Low frequency noise of a 980 nm InGaAs/GaAs strained quantum well laser

B. Orsal, J. Peransin, P. Signoret, K. Daulasim

► To cite this version:

B. Orsal, J. Peransin, P. Signoret, K. Daulasim. Low frequency noise of a 980 nm InGaAs/GaAs strained quantum well laser. Journal de Physique III, 1993, 3 (9), pp.1739-1749. 10.1051/jp3:1993234 . jpa-00249035

HAL Id: jpa-00249035

<https://hal.science/jpa-00249035>

Submitted on 1 Jan 1993

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Classification
Physics Abstracts
42.55P

Low frequency noise of a 980 nm InGaAs/GaAs strained quantum well laser

B. Orsal, J. M. Peransin, P. Signoret and K. Daulasim

Centre d'Electronique de Montpellier, CEM (CNRS URA 391), Université Montpellier II, Sciences et Techniques du Languedoc, 34 095 Montpellier Cedex, France

(Received 10 November 1992, revised 1 April 1993, accepted 8 April 1993)

Abstract. — The longitudinal mode hopping and the related terminal electrical noise in InGaAs/GaAs ridge single quantum well (SQW) lasers are investigated. It is found that electrical mode hopping has a Lorentzian dependence. The correlation with the optical noise is experimentally shown in the low-medium frequency range. Measurements of this electrical-optical correlation give a high value of this parameter ($0.8 \leq \gamma^2 \leq 0.9$) when the longitudinal mode hopping is present.

Introduction.

Several kinds of noise are generated in semiconductor lasers, because of the wideband response characteristics of carrier density fluctuations. $1/f$ noise, mode hopping noise or mode partition noise are troublesome : these kinds of noise impede attempts to improve optical coherence.

Many studies have been made in order to introduce the terminal electrical noise (TEN) as a mean of *in situ* characterization of laser diodes, in the high frequency range (10^8 Hz- 10^{10} Hz) [1]. Since the measurements are made without any optical components, undesired optical feedbacks are suppressed. The aim of our work is to confirm the correlation between electrical noise signature and optical power noise of strained quantum well lasers, in order to control the *in situ* characterization of these laser diodes, by the low frequency TEN (1 Hz-10 MHz).

1. Laser structure.

The device used in this work is a 980 nm ridge structure Quantum well (QW) laser grown on a GaAs substrate (Fig. 1). This laser, elaborated by Metal Organic Vapour Phase Epitaxy (MOVPE) method, consists of a strained single quantum well $\text{Ga}_{0.76}\text{In}_{0.24}\text{As}$ as material in a conventional double heterostructure. There are two confining regions the gap of which varies linearly with the composition in aluminium. The width of the ridge is 3 μm .

The strained QW laser diode was aged at 80 °C in the automatic current control (ACC) mode during 200 h. Current values were set in order to get an initial output power of 30 mW.

Fig. 1. — Schematic diagram of a 980 nm InGaAs/GaAs strained Quantum Well laser.

2. Static characteristics.

The $I_{ph}(I_L)$ characteristic recorded after 200 h of ageing is shown in figure 2. I_{ph} is the photocurrent detected by the internal control photodiode. This photodiode is not biased in order to eliminate the $1/f$ noise it generates. I_L indicates the laser current.

On the $I_{ph}(I_L)$ curve, we see the three usual regions of the static characteristic of a laser diode :

- the linear zone where the optical power increases very slowly with the laser current : area of spontaneous emission ;
- the « elbow », just below threshold ($I_L = I_{th}$) ≈ 10 mA : super-radiative zone ;
- and the linear part above threshold, where the photocurrent increases very quickly : stimulated emission.

Fig. 2. — First order characteristic of the strained QW laser, after 200 h ageing : photocurrent I_{ph} versus laser current I_L .

But here we have to notice different break-points in the third part of this characteristic, it is not continuously linear. This phenomenon can be explained by the mode hopping behaviour : we shall come back on it in the next part.

In figure 3, the $P_{\text{opt}}(I_L)$ characteristic is shown. The optical power P_{opt} emitted by the laser is deduced from the photocurrent I_{ph} by the usual relation :

$$P_{\text{opt}} = \frac{I_{\text{ph}}}{\sigma} \quad (1)$$

where σ is the apparent sensitivity of the photodetector. Here $\sigma = 0.027 \text{ A/W}$.

Optical spectra of the laser are given in inserts in figure 3, for three different values of I_L : 13, 30 and 50 mA.

Fig. 3. — First-order characteristics of one strained QW laser : optical power *versus* laser current.

3. Low-medium frequency noise measurements.

In addition to this first order characterization, low frequency noise measurements have been performed on this device. We studied experimentally for the first time, in the low and medium frequency range ($1 \text{ Hz} < f < 10 \text{ MHz}$), the electrical noise of a strained QW laser during ageing. This was intended to provide additional data in order to specify and characterize the semiconductor lasers, for instance using electrical noise to qualify the noise behaviour of laser diodes [2].

On one hand, the total electrical noise is due to the fluctuations of the laser voltage $V_d(t)$ and is given by the voltage noise spectral density $S_{V_d}(\text{V}^2/\text{Hz})$. On the other hand, the optical noise is due to the fluctuations of the optical power P_{opt} of the laser. It appears as fluctuations of the detected photocurrent $I_{\text{ph}}(t)$ and is given by the photocurrent spectral noise density $S_{I_{\text{ph}}}(\text{A}^2/\text{Hz})$ [2] :

$$S_{I_{\text{ph}}}(\text{A}^2/\text{Hz}) = \sigma^2 S_{P_{\text{opt}}}(\text{W}^2/\text{Hz}) . \quad (2)$$

3.1 EXPERIMENTAL SET-UP. — In order to analyse the noise behaviour of the laser, we developed the experimental set-up shown in figure 4. In the first channel we measure S_{V_d} using a voltage amplifier, connected in parallel with the laser diode. With the second channel, we measure I_{ph} and $S_{I_{\text{ph}}}$ by means of a standard InGaAs PIN photodiode, *via* the DC and AC outputs respectively. Possible optical feedback is suppressed by an optical isolator.

Fig. 4. — Experimental set-up.

3.2 EXPERIMENTAL RESULTS. — The shape of the power spectral density of the electrical voltage noise at 20 °C and for a laser current I_L equal to 30 mA, can be approximated as Lorentzian [3] (Fig. 5). This fact is due to the *hopping noise*, which is attributed to the suppression of one mode when an other mode starts lasing. The insert shows time dependence of voltage and optical noises, given by $V_d(t)$ and $I_{ph}(t)$ respectively.

Fig. 5. — Spectral density of the electrical voltage noise : $S_{v_d}(f)$.

Furthermore longitudinal mode hopping is associated with output power fluctuations [1] and an excess noise both in the optical intensity noise and in the electrical noise [3]. It is attributed to the suppression of one mode by the decrease in carrier density because it is spent lasing by the other mode. This phenomenon is controlled by the randomly generated spontaneous emission that works as the triggering force for bringing one mode to lase. Intensity fluctuations follow the statistics of a Poisson process [3]. This fact introduces excess noise sources which can be detected by electrical and optical noise measurements [11].

In figures 6a and 6b both electrical and optical noises are given *versus* the laser current I_L .

First, comparing these figures with $I_{ph}(I_L)$ characteristic (Fig. 2), we can notice that the non linearities in the static characteristic correspond with the peaks in both electrical and optical noise curves. The same behaviour has been observed by Yoshikuni *et al.* on the optical noise [12].

Secondly figures 6 show that the electrical noise is *strongly correlated* to the optical noise. The fine structure observed at high polarizations in the behaviour of both noise sources can be explained by the hopping-noise phenomenon (see Fig. 5).

Fig. 6. — a) Electrical voltage noise of the strained QW laser versus laser current I_L . $T = 20^\circ\text{C}$, $I_{th} = 11.5$ mA. b) Optical noise of the strained QW laser versus laser current I_L . $T = 20^\circ\text{C}$, $I_{th} = 11.5$ mA.

3.3 MODE HOPPING PHENOMENON. — Mode hopping follows the stochastics of a Poisson process as was pointed out by Ohtsu *et al.* and the spectral density of power fluctuations exhibits a Lorentzian profile [3]. This model is based on the rate equations for the amplitudes of the electric field of the two neighbour modes (E_i ; $i = 1, 2$) and for the carrier density $n(t)$ in the active layer of the laser cavity. As computed by Ohtsu *et al.* [3], these equations are derived from the density matrix formulation and details of these equations are calculated by using the materials constants of the semi-conductor laser.

Noise terms are added to the rate equations for E_i to represent the contributions from spontaneous emission fluctuations, which work as random trigerring forces for mode hopping. In the opposite of the Ohtsu's assumption, we can not assumed the carrier density fluctuations are negligible because the Terminal Electrical Noise (T.E.N.), due to fluctuations (Δn) of the carrier number $n(t)$, is very strong and is correlated to the optical noise (see Figs. 5 and 6a, 6b).

In our case, if we consider thermal and $1/f$ noises of series resistance, S_{vd} can be written as : [1, 2, 5]

$$S_{vd}(F) = 4 KTR_S + \frac{\alpha}{fN} I_L^2 R_S^2 + \left(M \frac{kT}{q} \right)^2 \left\langle \frac{|\Delta n(F)|^2}{n_0^2 \Delta f} \right\rangle \quad (3)$$

$$M = 2 + \frac{n_0}{2 \sqrt{2} \text{Vol}} \left(\frac{1}{N_v} + \frac{1}{N_c} \right)$$

where N_c , N_v are the effective conduction and valence band densities, k is the Boltzmann's constant, T is the absolute temperature, n_0 is the steady state carrier number, $\Delta n(f)$ is the fluctuation of carrier density, Vol is the volume of the active layer and R_s is the series resistance. The first term gives the thermal noise due to the series resistance R_s , the second gives the $1/f$ noise source related to mean value of laser current I_L , α is the Hooge parameter, N the mean number of carriers which flow through the ohmic layers.

We can see that the electrical noise is not negligible, it is not constant (see Fig. 6a). It depends on the laser current I_L . It is tightly correlated to the optical noise (Fig. 6b).

Thus the equations to be solved for the following discussions are the rate equations for E_i and $n(t)$, with the noise terms due to spontaneous emission.

In this formulation, it is interpreted that the *occurrences* of mode hopping are caused by fluctuation of spontaneous emission and by non linear mode coupling due to the spectral hole burning induced by intraband relaxation of the carrier in the conduction band [3].

The mean value of this relaxation time τ_{in} has been reported as about : $10^{-13} \text{ s} \leq \tau_{in} \leq 4 \times 10^{-13} \text{ s}$.

By normalizing the rate equations for E_i , a set of non linear Langevin equations can be derived, which is expressed as [3, 8] :

$$\frac{dE_i}{d\tau} = (a_i - |E_i|^2 - \xi |E_j|^2) E_i + q_i(\tau) \quad (i, j = 1, 2; i \neq j) \quad (4)$$

where E_i is the normalized amplitude of the electric field of the i -th mode and τ is the normalized time. The quantity a_i is the pump parameter corresponding to the stationary mode power, normalized to the rms value of the power fluctuations of spontaneous emission. Therefore, the pump parameter a_i is proportional to the small signal gain and depends on the bias level and temperature. The quantity ξ represents the mode coupling constant between the modes and is expressed as

$$\xi = \frac{4}{3 \left[1 + 2 \pi c \tau_{in} \frac{\Delta \lambda}{\lambda^2} \right]^2} \quad (5)$$

where c is the speed of light, λ is the wavelength and $\Delta \lambda$ is the wavelength separation between the two modes [9].

Substitution of $\Delta \lambda = 0.79 \text{ nm}$, $\lambda = 783 \text{ nm}$, and $\tau_{in} = 0.2 \text{ ps}$ into this equation gives a value of the mode coupling constant ξ of 1.08, which is larger than unity and represents a strong coupling between the two modes [9, 11, 12].

The quantities $q_i(\tau)$ ($i = 1, 2$) are Langevin noise terms which represents the fluctuations of spontaneous emission. They are supposed to be delta-correlated Gaussian random processes with zero mean and

$$\langle q_i^*(\tau) \cdot q_j(\tau') \rangle = 4 \cdot \delta_{ij} \cdot \delta(\tau - \tau') \quad (i, j = 1, 2) \quad (6)$$

where* means the complex conjugate, δ_{ij} is the Kronecker delta, and $\delta(\tau - \tau')$ is the delta function. If $\xi < \frac{a_1}{a_2}$ a set of Langevin equations given by (4) has a set of stationary stable solutions of $(|E_1|^2, |E_2|^2) = (a_1, 0)$ and the two mode powers fluctuate around these values by fluctuations of spontaneous emission.

These power fluctuations correspond to the mode partition phenomenon.

If $\frac{1}{\xi} < \frac{a_1}{a_2} < \xi$, on the other hand, these equations have two sets of stationary stable solutions, i.e. $(a_1, 0)$ and $(0, a_2)$. Fluctuations of spontaneous emission drive the two mode powers from one of the solutions to the other at random points in time. Each mode power therefore tends to jump randomly between zero and non zero values, which corresponds to the mode hopping phenomenon. Both of the phenomena can therefore be described by these equations if the values of the pump parameters are appropriately adjusted. In the experiments, these adjustments are performed by changing the bias level and the temperature.

4. Interpretation.

All these results could be explained by using the noise equivalent circuit of a semi-conductor mono- or multi-mode laser diode, derived by the rate equation taking into account Mc Cumber's, Harder's and Andrekson's theories and also by using the coherence function $\gamma_{I_{ph} - I_d}^2$ between photocurrent and electrical noises [1, 2, 5, 6].

The rate equations for a laser emitting into m longitudinal modes are [5, 7, 9] :

$$\frac{dn_k}{dt} = \frac{i}{q} - \frac{n}{\tau_s} - \sum_{k=1}^m g_k s_k + f_n(t) \quad 1 \leq k \leq m \quad (7)$$

$$\frac{ds_k}{dt} = g_k s_k + \gamma_k \frac{n}{\tau_s} - \frac{s_k}{\tau_{ph}} + f_{s_k}(t) \quad (8)$$

here n is the carrier number in the gain medium and s_k is the photon number in the lasing mode. $k \cdot \frac{i}{q}$ is the pump term. τ_s is the carrier lifetime and τ_{ph} is the photon lifetime. γ_k is the spontaneous emission factor in the k mode.

Langevin noise source term due to emission and absorption of photons is $f_{s_k}(t)$ and Langevin noise source term due to the carrier generation and recombination (spontaneous and stimulated emissions) is $f_n(t)$.

Each mode contributes a parallel branch to the circuit with a current I_{Lk} corresponding to the k mode [2, 4, 5, 7] (see Fig. 7).

The gain of the k -th mode is taken as [7, 8] :

$$g_k = g_{0k} + A_k n_{l_k} \quad (9)$$

The intensity fluctuations of different modes are negatively correlated because the different modes are competing for gain from the electron « tank » [9]. This so-called competition noise significantly reduces the signal to noise ratio in communication systems.

Fig. 7. — Noise equivalent circuit of a multimode laser.

Our results clearly show the expected correlation between the electrical noise and the optical noise, particularly at the onset of stimulated emission.

5. Electrical-optical coherence function of strained QW lasers.

The coherence $\gamma_{vp}^2(f)$ between the voltage noise $S_{V_d}(f)$ (V^2/Hz) and optical noise $S_p(f)$ in (W^2/Hz) is given by :

$$\gamma^2(f) = \frac{|S_{vp}(f)|^2}{S_{V_d}(f) \cdot S_p(f)} \quad (10)$$

where $S_{V_d}(V^2/\text{Hz})$ is the spectrum density of total voltage noise of the laser diode, $S_p(W^2/\text{Hz})$ is the spectral density of light output power noise, $S_{vp}(VW/\text{Hz})$ is the cross spectral density between power noise and electrical noise. If we consider the relation (2), equation (10) can be also written as :

$$\gamma_{I_{ph}-I_d}^2 = \frac{|S_{I_{ph}-I_d}(f)|^2}{S_{I_{ph}}(f) \cdot S_{V_d}(f)} \quad (11)$$

where $S_{I_{ph}-I_d}(f)$ is the cross spectrum between photocurrent noise and electrical noise.

In figures 8 we give the coherence function $\gamma_{I_{ph}-I_d}^2$ of the strained QW laser *versus* the normalized laser current I_L/I_{th} at low and medium frequency ($f = 10 \text{ Hz}$, 100 kHz). Under threshold, electrical and optical noises are strongly correlated : about 80 %. We can think that the $1/f$ noise fluctuations highly depend on the spontaneous emission [10]. During the transition from the spontaneous emission to the stimulated emission, we observe a decrease of the coherence which is due to the fast decreasing of the electrical noise $S_{V_d}(I_L)$ at the threshold. Just above the threshold, the γ^2 coherence reaches its maximum (around 90 %) which can be explained by the very fast increasing of electrical and optical noises. This fact is due to mode hopping phenomenon which generates a very high noise-level (Figs. 6a and 6b). When the current become higher than 50 mA, hopping process disappears and the coherence function γ^2 decreases because optical and electrical noise sources are decorrelated.

Fig. 8. — a) Coherence of the strained QW laser, after 200 h ageing, $I_{th} = 11.5$ mA. b) Coherence of the strained QW laser, after 2 000 h ageing, $I_{th} = 15$ mA.

Conclusion.

The measurements of electrical and optical noises, in the low-medium frequency range (10 Hz-100 Hz), have shown the presence of mode hopping noise in the strained QW lasers studied. This presence is confirmed by the measurements of the electrical-optical coherence function, which is very high when the mode hopping phenomenon is present.

The experimental results displayed above confirm that it is possible, by means of TEN, to appraise the noise performances of lasers: TEN is used for *in situ* measurement and characterization of laser diodes, particularly during ageing process, without any optics and accompanying alignments [1, 2].

Acknowledgments.

The authors wish to thank Ms Dr I. Joindot and Mr Dr P. Devoldère from France Telecom (CNET, Lannion) France and Mr Dr M. Fukuda from N.T.T. Opto Electronics Laboratories, Japan. This work was supported by France Telecom (CNET, Lannion) under contract 908B059007909245 LAB/OCM/TOH.

References

- [1] Andrekson P. A., Andersson P., Alping A. and Eng S. T., In situ characterization of laser diodes from wideband electrical noise measurements, *IEEE J. Lightwave Technol.* **LT4**, N° 7 (1986).
- [2] Orsal B., Alabedra R., Signoret P. and Letellier H., InGaAsP/InP Distributed Feedback Lasers for long wavelength optical communication systems, $\lambda = 1.55 \mu\text{m}$: Electrical and Optical noises study, Proceeding of S.P.I.E., E.C.O.4, « Infrared Material and Devices », The Hague The Netherlands, vol. **1512A** (March 1991).
- [3] Ohtsu M. and Teramachi Y., Analyses of mode partition and mode hopping in semi-conductor lasers, *IEEE J. Quantum Electron.* **25** (1989) 31-38.
- [4] Signoret P., DEA Report, Study of semiconductor DFB lasers emitting at $\lambda = 1.5 \mu\text{m}$: Optical and Electrical Noise Measurements, University of Montpellier II (June 1990).
- [5] Harder C., Katz J., Margalit S., Schacham J. and Yariv A., Noise equivalent circuit of a semiconductor laser diode, *IEEE J. Quantum Electron.* **18** (1982) 333-337.
- [6] Mc Cumber, Intensity fluctuations in the output of C.W. laser oscillations, *Phys. Rev.* **141** (1966) 306-322.
- [7] Raniriharinosy K., Ph. D Thesis, Analysis of electrical and optical noise of semiconductor lasers emitting at the wavelength $\lambda = 0.8 \mu\text{m}$, University of Montpellier II, Sciences et Techniques du Languedoc (1988).
- [8] Orsal B., Raniriharinosy K., Alabedra R., Joindot I., Proc. 10th Int. Conf. on Noise in Physical Systems, Budapest, Hungary (1989) 159-166.
- [9] Joindot I., Ph. D Thesis, Relative intensity Noise of Semiconductor lasers, C.N.E.T. Lannion, University of Montpellier II, Sciences et Techniques du Languedoc (1990).
- [10] Fronen R. J., Wavelength dependence of $1/f$ Noise in the light output of laser diodes : an experimental study, *IEEE J. Quantum Electron.* **26** (1990) 1742-1746.
- [11] Andrekson P. A., Alping A., Electrical mode hopping noise in external cavity semiconductor lasers and mode hopping estimation by a non optical control loop, *IEEE J. Quantum Electron.* **23**, n 12 (1987).
- [12] Yoshikuni Y., Kawagushi H., Tetsuhiko I., Intensity Fluctuation of $1.5 \mu\text{m}$ InGaAs/InP D.F.B. involving the optical feedback effect, *IEE Proceedings* **132Pt J**, n 1 (1985).