier (EDFA) was used with a narrow band filter to eliminate noise. The EDFA is positioned between the laser facet and the polarization controller (not shown in fig. 1). The amount of injected feedback into the laser is defined as the ratio $\Gamma = P_l/P_0$ where P_l 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 [11]:

$$\Gamma_{dB} = P_{BRM} - P_0 + C \quad (7)$$

where P_{BRM} is the optical power measured at port 4, C is the optical coupling loss of the device to the fiber which was estimated to be about -4dB 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 coherence collapse 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. Details of the structure have already been published elsewhere [12]. The threshold current leading to a GS-emission is $\sim 45\text{mA}$ and the external differential efficiency is about 0.2W/A. Beyond a pump current of $\sim 100\text{mA}$, excited state (ES) lasing emission occurs. In particular, it was shown in [8] that the GS α_{H} -factor drastically increases from ~ 1 to ~ 14 as the bias current goes beyond the threshold value. This enhancement was attributed 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]. This strong degradation of the α_{H} -factor with the bias current was expected to produce a significant variation in the feedback laser sensitivity. In fig. 2, the measured onset of the coherence collapse 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 [13] 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 according to the numerical studies. 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 the GS and the ES need to be considered simultaneously. Fig. 2 shows the GS and ES calculated contributions as a function of the bias current assuming an internal roundtrip time of 10ps and a

coupling coefficient $C = (1 - R) / \sqrt{R} \sim 0.6$ (for an as-cleaved laser). Solid lines in fig. 2 are used for guiding the eyes only. On one hand, when plotting only the contribution of the GS 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 of the ES in (5), an opposite trend is observed. This contribution can be seen as a significant perturbation that results in a shift in the overall coherence collapse threshold. Thus, when both the GS and ES contributions are considered in the overall coherence collapse threshold, the calculated coherence collapse threshold is found to decrease with bias current (grey solid line). Let us stress that these calculated values are in good agreement with experimental ones except at low bias current for which a saturation is theoretically predicted around 20-dB. This 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. 2 appears unconventional since it does not follow the relaxation frequency variations even at low bias current levels for which the coherence collapse is up-shifted. This different behavior is specific to QDash structures in which the non-linear effects associated with the ES can be much more emphasized. This phenomenon can make QD lasers more sensitive to optical feedback, which results in larger variations in the onset of the coherence collapse compared to that of the quantum well (QW) devices.

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 $\sim 8\text{mA}$ 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. 3 shows the measured coherence collapse threshold as a function of the bias current. An increase in the critical feedback level is found from 36-dB to 27-dB when the current increases from 12mA to 70mA. The onset of the coherence collapse follows the variations of the relaxation frequency. This conventional trend was previously observed in fig. 2 when

considering the GS contribution as a function of the bias current. Fig. 4 shows the measured coherence collapse 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 turn on in a semiconductor laser; indeed depending on how the above-threshold α_H -factor behaves, the sensitivity to the coherence collapse is tuned and may be improved or altered. As regards the QW device, the sensitivity to optical feedback is improved when increasing the current. This conventional behavior which has already been observed many times [15] 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 driven by the first term of equation (1) such as $\alpha_{GS} \gg \alpha_{ES}$. It is important to note that a similar expression was derived in earlier studies [16]. Expression (52) in [16] already shows that the α_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 the 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 α_H -factor variations of the QDash FP laser are now much more important since for instance $\alpha_{GS} < \alpha_{ES}$. This means that the carrier filling in the ES has to be considered in order to explain the non-linear increase of the above-threshold α_H -factor. As a consequence, the critical feedback level does not follow the relaxation frequency variations since the coherence collapse is found to be up-shifted when decreasing the bias current level. Such behaviors can mostly occur in QD lasers in which the influence of the ES coupled to the non-linear effects are emphasized.

IV. Conclusions

The onset of the coherence collapse 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 ES filling produces an additional term, which accelerates the route to chaos. This

contribution can be seen as a perturbation that reduces the overall coherence collapse threshold. Depending on the variations of the α_H -factor above threshold, the feedback resistance can be improved or deteriorated from one laser to another. The design of QDash lasers with no excited state, reduced gain compression effects, lower and quasi-constant α_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 [17]. The laser characteristics published exhibited an almost constant α_H -factor as well as no excited state over a wide range of current. These results highlight that the control of the α_H -factor has to be considered as a significant input for the realization of feedback-resistant lasers. It is also pointed out that the prediction of the onset of the coherence collapse remains an important feature for all applications requiring a low noise level or a proper control of the laser coherence.

V. References

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Figure captions

Figure 1: Schematics of the experimental apparatus for the feedback measurements

Figure 2: Coherence collapse threshold as a function of the bias current including the contributions of the GS only, the ES only, both the GS and the ES and comparison with the measured data (black squares).

Figure 3: Coherence collapse threshold as a function of the bias current for the QW DFB laser. Solid line is added for visual help only.

Figure 4: Coherence collapse 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. Solid lines are added for visual help

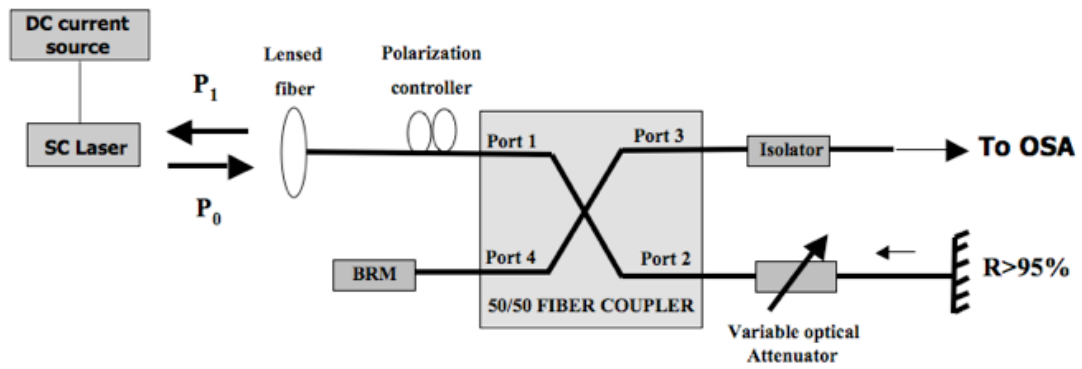


Figure 1

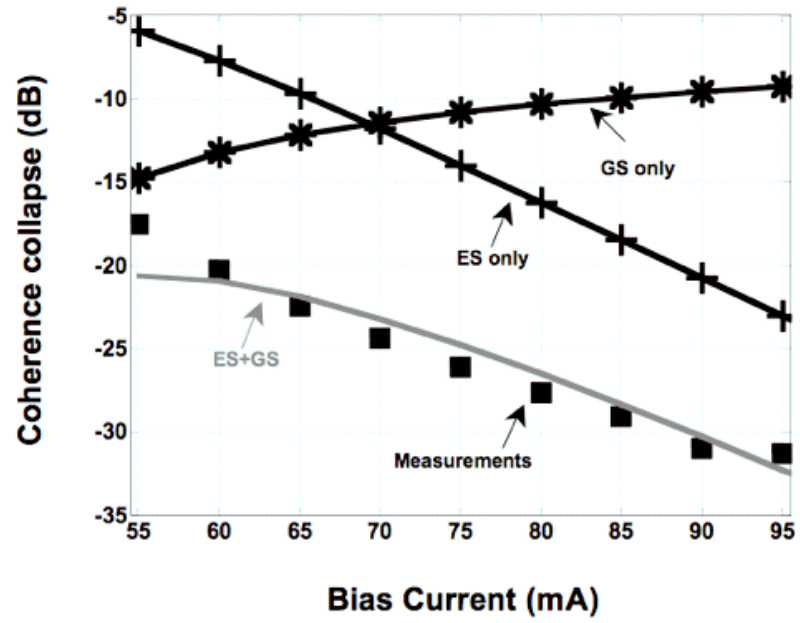


Figure 2

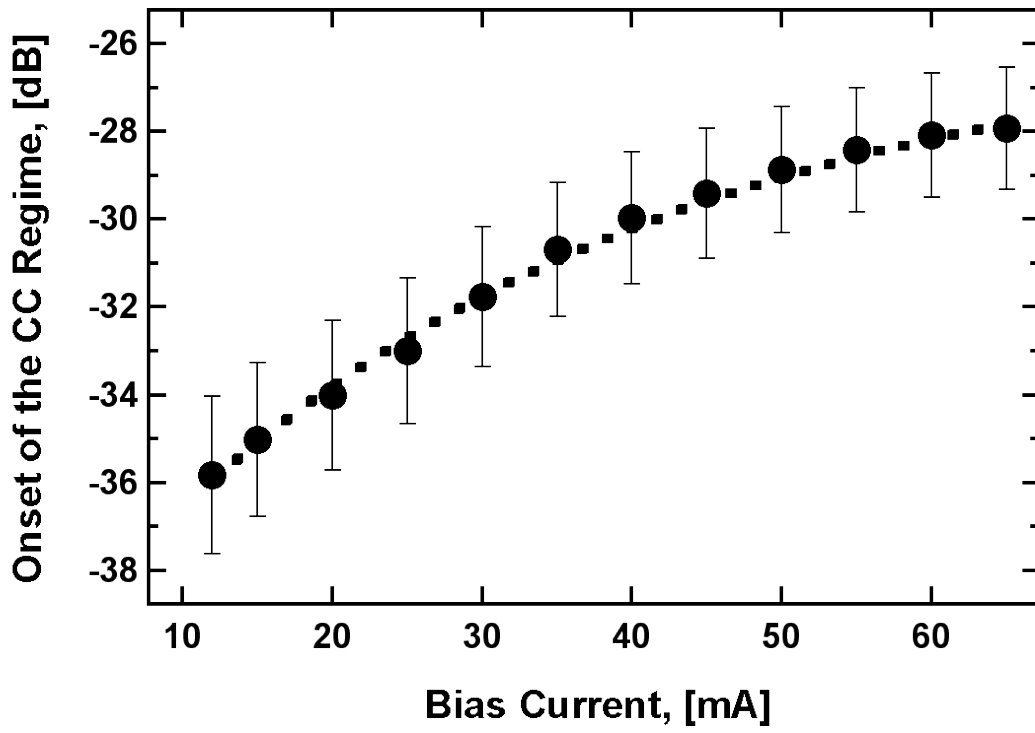


Figure 3

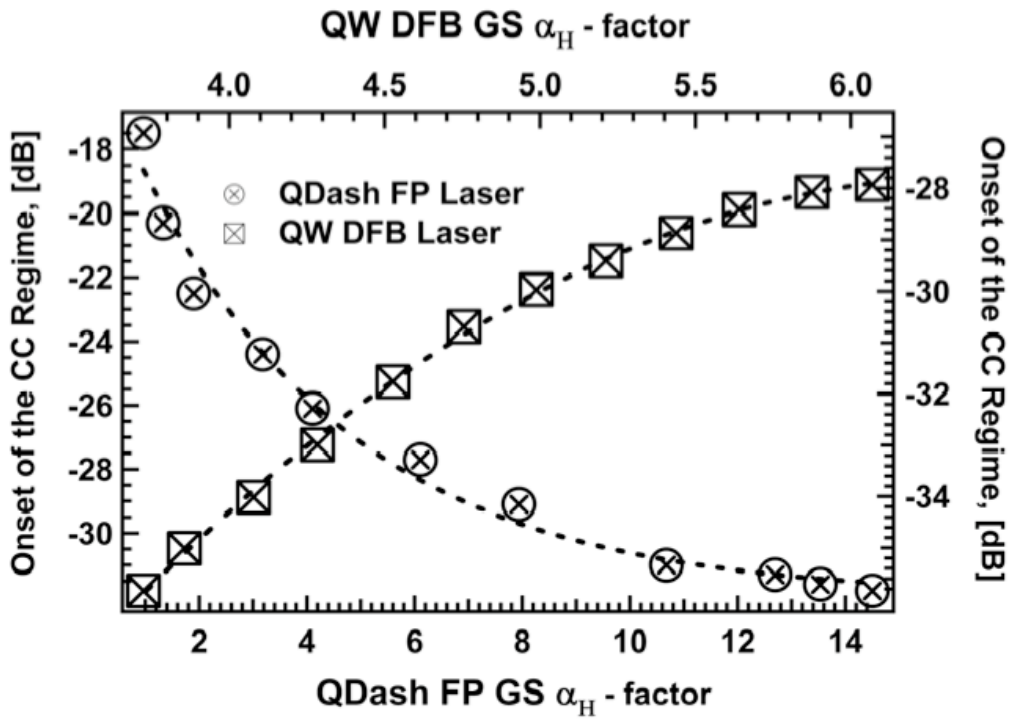


Figure 4