QUANTUM NOISE IN LASER DIODES

E. Giacobino, F. Marin, A. Bramati, V. Jost
Laboratoire Kastler Brossel, Université Pierre et Marie Curie, F-75252 Paris Cedex 05 - France

J.-Ph. Poizat, J.-F. Roch, P. Grangier
Institut d'Optique, B.P. 147, F-91403 Orsay Cedex - France

T.-C. Zhang
Institute of Optoelectronics, Shanxi University, Taiyuan 030006, China

Abstract

We have investigated the intensity noise of single mode laser diodes, either free-running or using different types of line narrowing techniques at room temperature. We have measured an intensity squeezing of 1.2 dB with grating-extended cavity lasers, and 1.4 dB with injection locked lasers (respectively 1.6 dB and 2.3 dB inferred at the laser output). We have observed that the intensity noise of a free-running nominally single mode laser diode results from a cancellation effect between large anticorrelated fluctuations of the main mode and of weak longitudinal side modes. Reducing the side modes by line narrowing techniques results in intensity squeezing.

1 Introduction

Quantum noise in the intensity of a light beam can be viewed as the result of the random distribution of photons in the beam. It can be fully suppressed if the field is in a particular state where the number of photons is known perfectly, a photon number state. The reduction of the intensity noise below the standard quantum noise is then done at the expense of increased fluctuations in the phase, which is completely undetermined for a number state. Photon number states containing more than one photon have never been produced. However, specific non classical states of the light in which the intensity fluctuations are reduced have been generated using several kinds of methods. One of them relies on the fact that part of the quantum noise in the laser emission comes from the random character of the pumping process, which can be suppressed in some cases.

Quantum noise reduction in laser emission based on pump noise suppression was first predicted in 1984 [1]. Semiconductor lasers are particularly well suited for the implementation of this idea [2]. Furthermore, laser diodes are widely used and are considered as powerful and convenient tools in the field of telecommunications [3] and spectroscopy [4]. Their main advantages are compactness, energy efficiency, tunability, and low intensity noise. It is the latter property that can be brought into the quantum domain by driving the laser with a current whose noise is well below shot-noise.

Since the noise in an electrical current is limited by thermal noise, it is easy to have a noise in the driving current that is well below shot noise. If the quantum efficiency of the carrier to photon conversion is high enough, the electron statistics of the pumping can be transferred to the light emission, yielding sub-poissonian operation of the laser. Quantum noise in the intensity of constant-current-driven laser diodes was observed for the first time by Machida *et al* in 1987 [5], and further improved to 8.3 dB in 1991 [6]. But the very mechanisms capable of explaining why some laser diodes and not others generate sub-shot-noise light remained unclear.

Actually, other factors than the constant current supply can be important for the noise reduction. In 1993, intensity squeezing was observed with so-called "single mode" commercial laser diodes by Steel and his group [7, 8]. It was shown that line narrowing techniques greatly helped in the noise reduction by further suppressing the weak but very noisy longitudinal side modes. We have investigated intensity noise of laser diodes, using various methods for line narrowing, including injection-locking with another diode laser and feedback from an external grating. The best intensity squeezing at room temperature was 1.4 dB (2.3 dB when corrected from the detection efficiency), and was obtained with injection-locking.

In order to explore the role of the line narrowing processes in squeezing more precisely, we have investigated the noise properties of the individual side modes. 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] for multimode semiconductor lasers. We have shown that the noise of the free-running diode lasers 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, 10], but we show that, in some cases, the sub-Poissonian character of the light can be due to a cancellation effect between large anticorrelated noises of the various modes. Thus sub-shot-noise operation of these lasers does not always correspond to single mode squeezing.

2 Experimental set-up

The laser diodes we have used are index-guided quantum well GaAlAs laser diodes (model SDL 5422-H1 and SDL 5411-G1). Appropriate electrical filtering is used on the power supply in order to stabilize the current. The free-running laser diodes have a low threshold of 18 mA and a differential quantum efficiency (slope above threshold) of 66%. The operating current in the experiments described below is typically 5 to 7 times larger than the threshold current, and the resulting high overall quantum efficiency is at the origin of squeezing. No squeezing was found in similar experiments performed on laser diodes with higher threshold (80 mA), which operate only twice above their threshold.

The quantum noise in the intensity is measured in the standard way with a balanced detection [11]. The beam going out of the laser is split in two equal parts by a beamsplitter. Each output of the beamsplitter is sent into a high efficiency (90%) photodiode. The amplified AC signals, proportional to the noise signals, are either subtracted or added by a RF +/- power combiner to measure the shot-noise (in the difference position) and the intensity noise (in the sum position). We have then sent the laser beam through a high resolution monochromator (Jobin-Yvon HR1000) which allowed us to clearly separate the different modes. We have measured the noise both before and after the spectrometer.

3 Intensity squeezing

Intensity squeezing in the laser diodes was obtained by using constant current supply and line-narrowing techniques, either cavity extension with an external grating, or injection-locking with another laser.

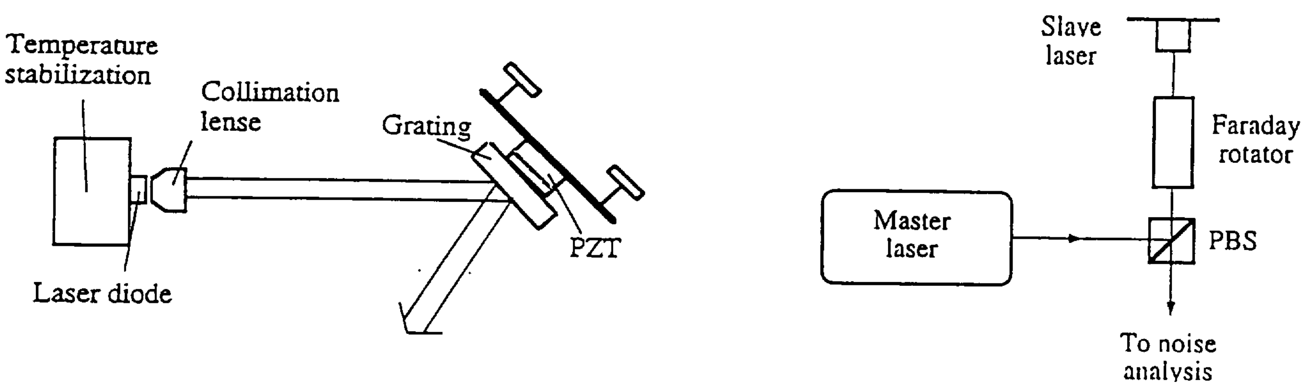

Figure 1: (a) external grating stabilization scheme; (b) injection locking scheme

The extended-cavity laser diode is shown in Fig. 1. The beam going out of the laser diode is collimated with a $f = 8$ mm objective placed in front of the output facet of the diode. The cavity is extended to 10 cm with a reflection holographic grating reflecting the first order into the cavity, while the 0 order goes out of the cavity (Littrow configuration). The efficiency of the grating is 60% in the 0 order (output coupling) and 24% in the first order (feedback to the laser), with 16% losses. The alignment of the grating is critical. When it is achieved, the threshold of the laser is lowered from 18 to 13 mA and the DC power of the side modes goes down to -60 dB below the DC power of the main mode, while the total intensity noise is decreased below the shot-noise level.

The injection-locking scheme is depicted in Fig. 1(b). The master laser is either an external-grating diode laser or a Ti:Sapphire laser. It is injected into the slave laser by means of an optical isolator. The master beam enters through the escape port of the polarizer placed after the Faraday rotator. Locking is observed on a rather broad power range of the master laser, from 1 to 4 mW.

We have investigated intensity squeezing in the two cases described above. Noise spectra were recorded for various supply currents. Squeezing was observed for currents higher than 50 mA ($I/I_{th} = 2.8$) for the injected laser and 30 mA ($I/I_{th} = 2.4$) for the extended cavity laser, at noise frequencies from 1 to 30 MHz (limited by our detection bandwidth). The noise, measured with a resolution bandwidth of 1 MHz, was nearly constant from 7 MHz to 30 MHz.

The optimum squeezing was observed in the injection-locking scheme. At 7 MHz, with a driving current of 130 mA, we obtained a noise reduction of 27%, i.e. 1.4 dB. Taking into account the total detection quantum efficiency of 65% from the laser output power to the photodiode current (through the optical isolator), we infer a value of 2.3 dB at the output of the laser diode.

The best squeezing obtained with the grating-extended cavity is 25% (1.2 dB) at 30 MHz and 110 mA, from which we infer a 1.6 dB noise reduction at the output of the grating. The fact that the squeezing is better with the injection-locking scheme can be attributed to the large losses due to the grating.

These numbers are similar to those of refs. [7, 8]. They are below the theoretical maxima expected from the quantum efficiency of the laser, which are respectively of 58% (3.8 dB) at 130 mA for the injected laser and 42% (2.4 dB) at 110 mA for the grating-extended cavity. Actually, the ratio between the intensity squeezing and the current-to-current efficiency goes towards a maximum asymptotical value of 0.75, instead of the expected unity value. The authors quoted above obtained comparable values for this ratio. This non-unity value can be attributed to additional noise sources in the semiconductor devices which are not included in the simple theoretical prediction mentionned above.

4 Intermode correlation

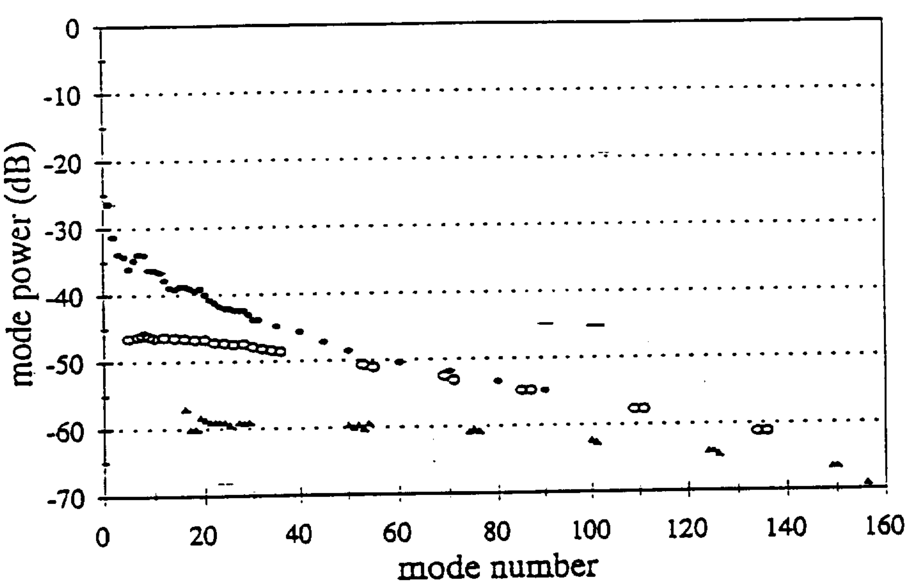

Figure 2: Power of individual longitudinal modes for a driving current of 80 mA. On the x-axis each mode is labelled by a number, the number 0 corresponding to the main mode. (• : free-running laser. o : injection-locked laser. ▲ : extended cavity laser).

The free-running laser diodes apparently operates on a single mode. However, the longitudinal side modes have a non negligible power, the closest ones being only -10 to -25 dB below the main mode (Fig. 2). 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.

As far as the noise of the individual modes is concerned, 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 is only 2 dB above SNL. The intensity noise of the sidemodes is then expected to be comparable to the intensity noise of the main mode despite their much weaker power. To check this assumption, we compared the noise of the main mode alone to the noise of the main mode plus two side modes, four side modes, etc. For this measurement, the output slit of the spectrometer was kept centered on the main mode, and was progressively opened. Figure 3 shows that the intensity noise decreases, with steps corresponding to the point where symmetrical side modes enter the detector. This clearly demonstrates that the observed total intensity fluctuations results 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.

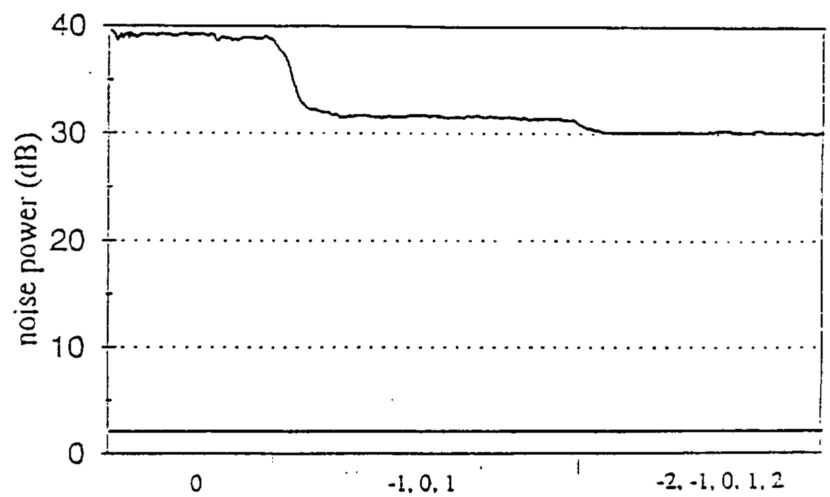

Figure 3: Intensity noise of the free-running laser diode, referred to the shot noise, as the output slit is opened. In the first section, only the main mode is detected, while the two steps correspond to the entrance of the two couples of side modes (-1,1) and (-2,2). The straight line at 2 dB shows the total intensity noise level (measured before the spectrometer).

As can be seen from Fig. 2, the power of the first side modes of the injection-locked laser is reduced down to less than -45 dB 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 SNL (see [10]), while the intensity noise of the main mode alone is still well above the quantum limit. The total intensity noise of the injection-locked laser again results from a cancellation effect among anticorrelated fluctuations of the main and side modes. 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, 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. 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.

Acknowlegments. This research was carried out in the framework of the ESPRIT Basic Research Project 6934 QUINTEC, and of the HCM network "Non-Classical Light" (ERB CHRX CT93 0114). Two of us aknowledge the support of fellowships : A.B. was supported by the HCM program from the European Community (ERB CHBG CT93 0437), and T.C.Z. was supported by a Programme International de Coopération scientifique (PICS) sponsored by the CNRS.

References

[1] Yu. M. Golubev, I.V. Sokolov, Zh. Eksp. Teor. Phys, **87**, 804, (1984) (Sov. Phys. JETP **60**, 234 (1984)).

[2] Y. Yamamoto, S. Machida, and O. Nilsson, Phys. Rev. A **34**, 4025 (1986).

[3] See for example, J.-C. Bouley and G. Destefanis, IEEE Comm. Magazine **32**, 54 (1994).

[4] C.E. Wieman and L. Hollberg, Rev. Sci. Instrum. **62**, 1 (1991).

[5] S. Machida, Y. Yamamoto, and Y Itaya, Phys. Rev. Lett. **58**, 1000 (1987).

[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] 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).

[11] H.P. Yuen and V.W.S. Chan, Opt. Lett. **8**, 177 (1983)