

## Squeezing and Intermode Correlations in Laser Diodes

F. Marin, A. Bramati, and E. Giacobino

*Laboratoire Kastler Brossel, Université Pierre et Marie Curie, F-75252 Paris Cedex 05, France*

T.-C. Zhang,\* J.-Ph. Poizat, J.-F. Roch, and P. Grangier

*Institut d'Optique, B.P. 147, F-91403 Orsay Cedex, France*

(Received 7 April 1995)

We demonstrate experimentally that the intensity noise of so-called “free-running single-mode” laser diodes results from a cancellation between very large anticorrelated fluctuations of the main mode, on one hand, and of many weak longitudinal side modes, on the other hand. When line narrowing techniques are used, intensity squeezing can be observed at room temperature, but this noise reduction is not always single-mode squeezing. These experimental results are in agreement with a simple phenomenological model using Langevin-type equations.

PACS numbers: 42.55.Px, 42.50.Dv, 42.62.Fi

Laser diodes have proved in the past two decades to be a very powerful and convenient tool in the field of telecommunications [1] and spectroscopy [2]. Their main advantages are compactness, energy efficiency, tunability, and low intensity noise. This last property has been brought into the quantum domain by Yamamoto and co-workers [3,4] about 10 years ago. The physical idea is that the intensity noise of a laser is related to the noise of the pumping process [5], and that appropriate control of the driving current in laser diodes allows one to generate sub-Poissonian light through pump-noise suppression. Very large noise reductions down to  $-8.3$  dB below the shot-noise level (SNL) were observed for free-running laser diodes cooled to 66 K [6]. However, the very mechanisms capable of explaining why some laser diodes and not others were generating sub-shot-noise light remained unclear.

Recently, intensity squeezing was observed with so-called “single-mode” commercial laser diodes using line-narrowing techniques such as injection locking or feedback from an external grating [7,8]. These experiments shed new light on the understanding of the noise reduction mechanisms by putting forward the existence of weak longitudinal side modes, and their importance concerning the intensity noise behavior of such “quasi-single-mode” lasers. The arguments given in Refs. [7,8] tended to suggest that the less powerful these side modes are, the less they will contribute to the total intensity noise. However, this argument ignores possible correlations between the modes, which were demonstrated for instance by Inoue *et al.* [9] (see also Refs. [10–12]) for multimode laser diodes (several modes above threshold).

In order to explore these arguments more precisely, we have investigated the noise properties of the individual modes by sending the beam of various types of single-mode laser diodes through a high resolution spectrometer, which enabled us to analyze not only the intensities but also the noise of the individual side modes (see Fig. 1). In this Letter, we demonstrate by this method that the

intensity noise of these so-called “free-running single-mode” lasers, which is typically a few dB above the SNL at room temperature, results from a cancellation effect between very large anticorrelated fluctuations of the main mode, on one hand, and of many weak longitudinal side modes, on the other hand. When line-narrowing techniques are used, the total intensity noise goes below the shot-noise level [7,8,12,13], but we show that the sub-Poissonian character of the light can still be due to a cancellation effect between large anticorrelated noises of the various modes. This points out that sub-shot-noise operation of these lasers is actually not always single-mode squeezing. We believe that these results could have important practical implications, since for most applications, in particular, when the laser diodes are to be used in spectroscopy, single-mode and multimode properties should be clearly discriminated.

The experimental apparatus is shown in Fig. 1. We have used several samples of quantum well AlGaAs laser diodes (SDL 5422-H1) operating at 800 or 852 nm with high impedance source pumping. The free-running diodes have a rather low threshold of 18 mA and a differential quantum efficiency (slope above threshold) of 66%. We

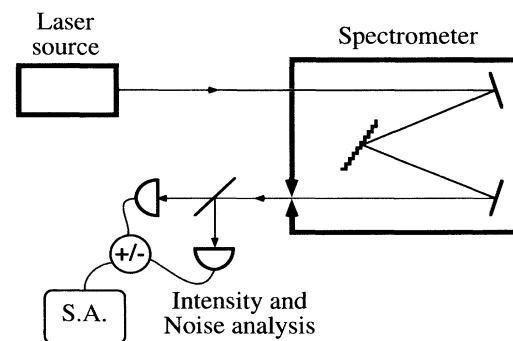


FIG. 1. Longitudinal side mode investigation scheme. S.A. is for spectrum analyzer.

have investigated the performances of free-running lasers, extended cavity lasers using feedback from an external grating, and injection-locked lasers. In the last case, the master laser was a semiconductor laser of the same kind in the external grating configuration.

The amplitude noise was measured by means of high efficiency *p-i-n* photodiodes (EG&G FND 100). The detected intensity noise was flat in the frequency region from 7 to 30 MHz. For an accurate comparison of the noise in different conditions, all data presented in this paper were measured at 7 MHz, with a detection bandwidth of 1 MHz. Great care was taken to avoid feedback to the laser, using several stages of optical isolation [14]. A polarizing cube was used in order to avoid spurious interference effects between the two orthogonal polarizations [15]. A more detailed description of the experimental apparatus can be found in [13].

By focusing the laser beam on the input slit, the overall transmission of the monochromator (Jobin-Yvon HR1000) was 25%. Its resolution was 0.03 nm, which was enough to resolve the laser modes separated by 0.12 nm. The negligible level of scattered light within the spectrometer allowed us to separate the different modes (all of them for the free-running laser and starting from the 5th–10th for the injected laser and from the 15th–20th for the grating stabilized laser). We have measured the noise either sequentially before and after the spectrometer with a standard balanced detection [16] or in parallel by splitting the beam and sending only one beam in the spectrometer. The second method used simultaneously two previously calibrated detectors, respectively, located before the spectrometer on one beam and after it on the other one, in order to ensure that the measurements of the total intensity noise and of the spectrally resolved noise were performed under the same laser conditions. The noise measurements have been confirmed using another grating with a higher efficiency (60% transmission), but poorer resolution and optical quality.

For the free-running laser, the power of one of the first side modes is typically  $-25$  dB lower than the one of the main mode (see Fig. 2), and the total power in the side modes is about  $-18$  dB below the main mode. The novel and rather unexpected result that we obtained concerns the noise of the individual modes: We have observed that the intensity noise of the main mode alone is much higher than the total intensity noise. For example, for a driving current of 80 mA the main mode exhibits an excess noise of  $+39$  dB, while the total intensity noise, measured before the spectrometer, is only 2 dB above the SNL (all noises are referred to the laser output). The intensity noise of the side modes is then expected to be comparable to the intensity noise of the main mode despite their much weaker power, and this is what was observed. Indeed, if the output slit is kept centered on the main mode, and is progressively opened, the intensity noise decreases, showing clear steps as symmetrical side modes enter the

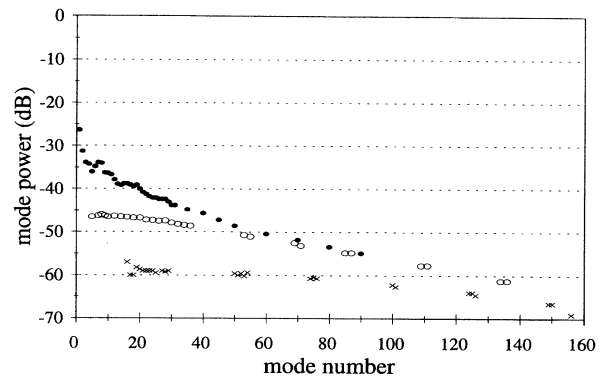


FIG. 2. Power of individual longitudinal modes (optical power in dB, with respect to the main mode), measured with a high resolution monochromator, for a driving current of 80 mA. On the  $x$  axis each mode is labeled by a number, the number 0 corresponding to the main mode. ( $\bullet$ : free-running laser.  $\circ$ : injection-locked laser.  $\times$ : extended cavity laser.)

detector (Fig. 3). The step size corresponds to the noise of the respective modes: For instance, when the noise in the main mode was  $2.5 \mu\text{V}/\sqrt{\text{Hz}}$ , the total noise in the two first adjacent modes was about  $2.15 \mu\text{V}/\sqrt{\text{Hz}}$ , and the noise for all three modes was  $0.3 \mu\text{V}/\sqrt{\text{Hz}}$ . This clearly demonstrates that the observed total intensity fluctuations result from a cancellation effect between the very large anticorrelated fluctuations of the main mode and of the side modes. In fact, all of the 160 side modes displayed in Fig. 2 contribute to some extent to this cancellation effect. This is demonstrated by the fact that the noise level after the spectrometer, with the output slit fully opened (about 15 modes detected), is still much higher than the total intensity noise level.

As seen from Fig. 2, the power of the first side modes of the injection-locked laser is reduced to less than  $-45$  dB

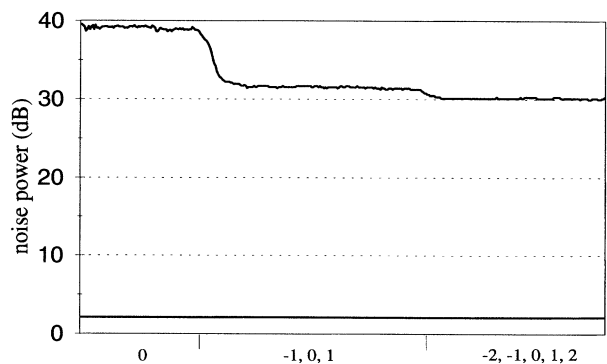


FIG. 3. Intensity noise of the free-running laser diode, referred to the shot noise, as the output slit is opened up. In the first section, only the main mode is detected, while the two steps correspond to the entrance of the two couples of side modes ( $-1.1$ ) and ( $-2.2$ ). The straight line at 2 dB shows the total intensity noise level (measured before the spectrometer).

below the main mode, while the total power in the side modes is  $-30$  dB below the main mode. The total intensity noise referred at the laser output is now squeezed by  $-2.3$  dB below the SNL (see [13]), while the intensity noise of the main mode alone is still well above the quantum limit. The level of this excess noise depends critically on the injection parameters, such as alignment, injected power, or master laser frequency, whereas the total intensity squeezing is unchanged (cf. the remark at the end of the theoretical discussion below). Optimization of these parameters does not only reduce the excess main mode noise, typically from 10 to 1 dB above the SNL, but also the power in the side modes, from  $-44$  to  $-49$  dB below the main mode for the first side mode. The total intensity noise of the injection-locked laser again results from a cancellation effect among anticorrelated fluctuations of the main and side modes. Note that in this case the sub-Poissonian intensity noise is not single-mode squeezing.

For the laser in the extended cavity configuration, the side modes are suppressed further down, to about  $-55$  dB below the main mode (see Fig. 2), which corresponds to a total side mode power of  $-35$  dB below the main mode. In that case, we have noticed virtually no difference between the total intensity noise and the noise of the main mode alone. For instance, at 80 mA, we have obtained a squeezing of  $-1.85 \pm 0.05$  dB for the total intensity, and of  $-1.6 \pm 0.3$  dB for the main mode alone (both referred to the laser output), and the noise in the side modes was too low to be detected (less than 7.5% of the SNL). In this case, and only in this case, it can be concluded that the side modes are actually negligible, and that true single-mode squeezing is generated.

In order to build a theoretical model for the observed correlations, a first possibility is to couple all the modes to the same excited carrier population [9]. This would be a correct description if a predominantly homogeneous behavior of the lasing junction is assumed. However, in a fully homogeneous gain medium, the anticorrelations between the modes should be perfect and the total intensity noise should always be squeezed, depending eventually on the quantum efficiency but not on the size of the side modes. This is not what we have observed. Therefore, for a description of our experimental results, we have modified an homogeneous multimode Langevin model, as introduced by Inoue *et al.* [9], by bringing in some inhomogeneity as suggested by Wang *et al.* [8]. A simple model for inhomogeneous noise behavior is to introduce a small self-saturation of each mode by its own fluctuations, which adds up to the homogeneous saturation process due to the excited carrier population. It will be shown below that the correlations between the main and side modes are then degraded as the power of the side modes gets larger (case of the free-running diode), resulting in an increase of the total intensity noise.

The quasi-single-mode laser diode is described by three modes (one main mode, labeled "1" and two side modes,

labeled "2" and "3") coupled to a common carriers population (homogeneous behavior) [9]. The dynamic variables are the photon number  $n_i(t)$  of the  $i$ th mode and the total number of excited carriers  $N_c(t)$ . The equations obeyed by these quantities are then

$$\frac{dn_i(t)}{dt} = -\frac{n_i(t)}{\tau_i^{(p)}} + A_i N_c(t)[n_i(t) + 1] + S_i(t) + G_i(t) + g_i(t) + f_i(t). \quad (1)$$

The quantity  $1/\tau_i^{(p)} = 1/\tau_i^{(po)} + 1/\tau^{(pe)}$  is the photon decay rate of mode  $i$ , decomposed into internal losses  $1/\tau_i^{(po)}$  and output coupling losses  $1/\tau^{(pe)}$ . The coefficient  $A_i$  is the spontaneous emission rate into the corresponding lasing mode, given by  $A_i = \beta_i/\tau^{(sp)}$ , where  $\beta_1$  and  $\beta_{2,3} = m\beta_1$  (with  $m < 1$ ) are the spontaneous emission coefficients in mode  $i$ , and  $\tau^{(sp)}$  is the spontaneous electron lifetime. The term  $S_i(t)$  describes self-saturation of mode  $i$ , and is taken equal to  $\tau_i^{(p)} S_i(t) = -s_i[\langle n_i \rangle / (P\tau_i^{(p)})] \delta n_i(t)$ , with  $s_i$  being a small adjustable parameter,  $P$  the pumping rate [see Eq. (2) below], and  $\delta n_i(t) = n_i(t) - \langle n_i \rangle$  the fluctuations of the photon numbers around their mean values. The last three terms are Langevin noise terms, respectively, associated with the stimulated-emission gain [correlation  $\langle G_i(t)G_i(t') \rangle = \delta(t-t')A_i\langle N_c \rangle \langle n_i \rangle$ ], the internal losses [correlation  $\langle g_i(t)g_i(t') \rangle = \delta(t-t')\langle n_i \rangle / \tau_i^{(po)}$ ], and the output coupling [correlation  $\langle f_i(t)f_i(t') \rangle = \delta(t-t')\langle n_i \rangle / \tau^{(pe)}$ ].

The equation of motion for the total excited carrier number  $N_c(t)$  is

$$\frac{dN_c(t)}{dt} = P - \frac{N_c(t)}{\tau^{(sp)}} - \sum_i A_i [n_i(t) + 1] N_c(t) + \Gamma^{(p)}(t) + \Gamma^{(sp)}(t) + \Gamma(t). \quad (2)$$

The last three terms are Langevin noises. The first one  $\Gamma^{(p)}(t)$  is associated with the pump noise, and for a pump-noise-suppressed laser its correlation function is  $\langle \Gamma^{(p)}(t)\Gamma^{(p)}(t') \rangle = 0$ . The term  $\Gamma^{(sp)}(t)$  is associated with spontaneous noise and its correlation is  $\langle \Gamma^{(sp)}(t)\Gamma^{(sp)}(t') \rangle = \delta(t-t')\langle N_c \rangle / \tau^{(sp)}$ , and  $\Gamma(t)$  is associated with stimulated noise and its correlation is  $\langle \Gamma(t)\Gamma(t') \rangle = \delta(t-t')\sum_j A_j \langle N_c \rangle \langle n_j \rangle$ . Finally, due to their same physical origin, the noise terms associated with the stimulated gain for the photons and stimulated emission for the electrons are perfectly anticorrelated and have cross correlations  $\langle G_i(t)\Gamma(t') \rangle = -\delta(t-t')A_i\langle N_c \rangle \langle n_i \rangle$ .

By neglecting the noise terms and the operator correlations in Eqs. (1) and (2), and by setting the time derivatives to zero, one obtains the average numbers of photons  $\langle n_i \rangle$  in each mode  $i$ . These numbers depend on the two ratios  $m = \beta_{2,3}/\beta_1$  (corresponding to the relative gains) and  $p = \tau_{2,3}^{(po)}/\tau_1^{(po)}$  (corresponding to the relative losses). The value of  $m$  can be determined from the value of the free-running diode, and then the mode

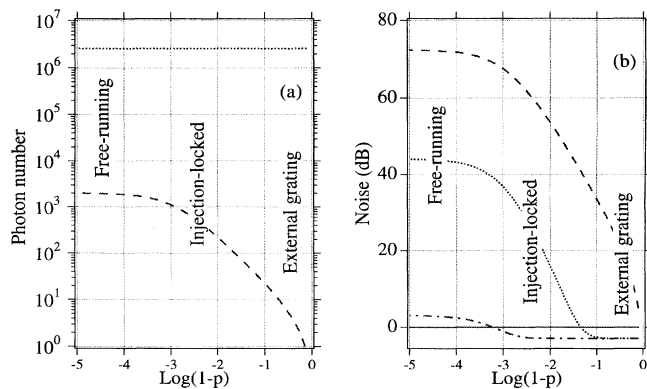


FIG. 4. (a) Calculated photon number in the main mode (dotted line) and in one side mode (dashed line) versus the deviation from unity of the relative optical losses  $p$ , for a given gain ratio  $m = 0.9995$ . (b) Noise power in the main mode (dotted line), in one side mode (dashed line), and in all the modes (dash-dotted line) versus  $1 - p$ . The 0 dB level is the SNL of each individual mode. The pumping rate is  $R = I/I_{\text{th}} - 1 = 7$ , the spontaneous coefficient is  $\beta = 2.7 \times 10^{-6}$ , the lifetimes are  $\tau^{(sp)} = 10^{-9}$  s,  $\tau^{(pe)} = 5.6 \times 10^{-12}$  s,  $\tau_1^{(po)} = 1.5 \times 10^{-11}$  s, and the self-saturation parameters are  $s_1 = s_2 = s_3 = 0.015$ .

selection process can be modeled by decreasing  $p$ . The average numbers of photons in each mode obtained using this procedure are plotted in Fig. 4(a) as a function of  $\log(1 - p)$ , for fixed  $m = 0.9995$ . It can be seen that the number of photons in the main mode varies very little with  $p$ , but the number of photons in the side modes exhibits much larger variations. In Fig. 4(b) are plotted the noise levels obtained from the above equations after a standard linearization procedure. Three regions appear clearly on this graph: on the left hand side, there is no squeezing; in the center, the total intensity is squeezed, but the individual modes are not; on the right hand side, both the main mode and the total intensity are squeezed, while the side modes still exhibit excess noise, but have negligible intensity. These three regions are in quite good agreement with the experimental results described previously, respectively, for free-running, injection-locked, and grating-stabilized diodes. Note that the behavior observed while optimizing the alignment in the injection-locked laser is nicely reproduced by the model. Indeed, in the central region, a change in the  $p$  parameter modifies the power in the side modes and the noise of the main mode, without changing the total intensity noise.

The basic physics of our observations is thus explained by strong mode competition due to the homogeneous broadening of the transition (which yields large anticorrelated noises), plus a small amount of inhomogeneities degrading the anticorrelation between the modes when the rejection rate of the side modes is not sufficiently large. The final amount of noise in the individual and total intensities depends therefore on this degree of rejection, which

is described in the model by the modal gain and loss parameters  $m$  and  $p$ . This simple model is in good agreement with the experimental data, and could provide us with some useful hints for more detailed calculations.

As a conclusion, we have shown that a thorough analysis of the quantum noise of laser diodes should distinguish between true single mode squeezing and sub-Poissonian light involving contributions from a large number of weak side modes. This distinction could allow one to understand better the underlying physics of the observed noise reductions in laser diodes, and therefore to progress towards the use of such devices in quantum optics experiments.

We thank A. Eschmann for fruitful discussions. This research was carried out in the frameworks of the ESPRIT Basic Research Project 6934 QUINTEC, and of the HCM network "Non-Classical Light" (ERB CHRX CT93 0114). Two of us had fellowships: A. B. was supported by the HCM program from the European Community (ERB CHBG CT93 0437), and T. C. Z. was supported by the Programme International de Coopération Scientifique (PICS) sponsored by the CNRS.

\*Present address: Institute of Optoelectronics, Shanxi University, Taiyuan 030006, China.

- [1] See, for example, J.-C. Bouley and G. Destefanis, IEEE Commun. Mag. **32**, 54 (1994).
- [2] C. E. Wieman and L. Hollberg, Rev. Sci. Instrum. **62**, 1 (1991).
- [3] Y. Yamamoto, S. Machida, and O. Nilsson, Phys. Rev. A **34**, 4025 (1986).
- [4] S. Machida, Y. Yamamoto, and Y. Itaya, Phys. Rev. Lett. **58**, 1000 (1987).
- [5] Yu. M. Golubev and I. V. Sokolov, Zh. Eksp. Teor. Phys. **87**, 804 (1984) [Sov. Phys. JETP **60**, 234 (1984)].
- [6] W. H. Richardson, S. Machida, and Y. Yamamoto, Phys. Rev. Lett. **66**, 2867 (1991).
- [7] M. J. Freeman, H. Wang, D. G. Steel, R. Craig, and D. R. Scifres, Opt. Lett. **18**, 2141 (1993).
- [8] H. Wang, M. J. Freeman, and D. G. Steel, Phys. Rev. Lett. **71**, 3951 (1993).
- [9] S. Inoue, H. Ohzu, S. Machida, and Y. Yamamoto, Phys. Rev. A **46**, 2757 (1992).
- [10] G. P. Agrawal, Phys. Rev. A **37**, 2488 (1988).
- [11] W. Elsässer, Appl. Phys. Lett. **48**, 1323 (1986).
- [12] J. Kitching, A. Yariv, and Y. Shevy, Phys. Rev. Lett. **74**, 3372 (1995).
- [13] T.-C. Zhang, J.-Ph. Poizat, P. Grelu, J.-F. Roch, P. Grangier, F. Marin, A. Bramati, V. Jost, M. D. Levenson, and E. Giacobino, Quantum Semiclass. Opt. **7**, 601 (1995).
- [14] The total optical isolation used was 60 dB. Moreover, we tried different types of darkened slits for the spectrometer in order to ensure that the laser behavior did not depend upon the degree of backreflection on the slit.
- [15] M. J. Freeman, H. Wang, D. G. Steel, R. Craig, and D. R. Scifres, Opt. Lett. **18**, 379 (1993).
- [16] H. P. Yuen and V. W. S. Chan, Opt. Lett. **8**, 177 (1983).