Tolerance to Optical Feedback of 10-Gb/s Quantum-Dash-Based Lasers Emitting at 1.51 μm

S. Azouigui, B. Dagens, F. Lelarge, J. G. Provost, A. Accard, F. Grillot, A. Martinez, Q. Zou, and A. Ramdane

***Abstract*—Tolerance to optical feedback is investigated on quantum-dash-based lasers emitting at 1.51 μm. The onset of coherence collapse regime is experimentally determined using three criteria: optical spectrum broadening, relative intensity noise increase, and bit-error-rate degradation. Measurements were first performed in static operation at different current values, using the first and second criteria. The onset of coherence collapse was found to increase from ~ -41 to -27 dB with the bias current. Then tolerance to optical feedback was assessed in dynamic operation at 10 Gb/s, using the third criterion. In spite of a relatively high linewidth enhancement factor ($\alpha_H \sim 4.5$), a -32-dB onset of coherence collapse corresponding to -24-dB maximum optical return loss tolerance was achieved at 10-Gb/s rate.**

***Index Terms*—Coherence collapse, optical feedback, quantum dash (QD), semiconductor laser.**

I. INTRODUCTION

QUANTUM-DOT-BASED semiconductor lasers have been the subject of intense investigations for the last ten years owing to their unique properties that arise from 3-D quantum confinement. Low threshold current densities, high characteristic temperatures, and small linewidth enhancement factors (LEFs) are indeed expected [1]. This latter property should lead to an increased tolerance to optical feedback with the perspective of achieving isolator-free lasers, of particular importance for low-cost lasers in metropolitan and local area networks [2].

The coherence collapse regime [3], in which the laser is subject to instabilities, is incompatible with data transmission because of induced high penalty. One way to investigate the tolerance to optical feedback is to evaluate the onset of this regime, i.e., the feedback level above which the laser enters it. In this letter, the feedback level γ is defined as the ratio P_1/P_0, where P_0 is the emitted power (Fig. 1) and P_1 the power fed back into the laser at the front facet. High tolerance to optical feedback has already been demonstrated for quantum-dot-based lasers emitting at 1.3 μm [2], [4], where -14- and -8-dB coherence collapse onsets were achieved.

Manuscript received February 27, 2007; revised May 3, 2007. This work was supported by the European Union IST/NMP Integrated Project ZODIAC.

S. Azouigui and A. Ramdane are with the Laboratory for Photonics and Nanostructures, Marcoussis 91460, France, and also with INT, CNRS Samovar, Evry 91011, France (e-mail: Sheherazade.Azouigui@lpn.cnrs.fr; Abderrahim.Ramdane@lpn.cnrs.fr).

B. Dagens, F. Lelarge, J. G. Provost, and A. Accard are with the Alcatel-Thalès III-V Laboratory, Palaiseau, 91767, France (e-mail: Beatrice.Dagens@3-5lab.fr; Francois.Lelarge@3-5lab.fr; Jean-Guy.Provost@3-5lab.fr; Alain.Accard@3-5lab.fr).

F. Grillot is with INSA, CNRS FOTON, Rennes 35043, France (e-mail: Frederic.Grillot@insa-rennes.fr).

A. Martinez is with the Laboratory for Photonics and Nanostructures, Marcoussis 91460, France (e-mail: Anthony.Martinez@lpn.cnrs.fr).

Q. Zou is with INT, CNRS Samovar, Evry 91011, France (e-mail: Qin.Zou@int-evry.fr).

Digital Object Identifier 10.1109/LPT.2007.901492

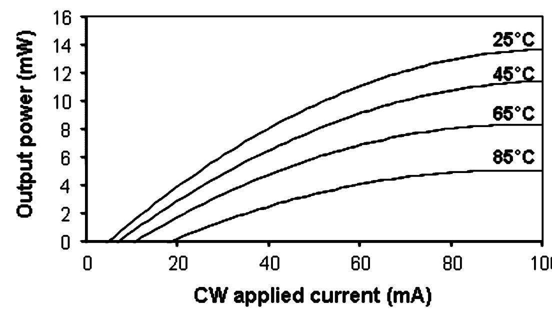

Fig. 1. Light–current characteristics at different temperature values.

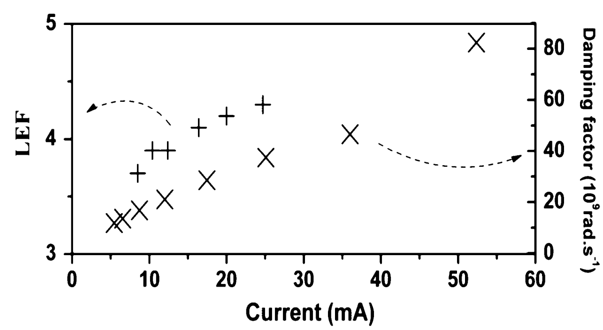

Fig. 2. LEF and damping factor versus current.

In this work, for the first time to our knowledge, we investigate the tolerance to optical feedback of quantum-dash (QD)-based lasers emitting at 1.51 μm in both static and dynamic operation at 10 Gb/s. The onset of the coherence collapse regime γ_{crit} is experimentally determined using optical spectrum broadening, relative-intensity-noise (RIN) increase, and the bit-error-rate (BER) degradation criteria. Although the LEF (Henry factor) α_H of QD-based lasers reported above threshold current is relatively high (Fig. 2), it is found that their onset of coherence collapse is better than that of quantum-well-based distributed feedback (DFB) lasers [5] and that these devices are close to meeting the 10-Gb/s Ethernet standard for optical feedback.

II. DEVICE AND EXPERIMENTAL SETUP

The dashes-in-a-well structure was grown by gas source molecular beam epitaxy on a (001) InP substrate [6]. It consists of six layers of InAs QDs, embedded within an InGaAsP quantum well each, and separated by InGaAsP barriers. A

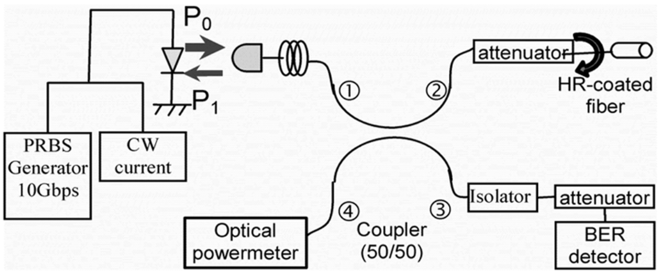

Fig. 3. Experimental setup for feedback tolerance measurements at 10 Gb/s.

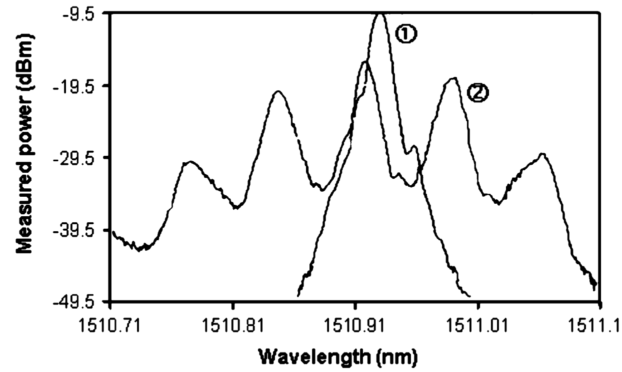

Fig. 4. Optical spectrum: (1) without optical feedback; (2) with optical feedback and beginning of coherence collapse.

separate confinement heterostructure provides the optical confinement. From this structure, a 205-μm-long buried ridge stripe index-coupled DFB laser was fabricated, with a high-reflectivity (HR)-coated rear facet and an as-cleaved front facet.

The LEF was measured by the FM/AM method [7] (Fig. 2). It increases with the bias current from 3.6 to $\sim$4.3 at 25 mA. This is attributed to the plasma effect [9], [10] as well as carrier filling of the nonlasing states (higher lying energy levels such as the wetting layer), which results in a differential gain reduction above threshold [11]. The damping factor was extracted from the small signal modulation bandwidth measurements (Fig. 2). It is found higher than that of conventional quantum-well-based lasers.

The potential of the device for 10-Gb/s operation was previously demonstrated through a 10-Gb/s transmission over an 8-km G652 span [8].

The experimental bench for dynamic operation under optical feedback is illustrated in Fig. 3. The laser is modulated at 10 Gb/s with a $2^{31} - 1$ pseudorandom bit sequence. The emitted light is injected into Branch 1 of an optical coupler using a lensed fiber. The optical feedback is generated with a reference reflector in Branch 2. Its level is controlled with a variable attenuator and its value determined by measuring the power in Branch 4. The effect of the optical feedback is analyzed in Branch 3, with a BER detector. In order to maximize the feedback effect, a polarization controller is used to make the feedback beam polarization identical to that of the emitted wave. For static operation, the experimental bench is the same, except that the BER detector is replaced by an optical spectrum analyzer or an RIN analyzer. All measurements were performed at room temperature (25°C).

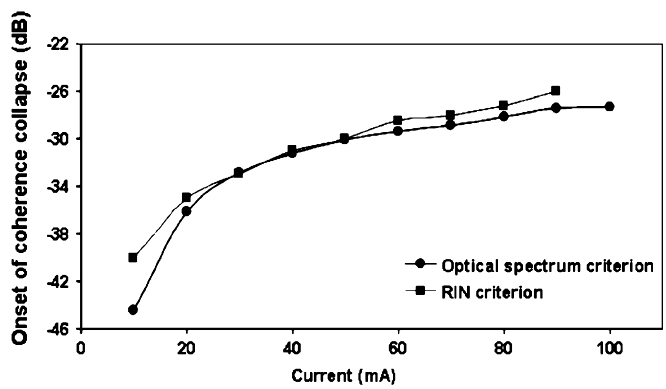

Fig. 5. Onset of coherence collapse (decibels) versus current.

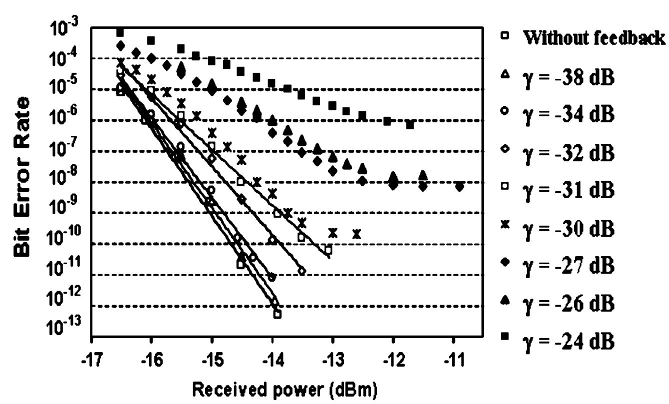

Fig. 6. BER versus received power for different feedback levels at 30 mA.

III. Results

For static operation, the onset of coherence collapse is determined from both the optical and the RIN spectra. In the first case, we consider that coherence collapse is reached when the optical spectrum begins to broaden with relaxation oscillations (incomplete coherence collapse) (Fig. 4), while in the second case, this regime reflects a sudden increase of the RIN.

Fig. 5 illustrates the onset of coherence collapse determined by the optical spectrum broadening and the RIN degradation criteria at different injection currents. Both methods result in almost the same values. In fact, operating the laser with a continuous current from 10 (2-mW output power) to 100 mA (14-mW) leads to an onset of coherence collapse varying from ~ -41 to -27 dB (Fig. 5). The smaller variation at higher current can be explained by the power saturation of the laser.

For dynamic operation, the back-to-back BER was measured as a function of received power for different feedback levels at the 30-mA operating point of the 10-Gb/s transmission experiment [8]. Increasing the optical feedback degrades the BER and introduces a penalty (Fig. 6). The BER begins to degrade for $\gamma = -32$ dB, and above -30 dB, no floor-free operation is possible. From Fig. 6, a $\gamma_{\rm crit} = -32$ dB onset of coherence collapse can be determined, which is consistent with the value of -32 dB observed in static operation.

IV. Discussion

Reference [5] reports on the tolerance to optical feedback at 5 mW of a 300-μm-long compressively strained multiquantum-well-based DFB laser emitting at 1.55 μm with $\alpha_H \sim 2-3$. In this reference, $\mathrm{RIN}_{\mathrm{peak}}$, which is the RIN value taken at the noise peaks appearing in the noise spectra, begins to degrade at about 0.02%, which corresponds to an onset of coherence collapse, as defined in our work, of $\gamma_{\mathrm{crit}} \sim -37$ dB. At 5 mW (∼23 mA), our device demonstrates an onset of coherence collapse $\gamma_{\mathrm{crit}} \sim -34$ dB (Fig. 5). The QD-based DFB laser tested in this work is, hence, more tolerant than the quantum-well-based DFB laser reported in [5], even though its LEF value is higher ($\sim 4-5$ compared to $\sim 2-3$) and its cavity shorter (205 μm compared to 300 μm). This may be explained by the fact that the QD-based laser presents a higher damping factor (82.10^9 rad $\cdot$ s^{-1} at 10 mW compared to a typical value of 20.10^9 rad $\cdot$ s^{-1} for quantum-well-based lasers) [12].

InGaAs–GaAs quantum-dot lasers emitting at 1.3 μm have demonstrated an onset of CC as high as -14 [2] and -8 dB [4] for a 300-μm-long HR-HR coated DFB laser and a 1500-μm-long as-cleaved Fabry–Pérot laser, respectively. The difference with the values obtained in this work may be attributed, for the former, to the HR coating on the front facet, and for the latter, to the difference in cavity lengths (1500 μm compared to 205 μm).

For data transmission, it is more relevant to determine the maximum return loss tolerance Γ from the system as defined in 10-Gb/s Ethernet standard

$$\Gamma_{\mathrm{crit}} = \gamma_{\mathrm{crit}} - (2 \cdot C) \quad (1)$$

where C represents the coupling losses of the laser estimated at ~ -4 dB.

By using (1) and $\gamma_{\mathrm{crit}} \sim -32$ dB at the 10-Gb/s operating point, a $\Gamma_{\mathrm{crit}} = -24$ dB maximum return loss tolerance can be deduced from these measurements. This is a rather interesting result since the laser should tolerate a return loss of -21 dB for isolator-free operation to comply with the 802.3ae 10-Gb/s Ethernet standard. .

V. Conclusion

For the first time, direct modulation at 10 Gb/s of a QD-based laser emitting at 1.51 μm was demonstrated up to the coherence collapse at -24-dB feedback from the network, with a penalty at 10^{-10} lower than 1 dB. It has been shown that this laser is more tolerant than quantum-well-based DFB lasers reported in [5], owing to a higher damping factor. Further work is under way for the optimization of the LEF which should lead to an optical feedback tolerance compliant with 10-Gb/s Ethernet standard for isolator-free operation.

References

[1] D. Bimberg, N. Kirstaedter, N. N. Ledentsov, Z. I. Alferov, P. S. Kop'ev, and V. M. Ustinov, "InGaAs-GaAs quantum-dot lasers," *IEEE J. Sel. Top. Quantum Electron*, vol. 3, no. 2, pp. 196–205, Apr. 1997.

[2] H. Su, L. Zhang, A. L. Gray, R. Wang, T. C. Newell, K. Malloy, and L. F. Lester, "High external feedback resistance of laterally loss-coupled distributed feedback quantum dot semiconductor lasers," *IEEE Photon. Technol. Lett.*, vol. 15, no. 11, pp. 1504–1506, Nov. 2003.

[3] D. Lenstra, B. H. Verbeek, and A. J. D. Boef, "Coherence collapse in single-mode semiconductor lasers due to optical feedback," *IEEE J. Quantum Electron.*, vol. QE-21, no. 6, pp. 674–679, Jun. 1985.

[4] D. O'Brien, S. P. Hegarty, G. Huyet, J. G. McInerney, T. Kettler, M. Laemmlin, D. Bimberg, V. M. Ustinov, A. E. Zhukov, S. S. Mikhrin, and A. R. Kovsh, "Feedback sensitivity of 1.3 μm InAs-GaAs quantum dot lasers," *Electron. Lett.*, vol. 39, pp. 1819–1820, Dec. 2003.

[5] T. Kurosaki, T. Hirono, and M. Fukuda, "Suppression of external cavity modes in DFB lasers with a high endurance against optical feedback," *IEEE Photon. Technol. Lett.*, vol. 6, no. 8, pp. 900–902, Aug. 1994.

[6] F. Lelarge, B. Rousseau, B. Dagens, F. Poingt, F. Pommereau, and A. Accard, "Room temperature continuous-wave operation of buried ridge stripe lasers using InAs–InP (100) quantum dots as active core," *IEEE Photon. Technol. Lett.*, vol. 17, no. 7, pp. 1369–1371, Jul. 2005.

[7] C. Harder, K. Vahala, and A. Yariv, "Measurement of the linewidth enhancement factor α of semiconductor lasers," *Appl. Phys. Lett.*, vol. 42, pp. 328–330, Feb. 1983.

[8] B. Dagens, D. Make, O. L. Gouezigou, J. G. Provost, F. Lelarge, A. Accard, F. Poingt, J. Landreau, O. Drisse, E. Derouin, F. Pommereau, and G. H. Duan, "First demonstration of 10 Gb/s direct modulation with a buried ridge distributed feedback laser based on quantum dash InAs/InP material at 1.55 μm," presented at the Tech. Dig. ECOC 2006, Cannes, France, Sep. 2006, Paper Mo3.4.2.

[9] J. H. Wei and K. S. Chan, "A theoretical analysis of quantum dash structures," *J. Appl. Phys.*, vol. 97, no. 123524, 2005, .

[10] S. Melnik, G. Huyet, and A. V. Uskov, "The linewidth enhancement factor α of quantum dot semiconductor lasers," *Opt. Express*, vol. 14, pp. 2950–2955, Apr. 2006.

[11] H. Dery and G. Eisenstein, "The impact of energy band diagram and inhomogeneous broadening on the optical differential gain in nanostructure lasers," *IEEE J. Quantum Electron.*, vol. 41, no. 1, pp. 26–35, Jan. 2005.

[12] J. Helms and K. Petermann, "A simple analytic expression for the stable operation range of laser diodes with optical feedback," *IEEE J. Quantum Electron.*, vol. 26, no. 5, pp. 833–836, May 1990.