Optical Feedback Tolerance of Quantum-Dot- and Quantum-Dash-Based Semiconductor Lasers Operating at 1.55 μm

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***Abstract*—This paper reports on the tolerance of low-dimensional InAs/InP quantum-dash- and quantum-dot-based semiconductor lasers to optical feedback in the 1.55 μm window. For this purpose, the onset of coherence collapse (CC) is experimentally determined and systematically investigated as a function of different laser parameters, such as the injection current, differential gain, temperature, and photon lifetime. It is in particular found that for both material systems the onset of CC increases with the injection current in a similar way to bulk or quantum-well-based devices. Of most importance, we experimentally show that the differential gain plays a key role in the optical feedback tolerance. It is indeed shown to determine not only the range of the onset of CC but also the dependence of this threshold both on the temperature and laser cavity length. Increasing the operating temperature from 25 °C to 85 °C leads to a decrease of the onset of CC by a factor of only ∼3 dB, well accounted for by the variation of the differential gain in this temperature range. We find no difference in the tolerance to external reflections of a truly 3-D confined quantum-dot-based laser and a quantum dash device of the same cavity length, which have similar differential gains. A tentative analysis of our data is finally carried out, based on existing models.**

***Index Terms*—Coherence collapse, optical feedback, quantum dash, quantum dot, semiconductor laser.**

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I. Introduction

TIME-DELAYED feedback can lead to very complex behavior in various areas, and many examples of problems induced by the feedback can be found in a large variety of systems: physics, economy, climatology, electricity, etc. In optical systems, controlled feedback of light can have many applications: It can be used, for instance, to reduce the linewidth of the emitted light or for other applications such as encryption based on chaos, frequency tuning, or velocity measurements. However, external optical feedback in lasers may be induced from unintentional and uncontrollable back-reflections and is thus difficult to avoid. Now, it was experimentally shown by Tkach and Chraplyvy that a semiconductor laser may be subject to instabilities when submitted to optical feedback and that it may operate in five distinct regimes [1]. The most critical one is the fourth regime, known as "coherence collapse" (CC) [2], since in this regime the lasing mode is unstable and is characterized by a drastic broadening of the laser linewidth due to undamped relaxation oscillations, the appearance of external cavity peaks in the electrical and optical spectra, and a sudden large increase of the relative intensity noise (RIN). To our knowledge, the first observation of this phenomenon has been reported in [3]. This regime is not desirable for data transmission in fiber optic telecom applications, which indeed require stable laser operation. Expensive optical isolators are hence usually used in order to avoid this kind of instabilities. One way to avoid these elements and consequently reduce the cost of the transmitter module would be to design and fabricate lasers insensitive to optical feedback.

Intensive work both theoretical and experimental has been carried out to understand which laser parameters may have an impact on the sensitivity to optical feedback. It was proposed in [1] and [4] that the onset of CC, i.e., the feedback strength for which the transition to CC occurs, takes place when the feedback rate becomes comparable to the relaxation frequency. However, it was later numerically shown in [5] that the onset of CC also depends in an explicit form on the linewidth enhancement factor (LEF or the so-called Henry factor α_H). This model has extensively been referred to since some important parameters for optical feedback tolerance of semiconductor lasers have theoretically been identified. Especially, an analytical formula was derived in [6] to predict the onset of CC. Of most importance, this formula predicts that a lower LEF should lead to a

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higher onset of CC and thus to a lower sensitivity of semiconductor lasers to optical feedback. Based on these conclusions and the fact that a lower LEF also leads to a lower chirp and thus to improved data transmission quality, a great effort has been dedicated to achieve lower LEFs in semiconductor lasers.

This constitutes one of the main drivers of the intense investigations carried out for the last decade or so on quantum-dot-based lasers. Quantum dots are nanostructures that allow 3-D confinement of the carriers and are expected to achieve higher laser performances than those of bulk and quantum-well-based ones. Unique properties are indeed predicted, some of which have readily been demonstrated such as low threshold current densities and high characteristic temperatures. Of particular importance for low chirp and low sensitivity to optical feedback, small even near-zero LEFs are predicted [7]. This is the case for injection current below threshold [8], but α_H increases above threshold reaching values similar to those of quantum-well-based lasers [9].

For lasers emitting at 1.55 μm, one of the first experimental reports on optical feedback deals with a 1.55-μm bulk laser [1]. The different regimes under optical feedback are clearly identified, and it is briefly mentioned there that the onset of CC increases with the emitted power, that is, with injection current. Other experimental investigations have often been performed on transmitter modules including an isolator as in [10] in which an optical return loss tolerance (defined in Section II-G) of approximately -10 dB is reported for a distributed feedback (DFB) laser module under 2.5 Gb/s modulation. In [11], 300-μm-long bulk and compressively strained multiquantum-well-based DFB lasers emitting at 1.5 μm are investigated. An onset of CC of approximately -35 dB for the bulk laser and an onset higher than -10 dB for an optimized multi-quantum-well DFB laser are reported. However, it should be noted that the criterion used in this paper to determine the CC is based on the increase of the RIN at the base level of the RF noise spectra peaks, which is misleading in the evaluation of the onset of CC [12].

Most of the reports on the tolerance to optical feedback of lasers emitting in the 1.3-μm telecom window were made for InAs/GaAs quantum-dot-based devices. A record approximately -8 dB onset is given in [13], [14] for a 1500-μm-long Fabry–Perot laser. The authors attribute this behavior to the high damping of the relaxation oscillations believed to occur in these devices, although a damping rate of only $\sim$6 GHz was measured in similar devices [15]. In [16], a DFB quantum-dot-based laser has been shown to be highly robust to external optical feedback since the onset of CC is estimated at a -14 dB level, mainly attributed to the very low LEF measured below threshold ($\alpha_H \sim 0.1$). In the dynamic regime, however, the eye diagram and the SNR under 2.5 Gb/s direct modulation have been shown to degrade from a approximately -30 dB feedback level. The laser is furthermore high reflectivity coated on both facets, and only a very weak fraction of the fed-back light enters the laser cavity.

To briefly summarize the state of the art in the field of semiconductor lasers under optical feedback, the influence of the injection current on the optical feedback tolerance has only been reported in [1] and [14], to our knowledge, and furthermore, no systematic experimental work could be found in the literature about the influence of the laser parameters on the optical feedback sensitivity. The aim of this paper is to investigate low-dimensional InAs/InP quantum dot and the so-called quantum-dash-based lasers emitting at 1.55 μm under optical feedback in a detailed and systematic way. We, in particular, investigate the onset of CC as a function of the injection current but also, for quantum-dash-based lasers, as a function of the temperature, laser cavity length, and dynamic parameters that have been assessed for each investigated structure. A systematic comparison with existing models has hence been made possible.

II. Investigation of InP Quantum-Dash-Based Lasers

Growth using molecular beam epitaxy on 100 oriented InP substrates leads to the formation of quantum dots [17] or quantum dashes [18]–[20], which are elongated dots, emitting at 1.55 μm. One of the advantages of quantum-dash-based lasers is the higher modal gain compared to that of quantum dots [21].

Our approach has first consisted in designing and fabricating single-transverse mode Fabry–Perot lasers based on different quantum dash structures. The dynamic parameters such as the LEF, relaxation frequency, and the damping rate have been systematically measured. The onset of CC has then been investigated.

A. Experimental Setup and Measurement Procedures

The experimental bench used to determine the optical feedback sensitivity is fully described in [12] and is similar to that used in [16]. The external cavity length is $\sim$18 m. The laser is temperature controlled by means of a Peltier cooler. The optical feedback is generated thanks to a reference reflector, and its level is controlled with a variable attenuator. The effect of the optical feedback is analyzed with a 10-pm resolution optical spectrum analyzer or a combined electrical spectrum/RIN analyzer. A polarization controller is used to match the feedback light polarization to the emitted TE-polarized light in order to maximize the feedback effect. The onset of CC is reflected by both a broadening of the optical lineshape with undamped relaxation oscillations (Fig. 1) and a sudden increase of the RIN [1], [5], [12], [22]. Hence, these two criteria can be used in static operation to determine the onset of CC, especially since it has been shown within our previous work that both criteria lead to similar values of the onset of CC (Fig. 2) [12]. As for devices investigated in dynamic operation (Section II-F), the onset of CC has been considered to be reached when a bit error rate (BER) penalty increase of $\sim$1 dB is induced by the optical feedback [12].

B. Structures and Devices

Quantum dash structures were grown by gas source molecular beam epitaxy (MBE) on (1 0 0) InP substrates using the self-organized Stransky–Krastanov growth mode [20]. The typical dashes height and width are, respectively, $\sim$2 nm and $\sim$15–20 nm. Their length ranges from 40 to 300 nm, depending on the growth conditions, and their surface density is between

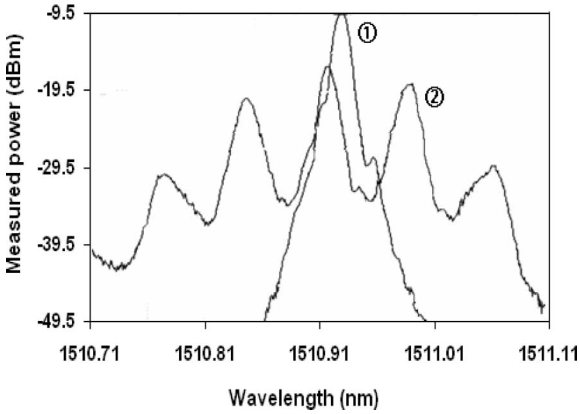

Fig. 1. Optical spectrum: (1) without optical feedback; (2) with optical feedback and onset of CC Reprinted with permission from [12].

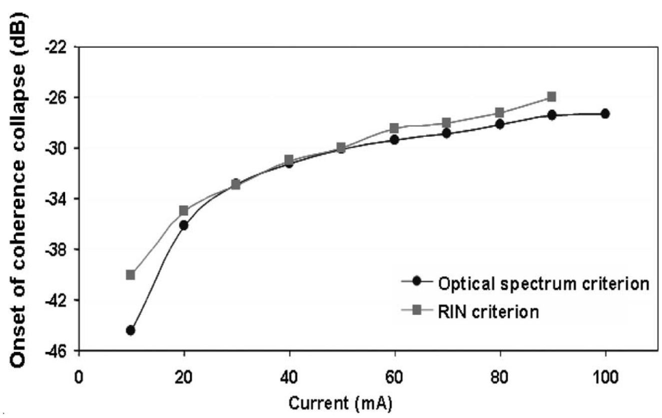

Fig. 2. Onset of CC, determined both from the optical spectrum and the RIN, of a 205-μm- long DFB quantum-dash-based laser versus the injection current. Reprinted with permission from [12].

1×10^{10} and 4×10^{10} cm^{-2} [20]. Three types of structures were investigated: dashes in a barrier (DBAR), dashes in a well (DWELL), and tunnel injection (TI). Dashes-in-a-well structures consist of quantum dashes, embedded within an InGaAsP quantum well, and separated by InGaAsP barriers, whereas in dashes-in-a-barrier structures the nanostructures are directly enclosed in the barriers [20]. Tunnel-injection structures consist of dashes in the barriers coupled with a quantum well carrier injector. The optical confinement is provided by two InGaAsP separate confinement heterostructure layers. Laser structures have been processed into either ridge waveguide or buried ridge stripe lasers.

C. Impact of the Current and Differential Gain

All the devices investigated here are Fabry–Perot lasers of the same cavity length (600 μm) with as-cleaved facets. The measurements were performed at 25 °C. The onset of CC has systematically been determined from the broadening of the optical lineshape, as a function of injection current for lasers fabricated from nine distinct structures. More details are given in [23]. For all investigated lasers, the measured onsets of CC (in a linear scale) are found to increase linearly with the current difference

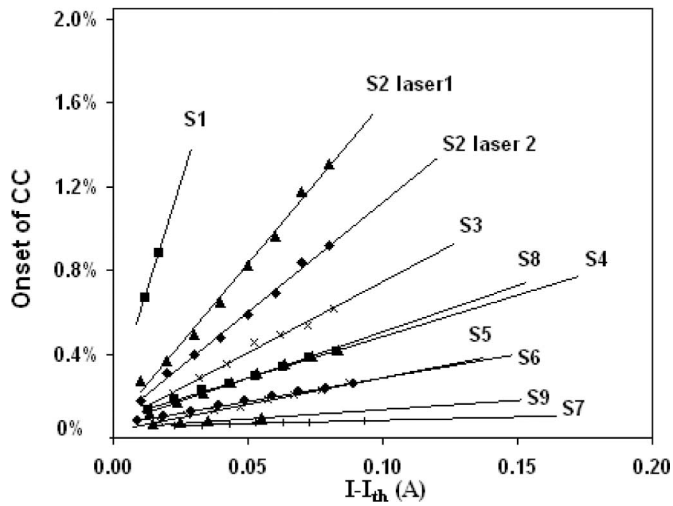

Fig. 3. Onset of CC of several 600 μm-long Fabry–Perot quantum-dash-based lasers as a function of the current difference. Reprinted with permission from [23].

$I - I_{\rm th}$, where I is the injection current and $I_{\rm th}$ is the threshold current, as shown in Fig. 3. This means that the optical feedback tolerance is enhanced with increased injection current and thus emitted power, whatever the designed structure. A detailed analysis of Fig. 3 has evidenced that the variation of the onset of CC with injection current $\partial\gamma_c/\partial I$ depends on both the type of structure and other parameters linked to the fabrication process. For all investigated designs (DBAR, DWELL, and TI), the onset of CC and the slope of this latter one with current may be very different from one structure to the other. The highest slope is obtained for the structure with the highest differential gain.

Further analysis has consisted in exploiting the dynamic parameters, that is, LEF, relaxation frequency, damping rate, and differential gain, to discuss the slope of these curves. For all lasers, the LEF was evaluated above threshold as a function of the injection current, using a high-frequency modulation technique [24]. It is found to steadily increase with current, with typical values of $\sim$3.6 and $\sim$11 (measured at $\sim$10 mA above threshold) for the lowest and highest values [23]. An analysis of the results only based on the LEF has not led to an overall consistent picture, since two laser structures may have almost same slopes $\partial\gamma_c/\partial I$, that is, same onset of CC, in spite of distinct LEFs [23]. If we now consider the other dynamic parameters, we show that the slopes of the onset of CC with injection current are related to $G_n\eta_I$, where η_i is the internal differential quantum efficiency and G_n is the effective differential gain defined by

$$G_n = \frac{\Gamma}{V}\frac{\delta g}{\delta n} \tag{1}$$

where Γ is the confinement factor in the active volume V and $\delta g/\delta n$ is the material differential gain. By plotting the slopes of the fitted lines of Fig. 3 as a function of $G_n\eta_i$ and by fitting the plotted points, it has clearly been shown that $\partial\gamma_c/\partial I$ is proportional to $(G_n\eta_i)^n$ with $n \sim 2$ [23]. This result is consistent with the conclusions of existing models, saying that higher relaxation frequency, and thus higher differential gain, leads to higher onset of CC. This implies that higher optical feedback

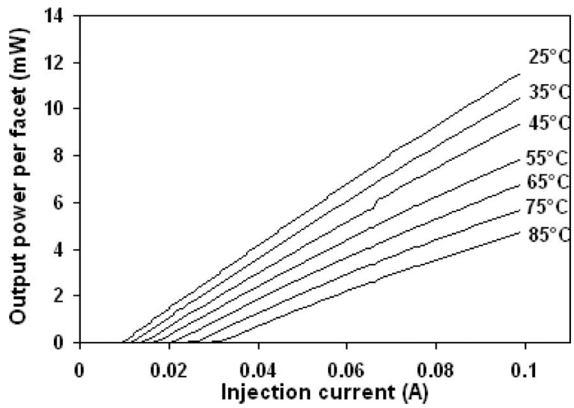

Fig. 4. Light–current characteristic of a quantum-dash-based laser as a function of the temperature.

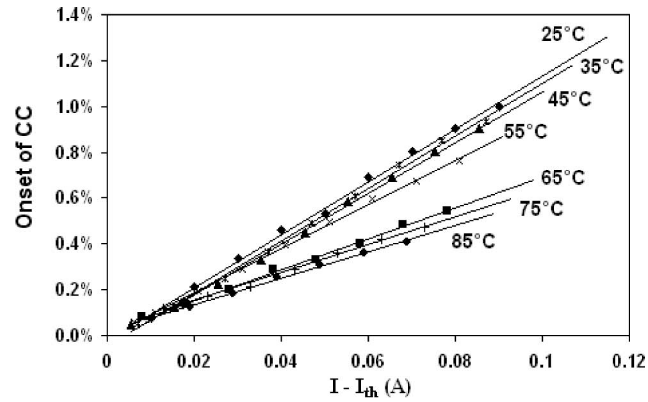

Fig. 5. Measured onset of CC of a quantum-dash-based laser as a function of the current difference and temperature.

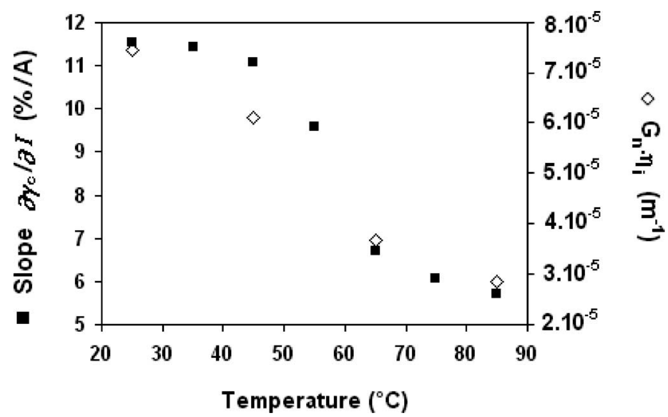

Fig. 6. Parameter $G_n\eta_i$ and slope $\partial\gamma_c/\partial I$ versus temperature.

tolerance can be achieved by designing laser structures with higher differential gain.

D. Impact of the Temperature

Isolatorless lasers are of particular importance for metropolitan area network (MAN) and local area network (LAN) applications, and the robustness of lasers to optical feedback should thus hold for the whole 25 °C–85 °C temperature range. We have hence investigated the influence of the temperature on optical feedback sensitivity using a 600-μm-long Fabry–Perot laser from a quantum-dash-in-a-barrier structure. The light–current characteristic of the assessed laser is shown in Fig. 4. The onset of CC has been measured from 25 °C to 85 °C using the optical spectrum broadening criterion (Fig. 5). As shown in Fig. 5, the onset of CC is found to linearly increase with the current difference $I - I_{\mathrm{th}}$ whatever the temperature. Moreover, the slope $\partial\gamma_c/\partial I$ is found to slightly decrease with the temperature, especially beyond 55 °C. Nonetheless, the onset of CC is only decreased by a factor of $\sim$3 dB from 25 °C to 85 °C, which is a rather interesting result. The decreased slope with the temperature may simply be explained by the decrease of the differential gain beyond $\sim$55 °C, as evidenced in Fig. 6. This figure indeed shows that the slope $\partial\gamma_c/\partial I$ has the same dependence on the temperature as the parameter $G_n\eta_i$, which is related to the differential gain [see (1)]. This study again emphasizes that low sensitivity of the onset of CC to the temperature can be achieved by designing lasers with an effective differential gain that is temperature-insensitive, implying a temperature- insensitive differential quantum efficiency.

E. Impact of the Laser Cavity Length

The effect of the laser cavity length on the tolerance to optical feedback has been investigated for three distinct structures: S2 (DBAR), S6 (DWELL), and S8 (TI). For instance, Fig. 7 illustrates the measured onset of CC as a function of the current difference for four lasers, with distinct cavity lengths, of the same structure and fabrication process. It is confirmed in this figure that the onset of CC linearly increases with current whatever the laser cavity length. An important feature shown in the figure is that the onset of CC increases with L at a fixed current difference. This is consistent with reports on quantum-dot-based laser emitting at 1.3 μm [14]. This result has systematically been found for the two other structures. Fig. 8 summarizes the results for all three investigated structures by giving the slope $\partial\gamma_c/\partial I$ as a function of L. It is clear that the slope $\partial\gamma_c/\partial I$ increases with L whatever the structure. It is also evidenced that the dependence of $\partial\gamma_c/\partial I$ on L is related to the laser structure. It was indeed found that it is especially linked to the differential gain. The highest (respectively lowest) variation of $\partial\gamma_c\partial I$ with L is obtained for the laser with the highest (respectively lowest) differential gain.

F. Assessment of a Directly Modulated DFB Laser

A buried ridge stripe index-coupled DFB laser has finally been investigated under optical feedback when directly modulated at 10 Gb/s [12]. The 205 μm-long laser was fabricated from a DWELL structure. The rear facet is high reflectivity coated, whereas the front facet is as cleaved. The measured LEF increases with the bias current from 3.6 near threshold current to $\sim$4.3 at 25 mA. The measurements have consisted in directly modulating the laser at 10 Gb/s with a $2^{31} - 1$ pseudorandom bit sequence and in measuring the BER as a function of the received power at an error detector. This was performed for different feedback levels at the 30 mA operating point of the 10 Gb/s transmission experiment [25], at 25 °C and in a

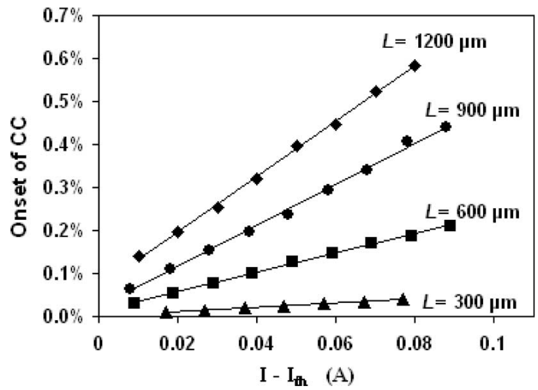

Fig. 7. Measured onset of CC of quantum-dash-based lasers of the same structure and fabrication process as a function of the cavity length.

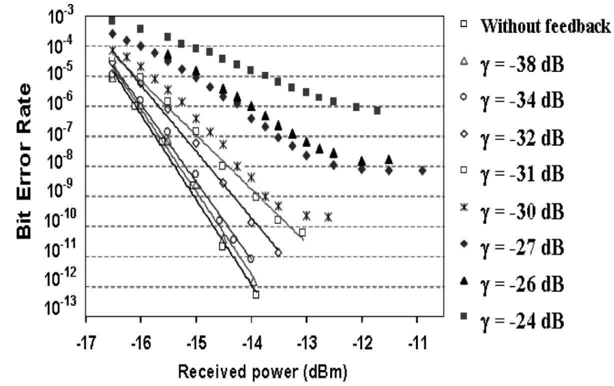

Fig. 9. BER versus received power for different feedback levels at 30 mA. Reprinted with permission from [12].

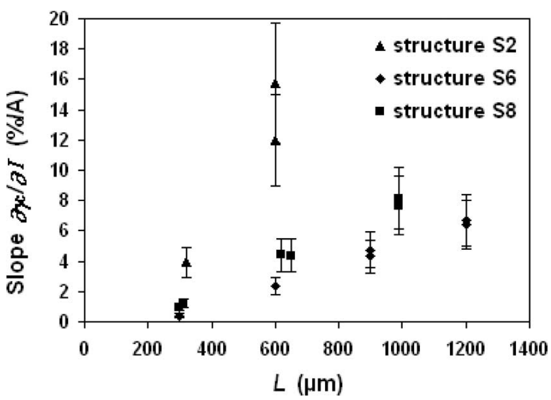

Fig. 8. Measured slopes of the onset of CC with injection current as a function of the cavity length for three distinct structures.

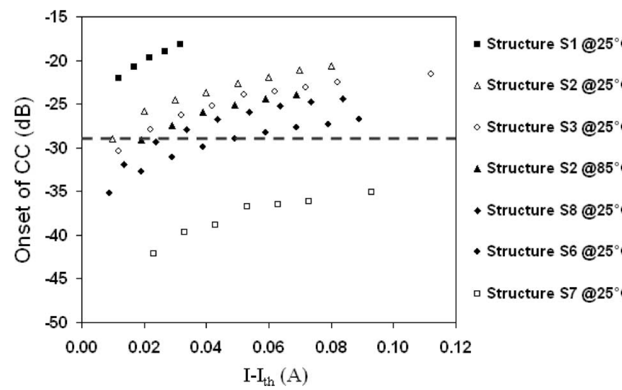

Fig. 10. Onset of CC of 600-μm- long quantum-dash-based lasers (the dashed line represents the minimum value required for isolator-free operation).

back-to-back configuration (see Fig. 9). Increasing the optical feedback degrades the BER and introduces a penalty as already experimentally shown in [26]. In fact, the BER degrades from −32 dB feedback level, and above –30 dB floor-free operation is not possible [12]. A –32 dB onset of CC could hence be extracted from these measurements.

A similar value of the onset of CC has been found when assessing the same laser in static operation [12]. This is a rather important finding as it implies that no systematic investigation in dynamic operation is required for feedback-tolerant laser design.

G. Isolator-Free Lasers

External reflections in optical systems are usually quantified by the optical return loss (ORL), defined as the optical feedback at the end point of the coupling fiber. It is related to the optical feedback at the laser facet by:

$$\mathrm{ORL}_{\mathrm{crit}} = \gamma_{\mathrm{crit}} - (2C_{\mathrm{fiber}}) \tag{2}$$

where C_{fiber} is the coupling losses between the coupling fiber and the laser. ORL up to −21 dB is tolerated in the IEEE 802.3 standard for 10 Gb/s data transmission for 1.55 μm operating wavelength (physical entity 10GBASE-E). Using (2), we obtain that the onset of CC must be higher than −29 dB for 1.55 μm wavelength if we consider coupling losses of approximately –4 dB. Fig. 10 is the same plot as Fig. 3, except that the onset of CC is plotted in a logarithmic scale. For clarity, only results for some of the assessed structures are plotted. Five of the nine investigated structures were found to achieve onsets of CC higher than −29 dB (see Fig. 10). Hence, quantum-dash-based lasers investigated here comply with the IEEE 802.3 standard for isolator-free operation. Low-cost transmitter modules can thus be achieved using quantum dash material. Furthermore, in the same figure the onset of CC was plotted both at 25 °C and 85 °C for structure S2 (DBAR) investigated in Section II-D. It appears that onsets of CC higher than −29 dB can thus be achieved up to 85 °C. Quantum-dash-based lasers can hence be used as light emitters in optical modules without optical isolator in the whole 25 °C–85 °C temperature range.

III. Investigation of InP Quantum-Dot-Based Lasers

To further assess the impact of reduced dimensionality on laser tolerance to optical feedback, we have investigated Fabry–Perot lasers based on truly 3D-confined quantum dots.

A. Structure and Devices

The structure was grown by gas-source MBE on a n-doped (311) B InP substrate [27]. The active region is composed of five InAs quantum dot layers. Ridge waveguide lasers were fabricated using this InAs/InP quantum dot structure. The

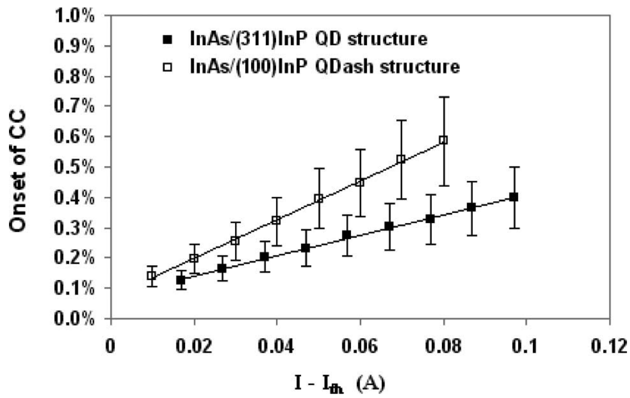

Fig. 11. Onset of CC as a function of the current difference for a 1100-μm-long quantum-dot-based laser and for a 1200-μm-long quantum-dash-based laser.

investigated device is a 1100-μm-long laser with uncoated facets. Emission occurs at $\sim$1.52 μm, and the threshold current is $\sim$43 mA at 25 °C. The measured LEF above threshold [28] is almost constant with current ($\sim$7).

B. Experimental Results

The onset of CC was determined from the optical lineshape broadening as a function of the driving current at 25 °C (Fig. 11). It is found to linearly increase with current, in a similar fashion than that of quantum dash lasers (Section II). For comparison, InAs/GaAs quantum-dot-based lasers emitting at 1.3 μm have shown a very differing behavior. Indeed, instabilities rather than real CC have been reported [14] and in [14], Fig. 2] it can be seen that the onset of these instabilities first decreases with current and then reaches a constant value above 1.2 times the threshold current, in contrast with our observations on 1.55 μm quantum dot lasers. This obviously requires more investigations to elucidate the origin of these differences.

To elucidate whether the investigated 1.55 μm quantum-dot-based lasers are more tolerant to optical feedback than quantum-dash-based ones, we have also carried out a comparison of these results with those of a quantum dash laser with almost the same cavity length ($\sim$1200 μm) and with comparable modulation efficiency (0.36 and 0.47 GHz/mA$^{1/2}$, respectively, for the quantum dot and quantum dash devices) and thus comparable differential gain. Fig. 11 shows the measured onsets of CC for both devices. The quantum dash laser shows a slightly higher onset of CC than the quantum dot one, which can simply be explained by the higher modulation efficiency. This study shows that at equal differential gain InAs/InP quantum dot lasers lead to similar sensitivity to optical feedback than InAs/InP quantum-dash-based lasers.

IV. Comparison to Existing Models

In this section, our experimental results are discussed in terms of existing theoretical models on semiconductor lasers under optical feedback, introduced in Section IV-A.

A. Existing Models on Optical Feedback

First theoretical modeling of time-delayed optical feedback in semiconductor lasers has been carried out by Lang and Kobayashi (LK) [29], who showed that optical feedback induces instabilities in semiconductor lasers due to the fact that the external mirror at which the optical feedback occurs forms an external cavity characterized by its own oscillating frequencies. Based on this statement, standard rate equations of the semiconductor lasers have been modified to take into account the optical feedback and new rate equations have hence been derived [29]. By numerically solving these LK rate equations, the CC regime is found to be characterized, as experimentally observed, by fluctuations in the photon density, a broadened optical lineshape, with undamped relaxations oscillations and external cavity modes, and an increase of the RIN [5]. The impact of laser parameters in this field has been further investigated by Schunk and Petermann in [5], who have shown that the stability of the laser under optical feedback does depend on the relaxation frequency as suggested in [1] and [4] but also on the LEF. Furthermore, using the microwave modulation response, Helms and Petermann derived an analytic formula to predict in a simple way the onset of CC [6]. Under the assumption of a long external cavity, i.e., for which the product of the relaxation oscillation frequency and the external cavity round-trip time is higher than unity, the authors showed that the onset of CC can be written as [6]

$$\gamma_c = \Gamma_d^2 \times \frac{1+\alpha_H^2}{\alpha_H^4} \times \frac{\tau_{\text{in}}^2}{16 \times C_{\text{ext}}^2} \tag{3}$$

where Γ_d is the damping rate, τ_{in} is the round-trip time in the laser cavity, and C_{ext} is the feedback sensitivity factor [6], [30], given for Fabry–Perot lasers by

$$C_{\text{ext}} = \frac{1-|r|^2}{2\,|r|} \tag{4}$$

where r is the reflectance of the facet submitted to the external reflections), whereas in DFB lasers C_{ext} depends on the grating parameters and the facet reflectivities and phases [30]. Numerically solving LK rate equations has both qualitatively and quantitatively confirmed the validity of the formula derived by Helms and Petermann [6], which has been widely used in the field of optical feedback.

Other works have also been carried out in this theoretical field. Based on experimental observations, it was proposed in [31] by Binder and Cormack that the CC occurs when the maximum feedback-induced frequency shift exceeds the relaxation frequency f_r. In their approach, the critical feedback level is given by

$$\gamma_{\text{crit}} = (2\pi)^2 f_r^2 \times \frac{1}{1+\alpha_H^2} \times \frac{\tau_{\text{in}}^2}{4 \times C_{\text{ext}}^2}. \tag{5}$$

We can note that (5) suggests that CC would not vanish in the case of zero LEF, contrary to (3). Equation (5) is thus consistent with conclusions of [32], where it is shown that the onset of CC indeed increases when the LEF decreases but converges to a finite value for zero LEF. Nonetheless, it should be noted that

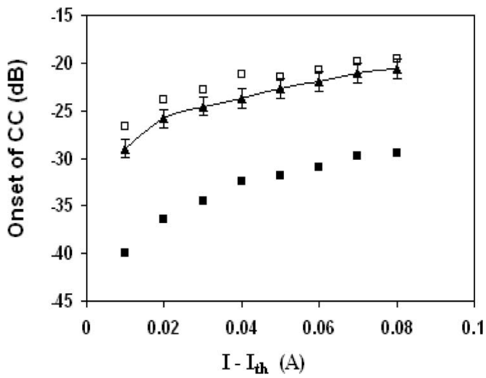

Fig. 12. Comparison of experimental data with predicted values for a quantum-dash-based laser (structure S2).

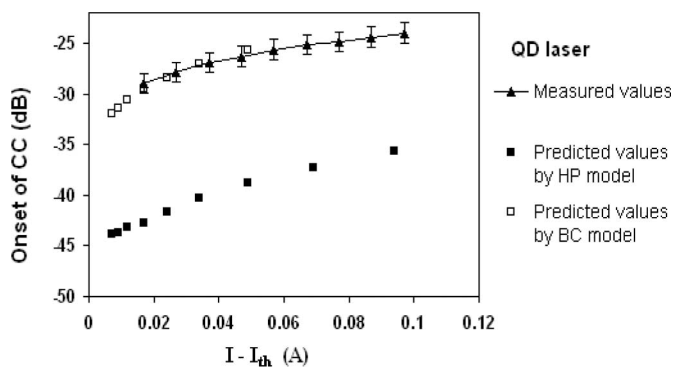

Fig. 13. Comparison of experimental data with predicted values for a quantum-dot-based laser.

(3) has empirically been derived from another expression of the onset of CC [6], which initially also suggests that the onset of CC would reach a finite value for zero LEF [6], Eq. (8)]. Moreover, a formula similar to (5) except for a factor of 2 has analytically been derived by Tromborg and Mork by analyzing the stability of the oscillating modes [33]. In spite of these differences, (3) and (5) nonetheless both predict that the onset of CC would increase for devices with small LEF. Hence, this suggests that a higher optical feedback tolerance could be achieved with lasers exhibiting lower LEFs. This is one of the main reasons of the huge interest of the scientific community in quantum-dot-based lasers, since these materials have been expected to exhibit near-zero LEFs.

B. Comparison to Helms and Petermann Model

Our experimental results were first compared to Helms and Petermann model to check its validity for the values of the onset of CC experimentally measured for quantum dash and quantum dot lasers emitting at 1.55 μm [23]. Using (3), the onset of CC has been calculated from the measured LEFs and extracted damping rates, as a function of the injection current, for all assessed Fabry–Perot devices. This study may only be relevant for Fabry–Perot lasers since the feedback sensitivity factor $C_{\rm ext}$ is independent of the facet phases and is simply given by (4) ($C_{\rm ext}$ is $\sim$0.6 for as-cleaved facets), contrary to DFB lasers. First, the comparison has been performed for quantum dash lasers investigated in Section II. Fig. 12 illustrates as an example the comparison of the measured onsets of CC for a 600-μm-long quantum dash laser with the predicted ones. It can be seen in this figure that the onset of CC predicted by Helms and Petermann model has the same increasing tendency with current, although with values $\sim$10 dB lower. This behavior has systematically been observed for all investigated Fabry–Perot quantum dash lasers. Predicted values indeed always show the same trend versus current as measured values, although together with a systematic $\sim$8–10 dB discrepancy [23].

The same comparison has also been performed for the InAs/InP quantum-dot-based lasers investigated in Section III. The predicted values using (3) again show the same increasing behavior with the injection current as the experimental points, nonetheless with a $\sim$12-dB discrepancy (see Fig. 13), similar to the case of quantum-dash-based lasers. Hence, although Helms and Petermann model predicts well the increase of the onset of CC with injection current, it yields values for the onset of CC lower by $\sim$10/12 dB than the measured ones, i.e., predicting a lower optical feedback tolerance for the assessed devices than the experimental one.

C. Comparison to Other Models

In a second step, we consider the Binder and Cormack criterion (5) using the measured relaxation frequency and LEF for each investigated laser. As shown in Fig. 12, the comparison of our experimental data for quantum-dash-based lasers with the values derived using (5) leads to a fair agreement, with a maximum discrepancy of $\sim$3 dB. The same comparison has been made for the quantum-dot-based lasers with a similar conclusion since again a good agreement between the experimental data and predicted values is achieved (Fig. 13). Furthermore, (5) does predict in an explicit way the linear dependence of the onset of CC with current whereas (3) does not. Indeed, (5) shows that the onset of CC is a function of f_r^2, implying that the onset of CC should be a linear function of the current difference $I - I_{\rm th}$, which is confirmed by our experimental data. Moreover, although the term f_r^2 in (5) would suggest that the onset of CC may be a function of $G_n \eta_i$, it should be reminded that the LEF is also a (reciprocal) function of the differential gain and thus of $G_n \eta_i$, which could explain the fact that we could fit the measured onsets of CC by a $(G_n \eta_i)^2$ dependence. Another point is that (5) implies a linear dependence of the onset of CC on the laser cavity L since the squared relaxation frequency is a reciprocal function of L and the squared round-trip time is proportional to L^2, which could explain our data plotted in Fig. 8. Binder and Cormack model described by (5) is thus fairly consistent with all our experimental observations and results.

V. Conclusion and Discussion

For the first time, 1.55 μm quantum-dash- and quantum-dot-based lasers are assessed in terms of tolerance to optical feedback to check their potential for isolator-free operation but also to identify the main parameters determining their sensitivity to optical feedback. A systematic investigation has been undertaken to elucidate the impact of the laser parameters such as the injection current, LEF, differential gain, temperature, and laser cavity length. The onset of CC, which is a measure of the tolerance to optical feedback, has been shown to linearly increase with injection current. Our study further suggests the differential gain as the main parameter that must be improved for an increased tolerance to optical feedback in semiconductor lasers. The dependence of the optical feedback tolerance on the temperature is similar to that of the differential gain. Lasers should hence be designed with a relatively temperature insensitive differential gain. Then we have investigated the impact of the laser cavity length, i.e., the photon lifetime. The onset of CC is shown to increase with the laser cavity length, meaning that higher optical feedback tolerance should be achieved with longer lasers. However, it should be reminded that the modulation efficiency is also related to the photon lifetime as a reciprocal function. Thus, a tradeoff on the laser cavity length should be made to achieve both good modulation efficiency and sufficient optical feedback tolerance. We have nevertheless shown that 600-μm-long quantum-dash-based devices fully comply with the 10 Gb/s Ethernet standard for isolator-free operation in the temperature range up to 85 °C. Investigation of 1.55 μm quantum-dot-based lasers also shows that the onset of CC linearly increases with the injection current. Furthermore, the important feature is that quantum-dash- and quantum-dot-based lasers with similar differential gain present similar tolerance to optical feedback. This again emphasizes that the differential gain is the main parameter in optical feedback assessment. The final part of this study has consisted in comparing the experimental results to existing models that predict the onset of CC. The Helms and Petermann model [6] yields a $\sim$10 dB (respectively $\sim$12 dB) discrepancy when comparing the predicted values to the experimental data obtained for quantum-dash (respectively quantum dot) based lasers. All the experimental data are found to agree fairly well with the expression for the onset of CC derived by Binder and Cormack [31]. Further work, both experimental and theoretical, is obviously needed to elucidate the discrepancy of the experimental data with the Helms and Petermann model.

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