Coherence-Collapse Threshold of 1.3-μm Semiconductor DFB Lasers

F. Grillot, *Student Member, IEEE*, B. Thedrez, O. Gauthier-Lafaye, M. F. Martineau, V. Voiriot, J. L. Lafragette, J. L. Gentner, and L. Silvestre

***Abstract*—The onset of the coherence-collapse threshold is theoretically and experimentally studied for monomode 1.3-μm antireflection/high reflection distributed-feedback lasers taking into account facet phase effects. The variation of the coherence collapse from chip to chip due to the facet phase is in the range of 7 dB and remains almost independent of the grating coefficient. Lasers that operate without coherence collapse under −15-dB optical feedback, while exhibiting an efficiency as high as 0.30 W/A, are demonstrated. Such lasers are adequate for 2.5Gb/s transmission without isolator under the International Telecommunication Union recommended return loss.**

***Index Terms*—Coherence collapse, distributed-feedback lasers, external optical feedback, facet phase effects, transmission.**

I. Introduction

THE EXTENSION of today's optical networks to the home requires the development of extremely low-cost laser sources [1]. While wafer fabrication techniques allow massive production, packaging remains a cost bottleneck, as it is not supported by parallel processing. Cost reduction must therefore be based on packaging simplification, such as flip-chip bonding and direct coupling of the laser to the fiber [2]. However, in order to realize an optical module without optical isolator, the conception of lasers having a higher resistivity against external optical feedback continues to remain a challenge. It is well known that the performances of a semiconductor laser operating under external optical feedback are strongly altered. Five distinct regimes based on spectral observation were reported for 1.55-μm semiconductor distributed-feedback (DFB) lasers [3]. Moreover, a full theoretical analysis showing the effects of external optical feedback on the threshold gain and spectral linewidth of DFB lasers has also been published [4]. More particularly, it has been shown that for a certain level of feedback, the laser tends to become unstable and operates within the coherence-collapse regime [5]. This particular state depends neither on the external cavity length nor the feedback phase. A drastic reduction in the coherence length may be observed within the coherence-collapse regime. It is important to stress that this chaotic behavior also alters the dynamic performances in transmission. It has been already shown, both theoretically [6] and experimentally [7], that the penalty degradation in the bit error rate (BER) plots is strongly linked to the threshold of the coherence-collapse regime. On another hand, an analytical expression of the coherence-collapse threshold based on a weak coherent-feedback hypothesis was introduced for Fabry–Pérot lasers [8]. By extending this analytical relation to the case of DFB lasers, the sensitivity to optical feedback of 1.3-μm antireflection/high reflection (AR/HR) DFB lasers is carefully studied in this letter. The dependence of the coherence-collapse threshold with facet phase effects which are due to the HR coating is clearly demonstrated and quantified both theoretically and experimentally. Finally, the coherence-collapse threshold and its consequences on the penalty degradation mechanism is discussed and analyzed.

Manuscript received May 17, 2002; revised August 29, 2002.

F. Grillot, B. Thedrez, O. Gauthier-Lafaye, M. F. Martineau, V. Voiriot, J. L. Lafragette, and J. L. Gentner are with ALCATEL-OPTO+, Alcatel Research and Innovation, F-91460 Marcoussis, France (e-mail: Frederic.Grillot@ms.alcatel.fr).

L. Silvestre is with Alcatel Optronics, F-91625 Nozay, France.

Digital Object Identifier 10.1109/LPT.2002.805771

II. Theory and Numerical Results

When an AR coating is used on both facets, DFB lasers which have a uniform grating emit on two longitudinal modes which are symmetrically located with respect to the Bragg wavelength. These two longitudinal modes have the same losses and allow to define the stopband of the laser. In order to obtain a monomode laser, an HR coating (an AR coating, respectively) is applied on the rear facet (on the front facet, respectively) to break down the longitudinal symmetry. Due to the HR coating, interference effects between the grating and the facets make the lasing properties highly dependent on cleavage plane variations as small as a part of a wavelength. In consequence, DFB lasers may lase either at the Bragg wavelength or at another wavelength located within the laser stopband. To take into account such a random phenomena, the normalized Bragg deviation is introduced as

$$\delta L = (\beta - \beta_{\mathrm{Bragg}})\, L \tag{1}$$

where β, β_{Bragg}, and L are, respectively, the emission angular wavevector of the laser, the Bragg angular wavevector (linked to the grating period), and the length of the laser. Let us consider an external optical feedback Γ produced on the AR-coated side by a reflector of amplitude reflectivity, R on an AR/HR DFB laser. The amount of light Γ injected into the laser cavity is defined by the relation $\Gamma = RL - 2C$ where RL and C are, respectively, the return-loss level and the optical coupling loss of the device to the fiber in decibels. The amplitude reflectivity of the laser is denoted ρ_r for the HR facet (ρ_l for the AR coating facet, respectively). By using Maxwell equations and the boundary conditions, a determinental equation for longitudinal modes [9] can be written in the simplified form

$$\frac{\gamma L}{th(\gamma L)} - \sqrt{(\gamma L)^2 - (\kappa L)^2} = -i\kappa L\tilde{\rho}_r. \tag{2}$$

In (2), the normalized coupling coefficient is denoted κL and the propagation constant γ satisfies the dispersion relation $\gamma^2 = \kappa^2 + q^2$where $q = \alpha - i\delta$ and α represents the threshold laser losses. The amplitude reflectivity on the right facet and on the left facet are respectively given by the relations $\tilde{\rho}_r = \rho_r e^{-i\varphi_r}$ and $\tilde{\rho}_l = \rho_l e^{-i\varphi_l}$ where the $(\varphi_r,\, \varphi_l)$ couple represents the facet phase terms depending on the position of the facets in the corrugation. By assuming a sufficiently low reflectivity on the AR facet, the optical field is not affected by φ_l and the laser only depends on the HR facet phase. For a weak optical feedback ($|R| \ll 1$), the equivalent facet (left facet) submitted to optical feedback can be written as

$$\rho_{l,\,eq} = \rho_l + \left(1 - |\rho_l|^2\right) Re^{-i\omega\tau}. \qquad (3)$$

In (3), ω is the emission angular frequency and τ the external round-trip time. Following the Lang and Kobayaschi [10] model, a complex coefficient corresponding to the left facet can be calculated following the relation [4]

$$C_l = \frac{\left[(qL)^2 + (\kappa L)^2\right]\left[2\tilde{\rho}_r(qL)/\kappa L - i\left(1 + \tilde{\rho}_r^2\right)\right]}{qL\left[\kappa L\left(1 + \tilde{\rho}_r^2\right) - i\tilde{\rho}_r\right] + 2i\tilde{\rho}_r\,(qL)^2 - \kappa L}. \qquad (4)$$

This coefficient describes the coupling of the laser to the external cavity. It allows to quantify the feedback induced perturbations of the modes given by (2) which affects such parameters as the threshold gain or the laser linewidth [4]. Yet, it is only linked to the intrinsic lasers characteristics [11]. This complex coefficient also serves to calculate the coherence-collapse threshold $\Gamma = \Gamma_C$ whose analytical expression described in [8] may be extended to the case of a DFB laser following the relation

$$\Gamma_c(\mathrm{dB}) = 10\,\log\left(\frac{\omega_r^4 \tau_i^2}{16\,|C_l|^2\left(1 + \alpha_H^2\right)\omega_d^2}\right) \qquad (5)$$

where ω_r is the relaxation frequency, ω_d is the laser damping frequency, α_H the linewidth enhancement factor, τ_i the internal roundtrip time, and C_l the complex coefficient. Equation (5) holds under the assumption of $\Gamma_C < -30$ dB (weak optical feedback), $\alpha_H > 1$, and $\omega_p\tau \gg 1$ with $p = r, d$. From (5), it appears that the coherence-collapse threshold at a given output power P depends on facet phase effects via the complex coefficient C_l and the resonance frequency ω_r whose expression is given by the relation $\omega_r = A\sqrt{P/\eta(\varphi_r)}$ [12] where A and $\eta(\varphi_r)$ are, respectively, a constant coefficient and the external efficiency (which depends on the facet phases). In order to compare to the system measurements, an external cavity of 13-m length corresponding to an external roundtrip time of 130 ns is chosen for the calculations. The lasers parameters are, respectively, $\tau_i = 7.5$ ps, $\alpha_H = 2.5$, $L = 350$ μm, $\omega_d = 15$ GHz, and $A = 2$ GHz/(mA)$^{1/2}$. The amplitude reflectivity of the laser is, respectively, equal to $\rho_r = 0.95$ for the HR facet and $\rho_l = 0.00$ is assumed for the AR coating facet. After calculating the modulus of the complex coefficient $|C_l|$ by varying φ_r with $0 \le \varphi_r \le 2\pi$ to cover each phase case, the coherence-collapse threshold may be predicted for a given output power P. In the simulations, the facet phase dependence of the external efficiency $\eta(\varphi_r)$ has been taken into account by recalculating the output external efficiency for each facet phase case. In Fig. 1, a simulation showing the coherence-collapse threshold versus the normalized Bragg deviation is depicted for four normalized coupling coefficients values: a) $\kappa L = 0.30$, b) $\kappa L = 0.50$, c) $\kappa L = 0.75$, and d) $\kappa L = 1.20$. In all cases, a quasiparabolic distribution having a local maximum located at the Bragg wavelength ($\delta L = 0$) is obtained. Thus, the best case for the laser in terms of resistivity against optical feedback is predicted for a laser emitting in the middle of the stopband. The highest calculated coherence-collapse threshold values are very closed to, respectively, $\Gamma_C = -41$ dB for $\kappa L = 0.30$, $\Gamma_C = -34$ dB for $\kappa L = 0.50$, $\Gamma_C = -28$ dB for $\kappa L = 0.75$, and $\Gamma_C = -16$ dB for $\kappa L = 1.20$. On another hand, the worst case for the laser is predicted for $\varphi_r = 2\pi$ and $\varphi_r = 0$. In that case, the laser has two degenerate modes on both sides of the stopband. For a normalized Bragg deviation in the range from $\delta L = -3$ to $\delta L = +3$, the overall variation of the calculated coherence-collapse threshold may reach up to 7 dB on average. Hence, a strong dependence of the coherence-collapse threshold with facet phase effects is theoretically predicted.

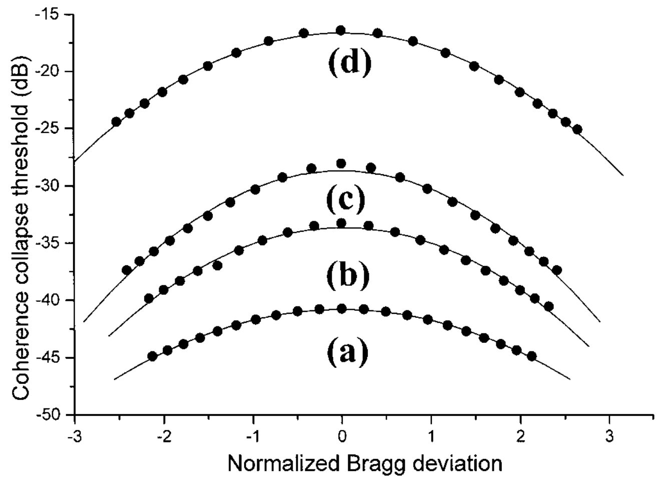

Fig. 1. Calculated coherence-collapse threshold variation versus the normalized Bragg deviation for an AR/HR 350-μm-long DFB laser ($T = 25$ °C, $P = 10$ mW). The line between calculated dots is to help the eye. (a) $\kappa L = 0.30$. (b) $\kappa L = 0.50$. (c) $\kappa L = 0.75$. (d) $\kappa L = 1.20$.

III. Experimental Results

The device under study is made of nine compressively strained InAsP quantum wells separated by InGaAsP tensile strained barriers. The optical confinement is provided by two Q1.1-μm 70-nm-wide separate confinement layers. The 2-in grating was defined using holographic techniques and etched in a passive layer located above the upper separate-confinement-heterostructure (SCH). After planarization regrowth, the active region was etched. The structure was then buried using metal–organic vapor phase epitaxy (MOVPE), as for standard buried ridge structures (BRS) [13]. The threshold current value is about 6.5 mA with an average efficiency of 0.34 W/A at 25 °C. The linewidth enhancement factor was measured according to the method described in [14] and was found to be equal to 2.5. Concerning the value of A it was measured

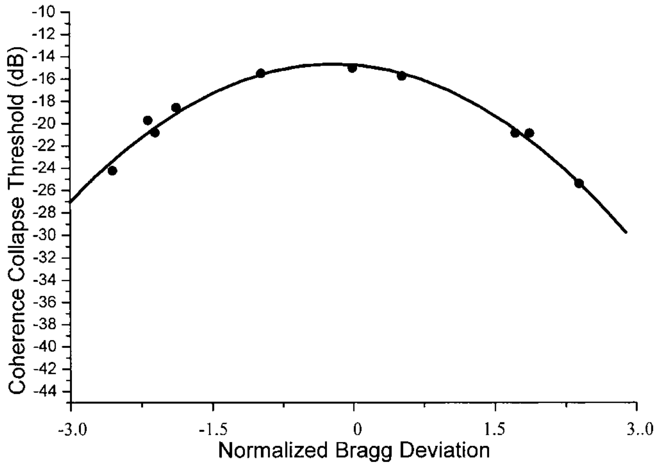

Fig. 2. Measured coherence-collapse threshold variation versus the normalized Bragg deviation for AR/HR 350-μm-long DFB lasers ($T = 25$ °C, $P = 10$ mW).

to be equal to (2.0 $\pm$ 0.1) GHz/(mA)$^{1/2}$. In Fig. 2, the coherence-collapse variation versus the normalized Bragg deviation is measured for 350-μm AR/HR DFB lasers at 10 mW and 25 °C. The measured plot is obtained by using a set of ten lasers having different facet phase cases. The determination of each coherence-collapse threshold is based on spectral observations and is set to be the point defined to $\pm$1 dB when a drastic broadening of the laser linewidth occurs. The laser coupling coefficient value is about $\kappa = 34$ cm^{-1} ($\kappa L = 1.2$). A very good agreement with calculated results is obtained since a quasiparabolic distribution is experimentally found. A slight asymmetry can be observed which, however, remains within experimental variations. The maximum of the coherence-collapse threshold is located at the Bragg wavelength while the sensitivity to optical feedback increases with the normalized Bragg deviation. The higher sensitivity of detuned DFB lasers can be traced back to a higher external efficiency and higher complex coefficient C_l. In the case of $\kappa L = 1.2$, the measured coherence-collapse threshold is $\Gamma_C = -15$ dB ($\delta L = 0$) to be compared to the predicted value of -16 dB. It decreases to $\Gamma_C = -21$ dB for $\delta L = -2$ and $\Gamma_C = -23$ dB for $\delta L = +2$ while the calculated value is -22 dB. It has been shown [7] that 1.3-μm 2.5-Gb/s transmission could be performed under feedback up to the coherence collapse, with a penalty degradation that remains below 1 dB when using a total fiber dispersion of 300 ps/nm. In order to allow for floor-free low penalty transmission under the -24 dB recommended return loss of the G.957 International Telecommunication Union (ITU) specification, a coherence-collapse threshold of -24 dB should therefore be reached on all lasers in the case of no coupling loss. Our experimental results show that, with the chosen value of the coupling coefficient, the whole DFB laser population fulfills this condition despite facet phase induced device-to-device variations. We also show that such a result is reached without degrading the external efficiency, since an average value of 0.34 W/A is obtained with a minimum efficiency of 0.30 W/A at minimum feedback sensitivity.

IV. Conclusion

We have presented the characteristics of 1.3-μm AR/HR DFB lasers in presence of external optical feedback. A full analysis of the coherence-collapse threshold has been realized both theoretically and experimentally. We have demonstrated that due to the HR coating, the coherence-collapse threshold is strongly linked to the facet phase effects. Such a dependence induces a variation of the coherence-collapse threshold which is closed to a 7-dB range. By properly choosing the normalized coupling coefficient, a coherence collapse as high as -15-dB optical feedback could be demonstrated, while maintaining a high average efficiency of 0.34 W/A over the whole DFB population. Finally, the lasers after standard monomode screening are usable independently of their facet phase for 300-ps/nm 2.5-Gb/s isolator-free transmission under the recommended -24-dB G.957 ITU return loss specification [15].

References

[1] Y. Tohmori, Y. Itaya, and H. Toba, "1.3 μm spot-size converter integrated laser diodes (SS-LD's) for access network applications," in *Proc. LEOS'97*, 1997, pp. 270–271.

[2] B. Fernier, K. Adams, C. Artigue, T. Barrou, A. Göth, E. Grard, W. Jörg, D. Keller, J. L. Lafragette, A. Lestra, P. Pagnod, S. Rabaron, J. M. Rainsant, J. Scherb, D. Toullier, D. Tregoat, and W. Rehm, "1.3 μm low cost plastic module for 622Mbit/s transmission at 85°C," in *Proc. ECOC'98*, vol. 1, 1998, pp. 445–446.

[3] R. W. Tkach and A. R. Chraplyvy, "Regimes of feedback effects in 1.5 μm distributed feedback lasers," *J. Lightwave Technol.*, vol. LT-4, pp. 1655–1661, Nov. 1986.

[4] F. Favre, "Theoretical analysis of external optical feedback on DFB semiconductor laser," *IEEE J. Quantum Electron.*, vol. QE-23, pp. 81–88, Jan. 1987.

[5] D. Lenstra, B. H. Verbeek, and A. J. Den Boef, "Coherence collapse in single-mode semiconductor lasers due to optical feedback," *IEEE J. Quantum Electron.*, vol. QE-21, pp. 674–679, June 1985.

[6] R. B. Clarke, "The effect of reflections on the system performances of intensity modulated laser diodes," *J. Lightwave Technol.*, vol. 9, pp. 741–749, June 1991.

[7] F. Grillot, B. Thedrez, J. Py, O. Gauthier-Lafaye, V. Voiriot, and J. L. Lafragette, "2.5 Gbit/s transmission characteristics of 1.3μm DFB lasers with external optical feedback," *IEEE Photon. Technol. Lett.*, vol. 14, pp. 101–103, Jan. 2002.

[8] 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, pp. 833–836, May 1990.

[9] W. Streifer, R. D. Burnham, and D. R. Scifres, "Effect of external reflectors on longitudinal modes of distributed feedback lasers," *IEEE J. Quantum Electron.*, vol. QE-11, pp. 154–161, Apr. 1975.

[10] R. Lang and K. Kobayashi, "External optical feedback effects on semiconductor injection laser properties," *IEEE J. Quantum Electron.*, vol. QE-16, pp. 347–355, Mar. 1980.

[11] O. Nilsson and J. Buus, "Linewidth and feedback sensitivity of semiconductor diode lasers," *IEEE J. Quantum Electron.*, vol. QE-26, pp. 2039–2042, Dec. 1990.

[12] R. S. Tucker and I. P. Kaminow, "High frequency characteristics of directly modulated InGaAsP ridge waveguide and buried heterostructure lasers," *J. Lightwave Technol.*, vol. LT-2, pp. 385–393, Aug. 1984.

[13] Ph. Pagnod-Rossiaux, F. Gaborit, N. Tscherptner, L. Roux, C. Stark, and B. Fernier, "High temperature (Ga)InAsP/high band gap GaInAsP barriers 1.3 μm SL-MQW lasers grown by gas source MBE," *J. Cryst. Growth*, vol. 175/176, pp. 948–954, May 1996.

[14] R. Schimpe, J. E. Bowers, and T. L. Koch, "Characterization of frequency response of 1.5μm InGaAsP DFB laser diode and InGaAs PIN photodiode by heterodyne measurement technique," *Electron. Lett.*, vol. 22, no. 9, pp. 453–454, 1986.

[15] F. Grillot, B. Thedrez, O. Gauthier-Lafaye, J. Py, M. F. Martineau, J. L. Lafragette, J. L. Gentner, and L. Silvestre, "2.5Gbit/s 85°C floor-free operation of 1.3μm DFB lasers under external optical feedback for different reflection distances," in *Proc. ECOC'02*, vol. 3, 2002, p. 2.18.