Semiclassical Model of Semiconductor Laser Noise and Amplitude Noise Squeezing—Part II: Application to Complex Laser Structures

Jean-Luc Vey and Philippe Gallion

***Abstract*— We present noise studies of distributed feedback (DFB) laser structures, where spatial hole burning (SHB) plays a key role performed using the model described in Part I of this paper with particular emphasis on the influence of SHB, on the coupling coefficient κL, and on the laser facet reflectivities. These structures exhibit high amplitude noise and the possible noise reduction is strongly reduced compared to Fabry–Perot structures. Didstributed Bragg reflector (DBR) lasers are better candidates even if their performances are also strictly determined by SHB and the loss in the Bragg reflector. Finally, limitations due to gain suppression are demonstrated for such complex lasers structures. We conclude on the optimum laser structure for amplitude squeezed states generation.**

***Index Terms*—Laser noise, modeling, semiconductor laser.**

I. Introduction

COMPLEX laser structures such as distributed feedback (DFB) and distributed Bragg reflector (DBR) structures, which were introduced less than 25 years ago [1], [2], are widely used for engineering applications and especially in telecommunications [3]. Their noise performances have been very much studied [4]–[6] but only a few publications are dedicated to their amplitude squeezing performances [7]–[10]. Most of these models have a quantum mechanical base and consequently problems may occur in dealing with the exact structure of these lasers.

We have used for this problem a semiclassical model for laser noise presented in the first part of this paper to study the amplitude noise squeezing performances of DFB and DBR lasers. Strong limitations related to the severe spatial hole burning (SHB) are pointed out. The influence of the laser parameters is also described showing that the closer the structure is to a Fabry–Perot, the better it is for its noise and its amplitude squeezing performances.

Amplitude noise squeezing with a quietly pumped DFB semiconductor laser is presented in Section II. The strong influence of SHB is first pointed out. Then the influence of the Bragg grating coupling coefficient κL and of the facet reflectivities is shown. All these dependencies can be described by three parameters, which are consequently defined. The pump noise also gives a strict limitation on the achievable amount of squeezing, as pointed out at the end of this section.

DBR lasers are then briefly studied in Section III. Their structure, which is closer than a Fabry–Perot laser, gives better performances than a DFB laser. However, it is also shown that SHB and loss in the Bragg reflector strongly limit the squeezing performances of such a laser.

Section IV deals with the impact of gain suppression on the amplitude noise squeezing of such complex semiconductor laser structures. The strong limitations due to this phenomenon are described with a qualitative discussion on the influence of the different assumptions normally used for the gain suppression. Finally, a general conclusion is drawn pointing out the best structures for amplitude noise squeezing.

II. Amplitude Squeezing with DFB Lasers

More complex laser structures such as DFB or DBR lasers present several interesting features such as a narrow linewidth, a wide tunability, and a dynamic single-mode operation [11]. These advantages are balanced by some major drawbacks, such as, e.g., a high influence of SHB [12]–[14]. The structure discussed in this paper is a quarter-wave-shifted DFB laser.

Using the semiclassical model already introduced in [10] and described more precisely in Part I of this paper [15], analytical expressions are found of the internal and external amplitude noise which are the following:

$$\begin{aligned} S_{A\,\mathrm{int}}(\Omega) &= \frac{\langle \Delta P(\Omega)\Delta P(\Omega)^*\rangle}{4\overline{P}} \\ &= L\int_0^L \frac{D_{NN}(z,\Omega)}{4\overline{P}}\,|H_P(z,\Omega)|^2\,dz \\ &\quad + \frac{D_{PP}}{4\overline{P}}\,|C_1(\Omega)|^2 \\ &\quad + 2\mathrm{Re}\left(\int_0^L \frac{D_{PN}(z,\Omega)}{4\overline{P}}\,C_1(\Omega)\,H_p(z,\Omega)^*\,dz\right) \end{aligned} \tag{1a}$$

$$\begin{aligned} S_{\omega\,\mathrm{int}}(\Omega) &= \langle \Delta\omega(\Omega)\Delta\omega(\Omega)^*\rangle \\ &= 2\,\mathrm{Re}\left(\int_0^L D_{PN}(z,\Omega)C_2(\Omega)H_f(z,\Omega)^*\,dz\right) \\ &\quad + L\int_0^L D_{NN}(z,\Omega)|H_f(z,\Omega)|^2\,dz \\ &\quad + D_{PP}|C_2(\Omega)|^2 + D_{\phi\phi} \end{aligned} \tag{1b}$$

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and

$$S_{A\,\mathrm{ext}}(\Omega) = \frac{(1-R_2)V}{\tau}\, S_{A\,\mathrm{int}}(\Omega) + \frac{R_2}{4} - \frac{\sqrt{R_2}(1-R_2)}{2}\,\mathrm{Re}[Z_1(L)]\mathrm{Re}[C_2(\Omega)] \tag{2a}$$

$$S_{\omega\,\mathrm{ext}}(\Omega) = S_{\omega\,\mathrm{int}}(\Omega) + \frac{\Omega^2 R_2}{4\overline{A}_{ext}^2} + \frac{\sqrt{R_2}\,\sqrt{1-R_2}}{2} \cdot \frac{\Omega\,\mathrm{Im}[Z_1(L)]}{\overline{A}_{\mathrm{ext}}}\{1 - \mathrm{Im}\,[C_2(\Omega)]\} \tag{2b}$$

using the notations from the first part of this paper.

In these four equations, the distribution of the field inside the cavity plays a key role, as well as other structural parameters of the laser, which all dominantly influence the noise and squeezing performances of complex laser structures greatly.

A. Spatial Hole Burning

Spatial hole burning is a very strong phenomenon in DFB structures with a highly inhomogeneous field inside the cavity and resulting in modifications of its static and dynamic properties [5], [6]. In our model, SHB influences mainly three noise contributions: 1) the spontaneous emission via the longitudinal Petermann factor K 2) the transmitted vacuum fluctuations via the two local Petermann factor introduced in Part I [15] of this paper; and 3) the changes in the correlation between the transmitted internal field fluctuations and the reflected vacuum fluctuations at the laser facets.

The external amplitude noise at low frequency is shown in Fig. 1 for an asymmetric ($R_1 = 1$) Fabry–Perot and an asymmetric quarter-wave-shifted DFB ($R_1 = 1$) laser having the same threshold current and quantum efficiency. No discrepancy appears at a low pump level but at higher ones, a floor value for the external amplitude noise appears for the DFB laser. The SHB effect and the nonuniform distribution of the field inside the cavity leads to an increase of the internal amplitude noise which is not reduced to 50% of the shot-noise as for the Fabry–Perot laser. This floor value for the internal field induces then a floor value for the external amplitude noise. A reduction of the possible amount of squeezing compared to a Fabry–Perot laser occurs. This reduction is only related to the high SHB present inside the cavity.

This also points out that for such complex structures the maximum achievable amount of squeezing is not directly given by the efficiency of the laser as can be easily deduced from a simple laser model, as already pointed out in Part I [15]. A strong influence of the laser structure through the effect of SHB modifies this limit. Additive phenomena such as gain suppression influence this limit as is shown further on.

B. Influence of Structural Parameters

The three major parameters defining the noise of such a structure are the longitudinal Petermann factor for spontaneous emission K [16], the local Petermann factor for the vacuum fluctuations Z_1, and the coupling of the vacuum fluctuations to the laser field C_{vac}.

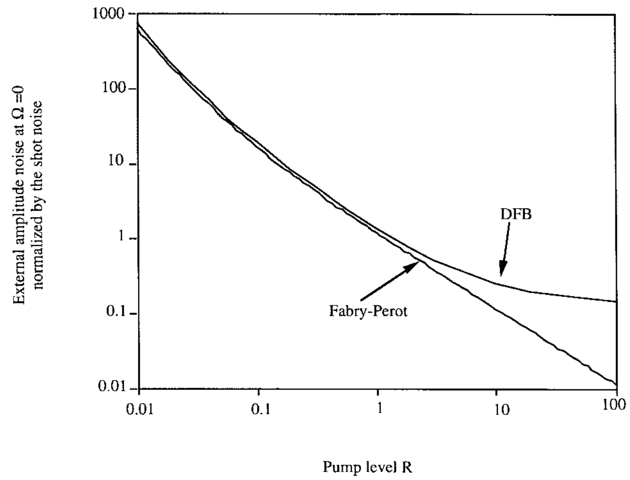

Fig. 1. External amplitude noise spectra value at $\Omega = 0$ as a function of pump level R for a Fabry–Perot laser and a DFB laser having the same threshold and quantum efficiency.

1) Laser Noise Parameters: These three parameters have very simple expressions for a Fabry–Perot laser structure but become more complex for a structure such as a quarter-wave-shifted DFB semiconductor laser. In fact, these factors depend strongly on the laser structure parameters such as the coupling coefficient of the Bragg grating and the laser facet reflectivities.

Fig. 2(a) presents the longitudinal Petermann factor K as a function of κL for different values of R_2, the other reflection coefficient R_1 being equal to 1. This coefficient can have a very high value and consequently the amplitude and phase noise increase. Structural parameters also strongly influence the local Petermann factor. As shown in Fig. 2(b), the same dependencies are obtained as for the Petermann factor K.

The calculation of the coupling of the vacuum fluctuations is more complicated. An average value for the photon round-trip time has to be calculated because the laser field is no longer homogeneous. For a longitudinally homogeneous laser, this factor can be approximated as, similar to calculations for the case of injection locking [27], as

$$C_{\mathrm{vac}} = \sqrt{\frac{\tau}{V}}, \qquad \text{where} \quad \tau = \frac{2L}{v_g}. \tag{3}$$

For a laser with an inhomogeneous internal field, an effective photon round-trip time inside the cavity and consequently an effective length is used in the model, as already introduced [22]:

$$\tau_{\mathrm{eff}} = \frac{2L_{\mathrm{eff}}}{v_g}, \qquad \text{with} \quad L_{\mathrm{eff}} = \frac{c}{2n_g}\frac{\partial\varphi}{\partial\omega}, \quad \rho_{\mathrm{eff}} = |\rho|e^{j\varphi} \tag{4}$$

where L_{eff} is the effective length of the cavity and ρ_{eff} the effective reflection coefficient of the laser structure [11].

Fig. 3 shows the effective length of an asymmetric quarter-wave-shifted DFB laser as a function of κL for the same structure as in Fig. 2. Its strong dependence on κL and the reflectivities also influences dramatically the internal and external noise spectra.

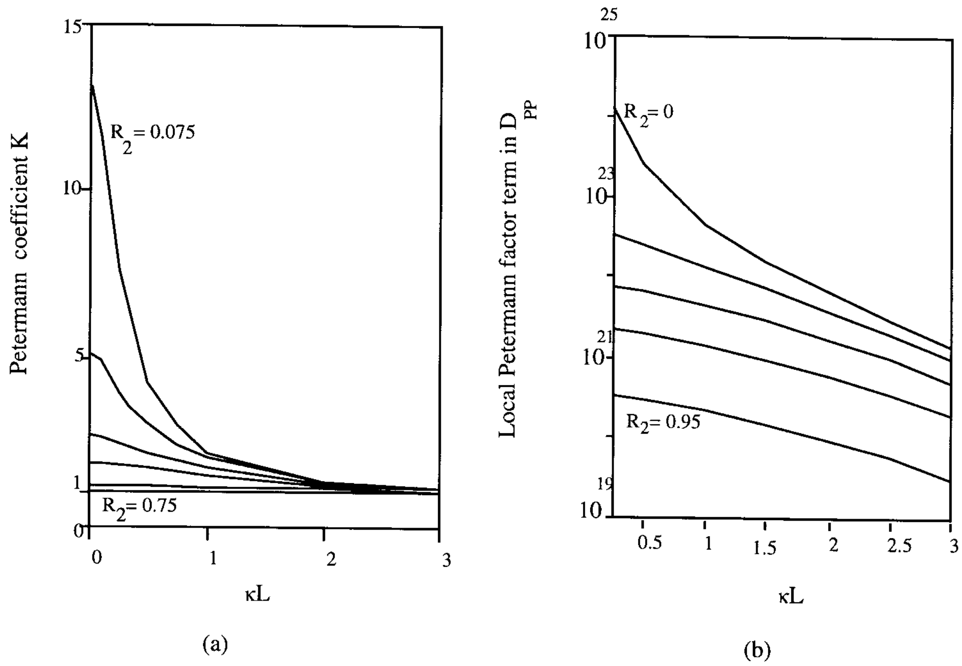

Fig. 2. Petermann coefficient K and term in D_{PP} due to the local Petermann factor $Z_1(L)$ for an asymmetric quarter-wave shifted DFB as a function of κL for (a) $R_2 = 0.075$, 0.1, 0.175, 0.25, 0.5, and 0.75, and (b) $R_2 = 0$, 0.25, 0.5, 0.75, and 0.95.

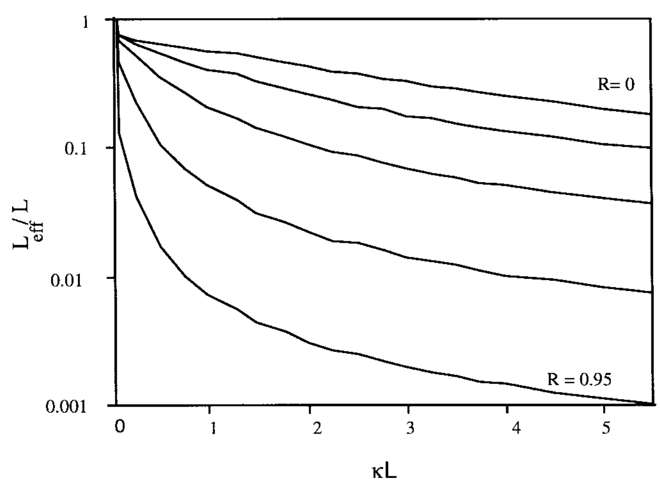

Fig. 3. Effective length of an asymmetric quarter-wave-shifted DFB laser as a function of κL for $R_2 = 0$, 0.25, 0.5, 0.75, and 0.95.

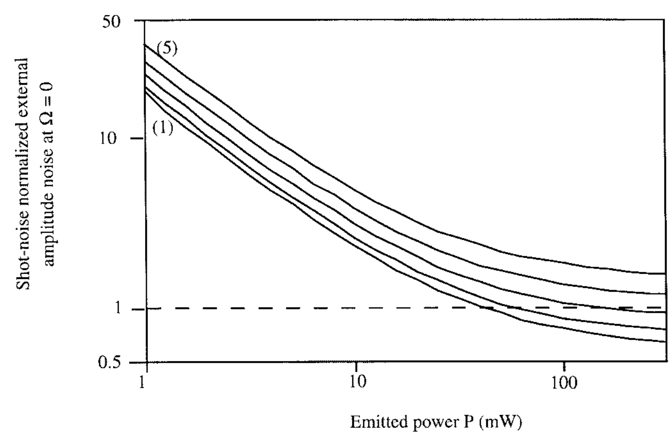

Fig. 4. Quiet pumped asymmetric DFB laser ($R_1 = 1$, $R_2 = 0.95$) external amplitude noise at $\Omega = 0$ normalized by the shot-noise level for $\kappa L = 0.25$ (1), 0.5, 1, 1.5, and 2 (5).

2) Influence of the Coupling Coefficient κL: The absolute value of the discussed three parameters introduced and their dependence on κL and the reflection coefficients including the SHB effect determine the noise of such a structure.

A high value of κL leads to an increase of the external amplitude noise directly because of the increase of the noise parameters introduced in the former paragraph, as can be directly seen in Fig. 4. These results also apply to the internal amplitude noise spectrum.

Let us now consider a symmetrical DFB laser. A higher external amplitude noise has been found as expected. But, in contrary to [6], the external amplitude noise is also an increasing function of κL. This is not surprising because, similar to an asymmetric DFB laser, the different coupling factors have the same variations and so does the external amplitude noise.

3) Influence of Laser Facet Reflections: Let us now consider only the external amplitude noise. The external amplitude noise normalized by the shot-noise level of a quietly pumped quarter-wave-shifted DFB laser with one facet high-reflection coated ($R_1 = 1$) is shown in Fig. 5 as a function of the other reflection coefficient R_2. The reflection coefficient necessary to achieve squeezing at high emitted power increases as the coupling coefficient of the Bragg grating increases and very drastic conditions for the laser facet power reflectivities appear for a too high κL. High reflectivities seems to be the best case, the DFB laser having no internal loss, which is a similar result as for a Fabry–Perot laser. However, calculations for a DFB laser with internal loss have shown that optimum values for the reflection coefficients exist when considering the squeezing of the external amplitude noise. The existence of this optimum reflectivity is due to the counteracting effect of SHB and of

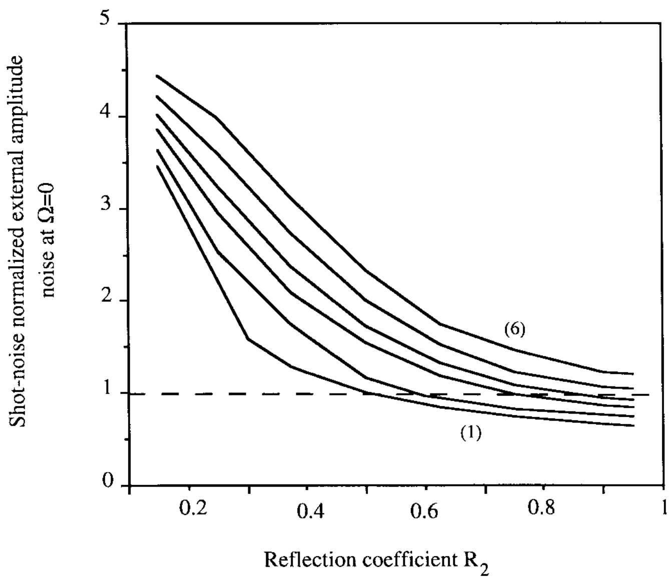

Fig. 5. External amplitude noise at $\Omega = 0$ and at high emitted power for a quarter-wave-shifted DFB laser with $R_1 = 1$ as a function of R_2 for $\kappa L =$ 0.25 (1), 0.5, 0.8, 1, 1.25, and 1.5 (6).

the facet reflectivities on the amplitude noise emitted by the DFB laser.

C. Influence of Pump Noise

Under practical conditions, the noise of the pumping current cannot be really reduced to zero but only to a very small value. It is then interesting to discuss how the residual pump noise influences the laser noise. Fig. 6 presents the shot-noise normalized external amplitude noise of a high-reflection-coated Fabry–Perot laser and of a high-reflection-coated quarter-wave-shifted DFB laser for a pump noise increasing from zero to a Poissonian level. X represents the relative amount of pump noise, i.e., the considered pump noise is X times the shot-noise level, X being between 0 and 1. The squeezing performances of the DFB laser are far more resistant to an increase of the pump noise than for the Fabry–Perot laser. But for the latter, it is always possible to get squeezing whatever the amount of pump noise is. On the contrary, a DFB laser cannot produce amplitude squeezed states if the pump noise is too high. This is only due to SHB, which induces an extra external noise at high emitted power.

In conclusion, DFB lasers have worse squeezing performances than Fabry–Perot lasers mainly because of SHB. A low value for κL, a good quiet pumping source, and an optimized value of the reflection coefficients are needed to get a strong squeezing, asymmetric structures being better than symmetric ones.

III. Amplitude Noise Squeezing with DBR Lasers

A DBR laser, when simply described, can be depicted as a Fabry–Perot laser with a distributed reflection at one facet, which can even be transformed into an effective reflection coefficient for the laser considered facet. A DBR laser should be consequently a very good candidate for squeezed states generation as pointed already in [8] and according to the results presented in Part I of this paper [15] and just above.

These results are only partly true. DBR lasers have better performances than DFB lasers but still suffer from strong limitations in their performances which are directly linked to their structure.

The first important phenomenon is spatial hole burning. When considering the exact structure of such a laser, the longitudinal extension of the Bragg reflector should be considered, with all the distributed reflections. In such a case, the typical distribution of the field inside the cavity corresponds to Fig. 7. As has been pointed out just before, an inhomogeneous field distribution induces an increase of the amplitude noise in the laser and limits its squeezing performances. This is also the case here. First simulations have shown that mostly three parameters determine these SHB influences which are the coupling coefficient of the Bragg reflector, its relative length compared to the cavity length, and the effective reflection coefficient given by the Bragg reflector. A thorough analysis as well as an optimization procedure has to be done, which will be the subject of a future paper.

A second phenomenon is the scattering losses inside the Bragg reflector. With such losses, the clamping of the carrier density is no longer possible to complete and the noise dramatically increases. The lower the loss in the Bragg reflector is, the better it is for the laser noise performances.

IV. Gain Suppression and Complex Laser Structures

Various physical phenomena induces gain suppression such as carrier heating [17], standing waves inside the cavity [18], [19], and spectral hole burning [20]. Gain suppression has a strong effect on laser performances. It induces a saturation of the emitted power by the laser and it also modifies its modulation performances and noise performances [21], [22]. Gain suppression shows its effect at high pump level, for which amplitude squeezing is also obtained. Consequently, quantum mechanical [23] and also semiclassical works [24], [25] have already been devoted to that subject.

This phenomenon can be taken into account using the standard phenomenological expression for the gain

$$g = g_d(N - N_0)(1 - \varepsilon\overline{P}) \tag{5}$$

where g_d is the differential gain, ε the gain suppression factor, and $\overline{P}$ the internal photon density.

Gain suppression has a strong influence on a semiconductor laser noise spectra. Its presence induces a strong decrease of the internal amplitude noise and also a floor value for the external amplitude noise at high emitted power [23]–[25]. It has been, in addition, demonstrated that not only a floor value appears [25] for the external amplitude noise but also an optimum, for which a maximum squeezing is obtainable. These results were obtained for a Fabry–Perot lasers. Let us now consider the case of a DFB semiconductor laser.

Gain suppression has a smaller influence on the performance of DFB lasers than on Fabry–Perot ones, and the effect becomes stronger when the active zone consists of quantum wells where gain suppression is enhanced [26]. Reduction of the internal amplitude noise and the existence of a minimum for the external amplitude noise are also found for such

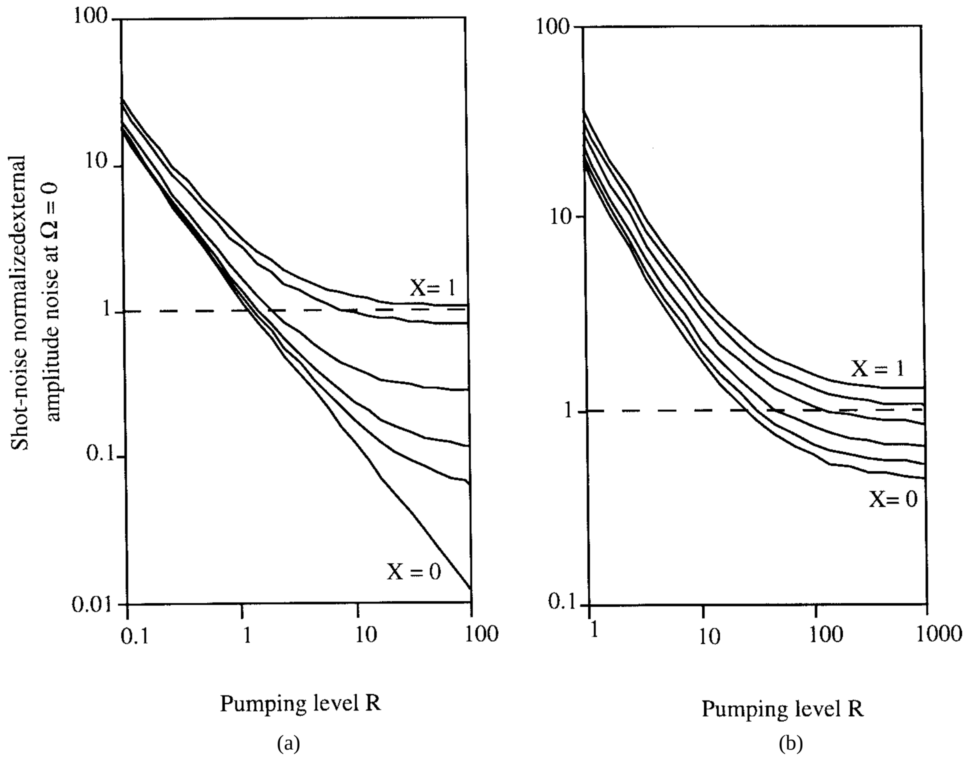

Fig. 6. External amplitude noise at $\Omega = 0$ for a high-reflection-coated Fabry–Perot laser as a function of the pump level for (a) $X = 0$, 0.05, 0.1, 0.25, 0.5, and 1, and (b) for a high-reflection-coated quarter-wave-shifted DFB laser as a function of the emitted power for $X = 0$, 0.1, 0.25, 0.5, 0.75, and 1.

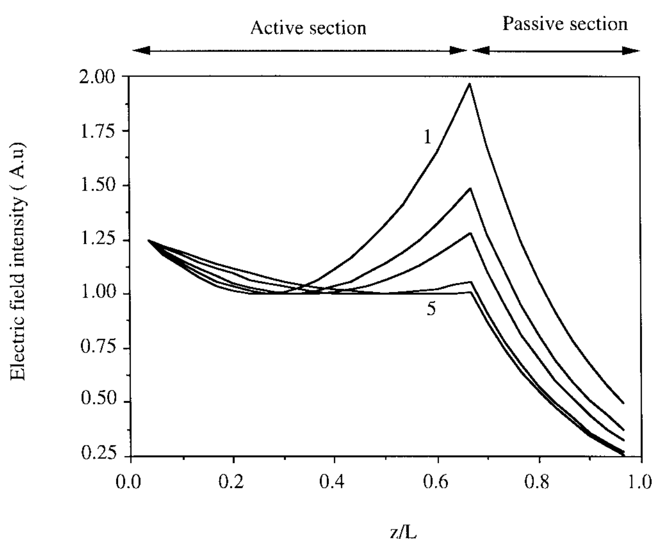

Fig. 7. Internal field distribution for a DBR laser with an active section of 400 μm and a Bragg reflector of 200 μm for different coupling coefficients of the Bragg reflection coefficient equal to 0.5 (1), 0.75, 1, 2, and 4, the right facet of the Fabry–Perot section having a reflectivity of 50%.

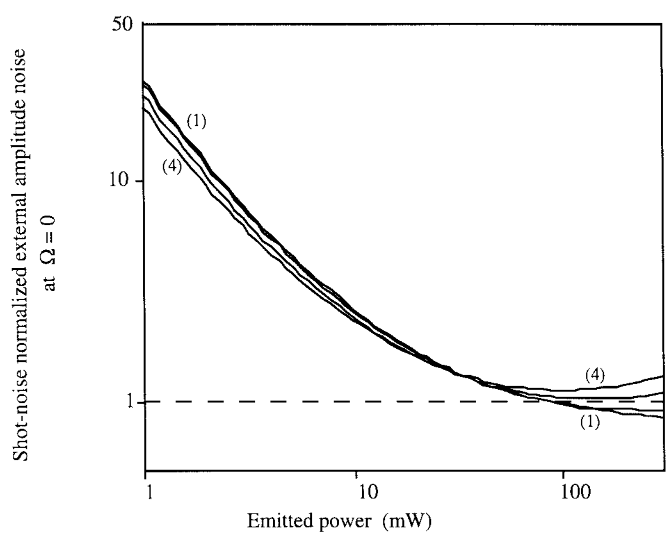

Fig. 8. External amplitude noise of a quietly pumped asymmetric quarter-wave-shifted DFB laser at $\Omega = 0$ as a function of the emitted power for different gain suppression coefficient $\varepsilon = 0$ cm^3 (1), 5×10^{-18} cm^3, 10^{-17} cm^3, and 5×10^{-17} cm^3 (4).

a structure as shown in Fig. 8. This minimum is not well pronounced and compression is no more possible for high value of gain suppression.

This is different than Fabry–Perot lasers, for which squeezing is always possible however strong the gain compression is. This minimum for a DFB laser also exists if the laser is normally pumped. This may explain already obtained experimental results [27], [28], where the relative intensity noise at low frequency exhibits a minimum as a function of the emitted power for a multiple-quantum-well DFB laser even if no increase of side modes appears.

The use of other gain suppression models does not modify the results presented above; the only difference is the absolute value of the amplitude noise spectra for the same operating conditions.

Gain suppression, even if it enhances the compression of noise of the internal field, is a very restrictive phenomenon for external amplitude noise squeezing. Having a laser with a very linear P–I curve seems to be an important factor to get strong amplitude noise squeezing.

V. Conclusion

Using our model, we have shown that DFB structures show reduced amplitude squeezing performances, being limited by SHB. As deduced from our comprehensive study, a low coupling coefficient and optimized facet reflectivities are needed to obtain good noise compression. DBR lasers show performances closer to Fabry–Perot ones. Gain suppression has also to be taken into account, introducing further limitations.

It must be pointed out that to estimate precisely the amplitude noise squeezing performances of a semiconductor laser the laser structure should be thoroughly considered. We have demonstrated that the maximum achievable squeezing is not directly given by the laser efficiency but must be modified, taking into account the laser structure through for example SHB as well as its performances through gain suppression and the saturation of the emitted power of the laser it induces.

To obtain the maximum amount of amplitude noise squeezing, a semiconductor laser should have linear P–I characteristics in a large current range as well as a good side-mode suppression ratio between the different longitudinal modes, higher then 30 dB at least. It should also have a low threshold current as well as high reflection coatings on the laser facets and a low coupling coefficient for a Bragg grating. It is difficult in practice to have all these requirements in the same structure. For example, quantum-well lasers have a low threshold current but have a gain suppression factor ε at least five times higher than for a bulk laser. In consequence, they suffer from a strong saturation of their emitted power and so their squeezing performances are limited. In consequence, a compromise between all these parameters is to be made and optimization calculations have to be performed. The work presented here should be pursued to study different more complex structures like multisection structures or vertical-cavity surface-emitting lasers to find out the best laser structure for amplitude noise squeezing, taking into account the laser parameters and its structure.

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Jean-Luc Vey, for photograph and biography, see this issue, p. 2104.

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