Facet phase effects on the onset of the coherence collapse threshold of 1.55 μm AR/HR distributed feedback semiconductor lasers

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ABSTRACT

The sensitivity to optical feedback of 1.55 μm AR/HR distributed feedback semiconductor lasers (DFB) is presented in this paper. The onset of the coherence collapse which is the most critical feedback regime for optical transmissions is theoretically investigated and with a stress on its dependence with facet phase effects (FPE). Taking into account FPE on both facets, the sensitivity to optical feedback is evaluated with respect to both the coupling strength coefficient and the feedback level. The first part of the paper shows that due to the HR-facet, a distribution up to several dB on the coherence collapse thresholds is predicted over the whole DFB laser population. The second part concentrates on the coherence collapse dependence with respect to the antireflection (AR) coating. Calculations show an enhancement of the coherent collapse threshold distribution up to 5 dB due to AR coating impairment. Those simulations are of first importance for optical transmissions since they show that for AR coatings beyond 10^{-4}, the sensitivity to optical feedback of AR/HR DFB lasers is extremely difficult to evaluate from a laser to another. On the other hand, for AR coatings below 10^{-4}, all feedback performances are directly connected to the laser wavelength and lasers can be selected for high bit rate isolator-free transmission.

Keywords: Distributed Feedback Lasers (DFB), external optical feedback, coherence collapse, facet phase effects (FPE).

1. 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 allows 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 design of feedback resistant lasers continues to remain a challenge. It is well known that the performances of a semiconductor laser are strongly altered by any type of external optical feedback. Five distinct regimes based on spectral observation were reported for 1.55 μm semiconductor distributed feedback lasers (DFB) [3]. The laser sensitivity can be such that even under a feedback level in the percent range, the laser becomes unstable and starts operating within the so-called coherence collapse regime [4]. The main consequence of such a regime on the semiconductor laser is a drastic enhancement of the laser linewidth up to several GHz which is very detrimental to most applications. In the important case of optical transmission, the coherence collapse leads to a strong degradation in the Bit Error Rate (BER) when the laser is used as a transmitter, as theoretically [5] and experimentally [6] demonstrated. More generally, the prediction of the coherence collapse threshold is an important feature for all applications requiring either a low noise level or a proper control of the laser coherence. Based on a weak coherent feedback hypothesis, the determination of the critical feedback threshold was analytically derived for Fabry-Perot lasers in [7]. An analytical method was also proposed to determinate the feedback sensitivity of DFB lasers [8]. Both approaches concluded on the importance of calculating the coupling strength coefficients [9]. Following [8], the coherence collapse threshold of DFB lasers having an antireflection (AR) coating on the emitted facet and a high reflection (HR) coating on the rear facet has been calculated and compared to experimental results [10]. It was both theoretically and experimentally shown in [10] that, due to the HR-facet, the feedback sensitivity as well as the coherence collapse threshold exhibit a quasi-parabolic distribution due to the facet phase dependence. The large dispersion among the critical levels observed for a given set of

DFB lasers leads to a wide range of behavior under external optical feedback which is detrimental to applications. The goal of this paper is to investigate the coherence collapse dependence with respect to the antireflection coating. We show that small variations on the order of 10^{-4} of the AR coating can critically affect the laser dependence with respect to optical feedback.
The paper is organized as follows: the theory of distributed feedback lasers operating under external optical feedback is at first presented. Numerical calculations are then conducted and the feedback sensitivity of DFB lasers is evaluated. Instead of assuming a facet phase distribution on the HR facet only, the facet phases on the AR facets due to a residual reflectivity are also taken into account. Simulations reporting variations of both the coupling strength coefficient and of the onset of the coherence collapse are presented and discussed. Those results are of first importance for optical transmissions since they show that by taking into account FPE on both facets, the sensitivity to optical feedback is drastically enhanced.

2. THEORY OF DFB LASERS

When an antireflection 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 define the stopband of the laser. In order to obtain a single mode laser, a high reflection coating HR can be applied on the rear facet to break down the longitudinal symmetry (see figure 1). To optimize the laser external efficiency, we assume a high 95% HR coating, while the front facet AR coating is kept as small as possible.

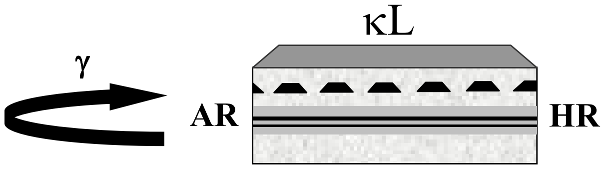

Figure 1: distributed feedback laser (DFB) submitted to an external reflection. The rear and front facets are respectively HR and AR coated. The normalized grating coupling coefficient is denoted κL.

Due to the high reflection 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. To take into account such a random phenomena, the normalized Bragg deviation is introduced as:

$$\delta L = \left(\beta - \beta_{Bragg}\right) L \tag{1}$$

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.
Since the front facet is AR coated, one may assume that the phase effect on the front facet is of little consequence. One of the paper's main contribution is to show that this is generally not true, and that extremely small AR coatings, below 10^{-4} are required in order to counteract the AR FPE deleterious phenomena. Let us consider an external optical feedback γ on the AR coated side induced by a reflector of amplitude reflectivity R on a AR/HR DFB laser (Fig.1*)*. The amplitude reflectivity of the laser is denoted ρ_2 for the high reflection facet (ρ_1 for the antireflection coating facet respectively). By using Maxwell equations and the boundary conditions, a determinental equation for longitudinal modes [11] can be written in the simplified form:

$$\frac{\gamma L}{th(\gamma L)^2} - \sqrt{(\gamma L)^2 - (\kappa L)^2} = -i\kappa L\tilde{\rho}_2 \tag{2}$$

In equation (2), the normalized grating coupling coefficient is denoted κL and the propagation constant σ satisfies the dispersion relation:

$$\sigma^2 = \kappa^2 + q^2 \quad (3)$$

where q = α - iδ and α represents the threshold laser losses. The amplitude reflectivity on the AR-facet and on the HR-facet are respectively given by the relations:

$$\tilde{\rho}_1 = \rho_1 \, e^{-i\varphi_1} \quad (4)$$

$$\tilde{\rho}_2 = \rho_2 \, e^{-i\varphi_2} \quad (5)$$

where (φ_1, φ_2) represents the facet phase terms depicting the facets and corrugation relative positions.

For a weak optical feedback ($|R|$<<1), the facet submitted to the optical feedback as shown in figure 1 can be replaced by an equivalent facet of reflection coefficient:

$$\rho_{1eq} = \rho_1 + \left(1 - |\rho_1|^2\right) R \, e^{-i\omega\tau} \quad (6)$$

In equation (6), ω is the emission angular frequency and τ the external roundtrip time. Following the Lang and Kobayaschi [12] model, a complex coefficient corresponding to the left facet can be calculated following the relation [8]:

$$C_1 = \frac{\left((qL)^2 + (\kappa L)^2\right)\left(2\tilde{\rho}_2 (qL)/\kappa L - i\left(1 + \tilde{\rho}_2^2\right)\right)}{qL\left(\kappa L\left(1 + \tilde{\rho}_2^2\right) - i\tilde{\rho}_2\right) + 2i\tilde{\rho}_2 (qL)^2 - \kappa L} \quad (7)$$

This coefficient denotes the coupling strength from the laser cavity to the external cavity. Let us stress that the coupling strength coefficient is only linked to the intrinsic lasers characteristics such as the optical losses, the normalized Bragg deviation, the coupling coefficient and complex reflectivity of the HR facet. Equation (7) holds only if a reflectivity on the AR facet equal to zero is assumed. As a consequence the optical field is not affected by φ_1 and the laser only depends on the HR facet phase φ_2. In order to take into account φ_1, equation (7) must be extended to a more general expression which takes into account FPE occurring on both facet reflectivities. As a result, the coupling strength coefficient of the facet submitted to external optical feedback can be expressed following the relation:

$$C_1 = \frac{2(1 - |\rho_1|^2) e^{-i\varphi_1}\left(q^2 + \kappa^2\right) L^2}{i\kappa L(1 + \tilde{\rho}_1^2) - 2\tilde{\rho}_1 qL} \left[\frac{1}{2qL - \sum\limits_{k=1,2} \frac{(1 - \tilde{\rho}_k^2)\kappa L}{2iqL\tilde{\rho}_k + \kappa L(1 + \tilde{\rho}_k^2)}} \right] \quad (8)$$

This equation allows us to evaluate the coupling strength coefficient by taking into account FPE occurring not only on the rear but also those induced on the front facet. Whatever the situation, equations (7) and (8) serve to quantify the sensitivity to optical feedback of a DFB laser operating within the different regimes such as the threshold gain and linewidth variations [13]. Thanks to the coupling strength coefficient, the onset of the coherence collapse regime (also called critical feedback level) occurring at a certain feedback level $\Gamma = \Gamma_C$ can be determined by using the well-known analytical relation [7]:

$$\Gamma_C = 10 \log\left(\frac{\omega_r^4 \, \tau_i^2}{16 |C_1|^2 \left(1 + \alpha_H^2\right) \omega_d^2} \right) \quad (9)$$

In equation (9), ω_r is the relaxation pulsation whereas ω_d the damping pulsation, α_H the linewidth enhancement factor, τ_i the internal roundtrip time. It is important to stress that such a relation holds under the assumption of Γ_C < -30 dB (weak optical feedback), $\alpha_H > 1$ and $\omega_p \tau >> 1$ with p = r,d standing either for relaxation or damping. The coherence collapse threshold 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. A lot of papers describe the coherence collapse regime as coexisting chaotic attractors [14] whereas others explain it as an importance source of noise [15] [16]. In the first case, the system is multistable and can choose from different chaotic attractors. In the second case, such a regime is seen as an enhancement of the spontaneous emission occurring when the laser and the reflected fields are not correlated. Hence, the irregular dynamics is a transient constantly fed by noise. As an example, typical spectra corresponding to this regime are shown in figure 2. As it has been previously mentioned, this regime leads to a drastic reduction in the coherence length of the laser, namely, an important increase of the spectral linewidth. In figure 2, the measured laser linewidth at -20 dB is about 45 GHz compared to ≈ 10 MHz for the spectrum recorded without optical feedback.

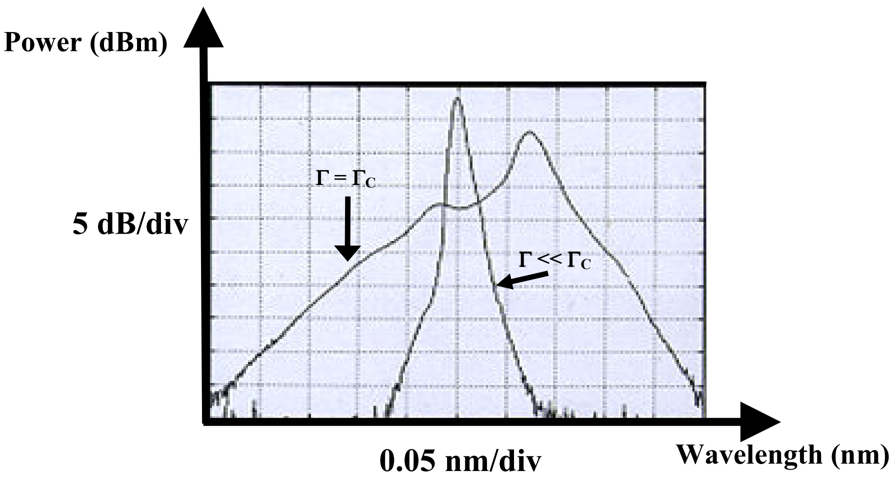

Figure 2: experimental spectra for a single-mode DFB laser recorded within the coherence collapse regime ($\Gamma = \Gamma_C$). The measured laser linewidth is enhanced up to 45 GHz by comparison with 10 MHz for the laser with lower optical feedback ($\Gamma << \Gamma_C$).

From equation (9), it also appears that the coherence collapse threshold depends on FPE via the complex coefficient C_1 and the resonance frequency ω_r. The resonance frequency is linked to the output power and to the external efficiency which also depends on FPE. In order to keep the output power constant in the simulations, the current was varied to counteract the facet phase dependence of the external efficiency. In what follows, the coupling strength coefficients as well as the coherence collapse thresholds are calculated on 1.55 µm AR/HR DFB lasers. FPE are taken into account on both facets by assuming an antireflection coating ranging from 0 and 2.10^{-4} and a 95% rear reflectivity.

3. NUMERICAL RESULTS

Let us consider an AR/HR DFB laser as the one shown in figure 1. The laser parameters used for the calculations are respectively chosen according to typical values encountered on those structures: τ_i = 7.5 ps, α_H = 3.0, L = 300µm, ω_d=12 GHz and A = 2 GHz/(mA)$^{1/2}$. The reflectivity of the laser is respectively equal to $|\rho_2|^2 = 0.95$ for the high reflection facet and $0 \leq |\rho_1|^2 \leq 2\ 10^{-4}$ is assumed for the antireflection coating facet. After calculating the modulus of the complex coefficient $|C_1|$ by varying φ_k with $0 \leq \varphi_k \leq 2\pi$ (k = 1 and k = 2) to cover each phase case, the coherence collapse threshold is predicted for a given output power. As it has been previously indicated, the current was varied to counteract the facet phase dependence of the external efficiency so as to keep the output power constant in the simulations.

3.1 Case of an AR/HR DFB laser with $|\rho_1|^2 \equiv 0$ and $|\rho_2|^2 = 0.95$

In figure 3, simulations showing the variations of both the coupling strength coefficient and of the coherence collapse threshold versus the normalized bragg deviation is depicted for a DFB laser. The normalized grating coupling coefficient κL is equal to 0.3 and reflectivities are respectively $|\rho_1|^2 \equiv 0$ and $|\rho_2|^2 = 0.95$. Under such situation FPE occur only on the rear facet since a zero AR-reflectivity is assumed. Thus, quasi-parabolic distributions exhibiting either a maximum or a minimum located at the bragg wavelength ($\delta L = 0$) is predicted. The best feedback resistant laser is predicted for a laser emitting in the middle of the stopband. This situation corresponds to the highest coherence collapse threshold (or the lowest coupling strength coefficient). On the other hand, the worst situation for the laser is predicted for $\varphi_2 = 2\pi$ and for $\varphi_2 = 0$. In that case, the laser has two degenerate modes on both side of the stopband. For a normalized bragg deviation in the range from $\delta L = -2$ to $\delta L = +2$, the overall variation of the calculated coherence collapse threshold reach up to 4dB. Hence, a strong dependence of the coherence collapse threshold with FPE is theoretically predicted. Let us note that such results have already been confirmed experimentally [10]. As a conclusion due to the high reflection coating, the coherence collapse threshold is strongly linked to FPE. Such a dependence induces a variation of the coherence collapse threshold meaning that by properly choosing the normalized Bragg deviation namely the emitting wavelength, lasers with the highest coherence collapse can be selected.

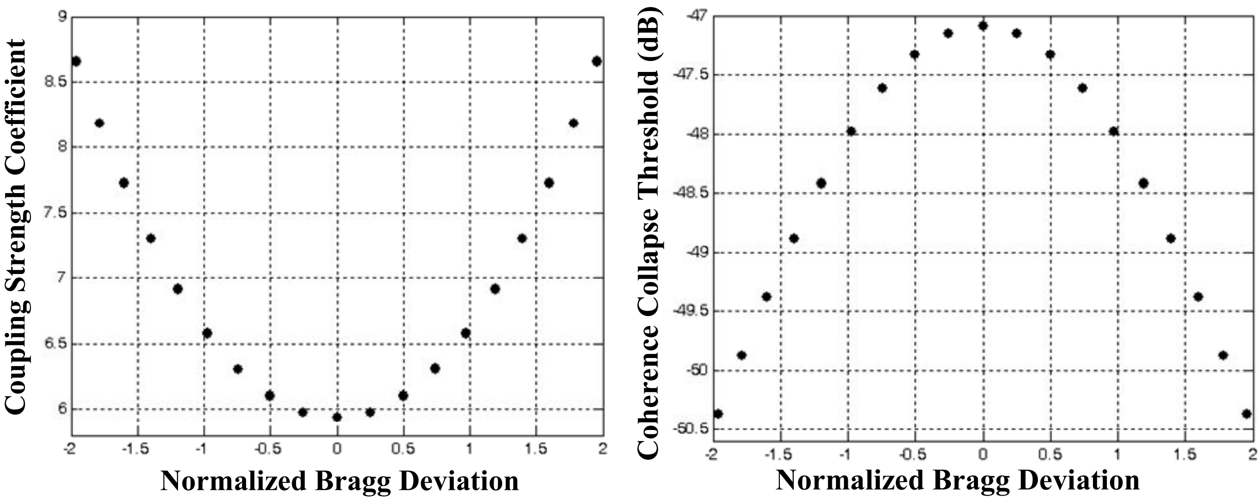

Figure 3: calculated coupling strength coefficients and calculated coherence collapse thresholds for a distributed feedback laser with $|\rho_1|^2 \equiv 0$ and $|\rho_2|^2 = 0.95$. The normalized grating coupling coefficient is $\kappa L = 0.3$.

3.2 Case of an AR/HR DFB laser with $10^{-6} \leq |\rho_1|^2 \leq 2\ 10^{-4}$ and $|\rho_2|^2 = 0.95$

Let us assume a DFB laser with a AR reflectivity not strictly equal to zero: FPE now occur on both facets. Keeping the laser parameters unchanged, variations of the calculated coupling strength coefficient and of the coherence collapse threshold have been recalculated with respect to φ_1. Their dependence as a function of the normalized Bragg deviation are depicted in figure 4 for a DFB laser with $\kappa L = 0.3$ as well as $|\rho_1|^2 = 10^{-6}$ and $|\rho_2|^2 = 0.95$. The parabolic distribution previously demonstrated is still present since the facet phase conditions do not change on the HR-facet. As the reflectivity of the front facet does not exceed 10^{-6}, a small effect on the calculated values is predicted. When increasing the reflectivity of the AR-facet to $|\rho_1|^2 = 10^{-5}$ (figure 5) quasi ellipses arise around the main parabolic distribution. It is however important to stress that even if these effects are linked to this residual reflectivity, they stay negligible than those induced by the HR facet. For instance, for a given Bragg detuning the variation on the critical feedback level is negligible for $|\rho_1|^2 = 10^{-6}$ and does not exceed 1dB for $|\rho_1|^2 = 10^{-5}$. However these numerical results demonstrate that all along the first parabolic distribution, several ellipses whose amplitudes enhance both with the bragg detuning but also with the AR-reflectivity occur.

Figure 6 reports the same calculations as previously but now for $|\rho_2|^2 = 2.10^{-4}$. The same behaviour as in figure 4 and in figure 5 is simulated but now it can be shown that FPE are considerably modified. The amplitude of each ellipse is drastically enhanced and this phenomena increases with the normalized Bragg deviation. For a laser emitting in the middle of the stopband, the highest resistance to optical feedback is obtained with a coherence collapse threshold of -47 dB. However, by varying φ_1 between 0 and 2π induces a supplementary variation close to 3 dB. If the laser is really detuned from the Bragg wavelength, the sensitivity to optical feedback is drastically enhanced. For instance, on the edge of the parabolic distribution, HR-facet cases which are either $\varphi_2 = 0$ or $\varphi_2 = 2\pi$ lead to the lowest coherence collapse threshold -51 dB. Keeping $\varphi_2 = 0$ or $\varphi_2 = 2\pi$ but by varying $0 \leq \varphi_1 \leq 2\pi$ induces this time to a stronger dispersion around -51 dB which can go up to 4dB. Larger variations are expected up to 10 dB if the quality of the antireflection is worst namely if $|\rho_2|^2 > 2.10^{-4}$.

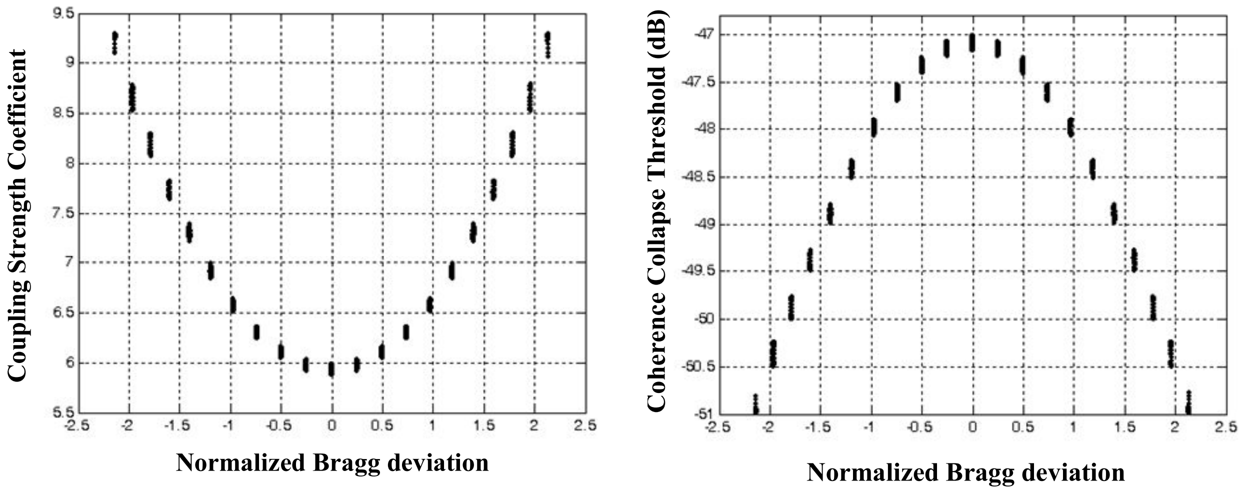

Figure 4: calculated coupling strength coefficient and calculated coherence collapse threshold for a distributed feedback laser with $|\rho_1|^2 = 10^{-6}$ and $|\rho_2|^2 = 0.95$. The normalized grating coupling coefficient is $\kappa L = 0.3$.

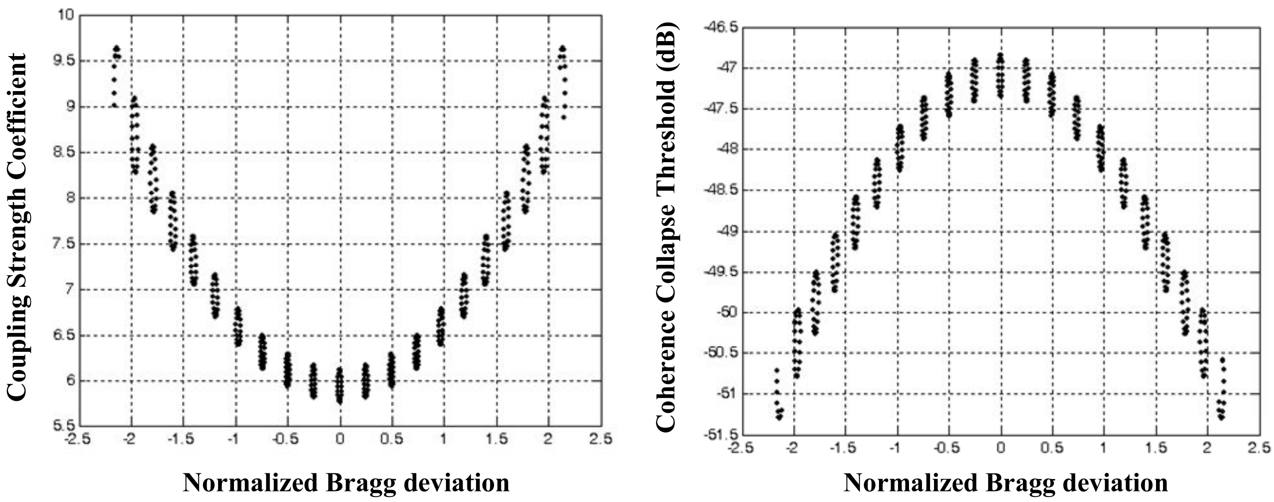

Figure 5: calculated coupling strength coefficient and calculated coherence collapse threshold for a distributed feedback laser with $|\rho_1|^2 = 10^{-5}$ and $|\rho_2|^2 = 0.95$. The normalized grating coupling coefficient is $\kappa L = 0.3$.

In all cases simulations demonstrate that the better the antireflection coating, the smaller the amplitude of the ellipse. This last point is determinant because the degradation of the penalty in optical transmissions occurs within the coherence collapse regime. Thus, the higher the critical feedback level, the better the bit error rate (BER) measurements. As a conclusion, investigation of FPE on the coupling strength coefficient as well as on the coherence collapse threshold is an important feature in the case of AR/HR DFB lasers. Instead of assuming only facet phases on the rear facet, complementary facet phases occurring on the front facet and due to a residual reflectivity have also been taken into account in the calculations. Simulations show that these FPE strengthen much more the dispersion among coherence collapse thresholds. Those numerical calculations can be a strong input for telecommunication applications because they clearly show that a high degree of accuracy on the antireflection coating is required to avoid new FPE. In all cases, extremely small AR coatings, below 10^{-4} are required in order to counteract the AR FPE deleterious phenomena which is determinant to improve the quality of optical transmissions. For AR coatings on the order of 10^{-6}, all feedback performances can be connected to the laser wavelength whereas for AR coatings beyond 10^{-4}, simulations show that the sensitivity to optical feedback of AR/HR DFB lasers is extremely difficult to evaluate. Best situation can be reached when single mode DFB lasers using taper section and coated antireflection on both facets are designed. In that case, it has been demonstrated that no FPE occur and a remarkable feedback uniformity is obtained among feedback performences [18].

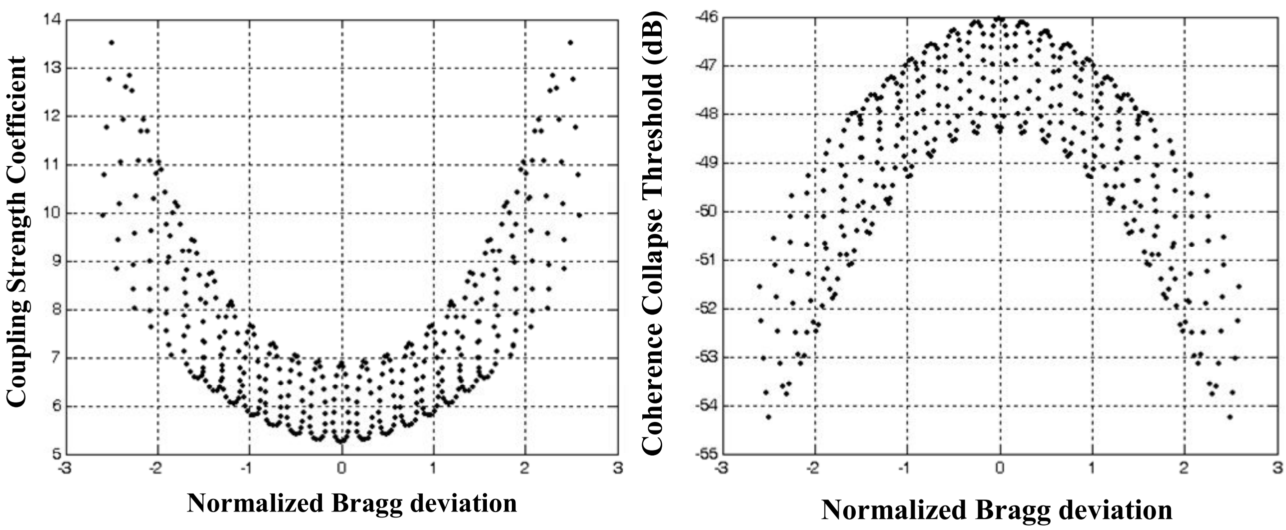

Figure 5: calculated coupling strength coefficient and calculated coherence collapse threshold for a distributed feedback laser with $|\rho_1|^2 = 2.10^{-4}$ and $|\rho_2|^2 = 0.95$. The normalized grating coupling coefficient is $\kappa L = 0.3$.

CONCLUSIONS

This paper reports a numerical study on the effects of facet phases on the sensitivity to optical feedback of AR/HR DFB lasers. It has been shown that these single mode components used for telecom applications suffer from FPE. If the antireflection coating is theoretically equal to zero, facet phases only occur on the rear facet coated HR. The coupling strength coefficients and the coherence collapse thresholds are linked to the normalized bragg deviation trough a quasi-parabolic distribution. It has been shown that depending of the phase case of the rear facet, a wide range of sensitivity to optical feedback can be obtained over the whole DFB laser population. Then, instead of assuming only facet phases on the rear facet, complementary facet phases arising on the front facet and due to an antireflection coating impairment have also been taken into account. Thus, simulations have shown that these new FPE induce a second distribution located across the first parabolic one. This second dispersion which is composed by several ellipses enhances the sensitivity to optical feedback. In all cases, simulations have shown that extremely small AR coatings, below 10^{-4} are required in order to counteract the AR FPE deleterious phenomena which is determinant to improve the quality of optical transmissions. But above all, those numerical calculations demonstrate that for AR coatings on the order of 10^{-6}, all feedback performances can be easily connected only to one parameter such as the laser wavelength. As a result, lasers emitting at wavelengths matching favourable facet phases can be selected for high bit rate isolator-free transmissions according to the recommended ITU (International Telecommunication Union) return loss specifications. On the other hand, it has been demonstrated that for AR coatings beyond 10^{-4}, the sensitivity to optical feedback is much more difficult to evaluate from a AR/HR DFB laser to another. The laser wavelength cannot be used as a selection criteria since it is hard to say if a laser emitting in the middle of the stopband is really better than one emitting on the edge.

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