Influence of spontaneous emission noise on the dynamics of an external cavity semiconductor laser

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Pumped close to threshold and subject to external optical feedback, the output of a semiconductor laser exhibits low frequency fluctuations. The main feature of this aperiodic behavior is a repetitive build-up of the laser intensity interspersed by sudden drops. While numerous numerical studies have shown the tremendous influence of spontaneous emission noise on this regime, I demonstrate the existence of large intervals of parameter numerical values for which spontaneous emission noise does not affect the laser dynamics.

Introduction

Subject to optical feedback, laser diodes can display complex dynamics such as deterministic chaos, which severely degrades their performances. As an example, when the diodes operate in the so-called coherence collapse regime, their linewidth increases up to several gigahertz. Pumped close to threshold and subject to a moderate amount of optical feedback, they operate in the low-frequency fluctuation regime [1]. In this regime, the laser output measured by a rather slow detector exhibits sudden drops, followed by progressive recoveries until it reaches a plateau and then drops again. The time interval between successive drops is aperiodic but can last from several tens of nanoseconds to several microseconds. This behavior is however the slow envelope of a much faster behavior: the lasers indeed emit trains of pulses. This behavior can be reproduced with a purely deterministic model [2], the Lang-Kobayashi equations [3], but the importance of the role of spontaneous emission noise has been a controversial subject in the past decades. According to several studies, the numerical models predict statistical distributions of the time interval between dropouts in a better agreement with experiments when noise is taken into account [4][5] although noise is not necessarily the cause of the low-frequency fluctuations; according to others studies, noise is the origin of the laser intensity dropouts [6][7].

In a recent experiment, Martinez Avila and coworkers [8] have tuned the current injected in a laser diode subject to optical feedback and operating in the LFF regime. They have found the existence of an optimal value of the injection current for which the slow dynamics was maximally ordered. They have reproduced similar results with the Lang and Kobayashi equations but without noise terms.

Since it is generally accepted that spontaneous emission noise has an important role whenever the laser diodes subject to optical feedback operate in the low frequency fluctuation regime, my motivation was to verify that the behavior reported by Martinez Avila and coworkers [8] could be still numerically reproduced when noise is taken into account in the simulations. I have not only observed that their experimental results can be numerically reproduced with a realistic noise level but also, and more importantly, that the laser dynamics remains unaffected on a statistical basis for their estimation of the laser parameters. The results that I present in the following are preliminary.

Equations

The behavior of a laser diode subject to optical feedback (see Fig. 1) is predicted by the Lang-Kobayashi equations [3] and, since we consider the role of spontaneous emission, Langevin noise forces are included, which yields

$$\frac{dE}{dt} = \frac{1+i\alpha}{2}\left[\frac{G_N(N-N_0)}{1+\varepsilon|E|^2} - \frac{1}{\tau_p}\right]E + \kappa E(t-\tau)\exp(-i\omega_0\tau) + F_E(t) \tag{1}$$

$$\frac{dN}{dt} = \frac{I}{e} - \frac{N}{\tau_s} - \frac{G_N(N-N_0)}{1+\varepsilon|E^2|}|E|^2. \tag{2}$$

$E(t)$ is the slowly varying complex electric field. $E(t)$ is normalized in such a way that $|E(t)|^2$ corresponds to the photon number inside the laser cavity. $N(t)$ is the electron-hole pair number and N_0 its value at transparency. G_N is the gain coefficient. ε accounts for the saturation of the gain. α is the linewidth enhancement factor. τ_p and τ_s are the photon lifetime and the carrier lifetime, respectively. κ is the feedback rate, τ the roundtrip time in the external cavity and $\omega_0\tau$ the feedback phase. I is the electrical current injected in the laser. The term $F_E(t)$ is a Langevin noise force accounting for spontaneous emission noise with $\langle F_E(t)F_{E^*}(t')\rangle = R_{sp}\,\delta(t-t')$ where R_{sp} is the spontaneous emission rate.

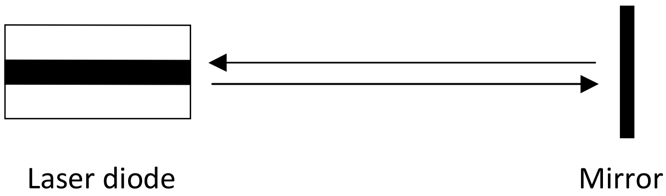

Fig. 1. Schematics of a laser diode subject to a conventional optical feedback: the light emitted by the laser is partially reflected by an external mirror and is then fed back into the laser with a delay.

Numerical results

The numerical values of the parameters are the same as in Ref. [1], the spontaneous emission rate excepted: $\kappa = 22$ ns^{-1}, $\tau = 6$ ns, $\omega_0\tau = 0$, $\varepsilon = 5 \times 10^{-7}$, $\alpha = 3.5$, $G_N = 3.2 \times 10^{-6}$, $N_0 = 1.5 \times 10^8$, $\tau_p = 3.55$ ps, $\tau_s = 0.60$ ns.

Figure 2 shows the behavior of the laser intensity when it is pumped with $I = 1.01 \times I_{th}$. The time trace has been averaged over several nanoseconds in order to mimic the effect of the limited bandwidth of a slow detector. After each drop, the intensity increases steadily and reaches a plateau until the next drop. Figure 3 presents the dependence of T, the mean time interval between successive drops, as a function of the electric current injected in the laser and for different values of the spontaneous emission rate, R_{sp}. We observe that T increases as the current decreases similarly to what has been reported in many studies (see for instance Ref. [4]). By contrast, T is barely modified by the spontaneous emission level, even for $R_{sp} = 10^{13}$ s^{-1}, which is a large value.

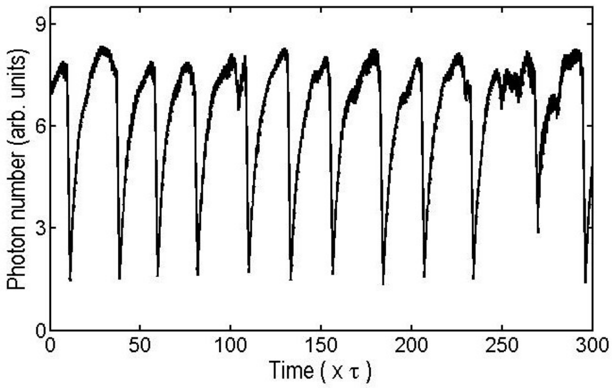

Fig. 2. Time trace of the output of the laser for $I = 1.01 \times I_{th}$. The time trace has been averaged to account for the finite bandwidth of a slow detector.

Following the authors of Ref. [8], the fluctuations of the time interval between successive drops can be characterized by the quantity R_T defined as $R_T = \sigma_T / \overline{T}$, the ratio between the standard deviation and the average of the time interval between successive drops. This quantity is commonly used in the study of coherence resonance [9]. It is minimal when the drops are the most regular. The dependence of R_T with respect to the injection current for different values of the spontaneous emission rate is presented in Fig. 4. In good agreement with Ref. [8], this quantity is the lowest in the range $1.01 \leq J/J_{th} \leq 1.02$ where the LFF drops occur the most regularly. Again, we can observe that, on a statistical basis and for a same injection current, the behavior of the laser is weakly modified for a spontaneous emission rate in the range $0 \leq R_{sp} \leq 10^{12}$ s^{-1}. For $R_{sp} = 10^{13}$ s^{-1}, R_T is larger but this is due to the difficulty to reliably detect the drops in the averaged time trace of the laser intensity: indeed, the noise level is so large that the LFF drops are almost indiscernible from the erratic fluctuations of the laser output.

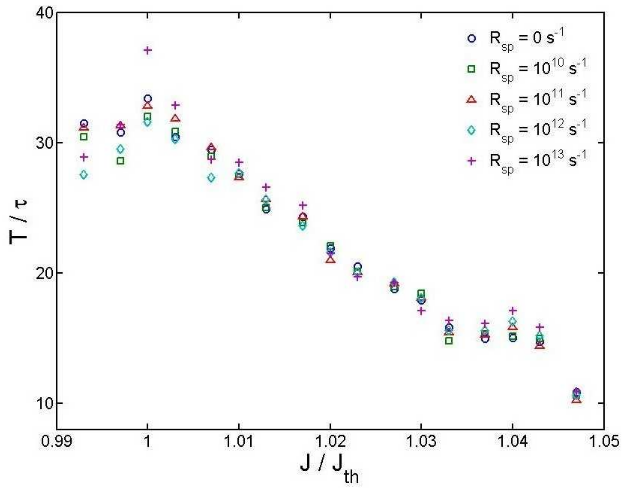

Fig. 3. Mean time interval between successive LFF drops as a function of the injection current and for different values of the spontaneous emission rate.

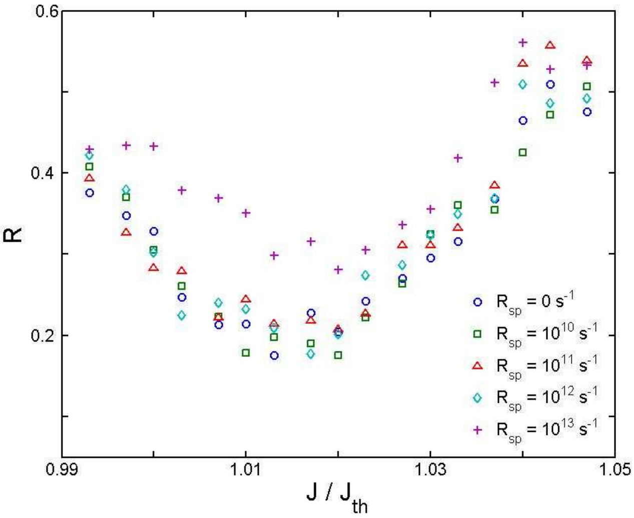

Fig. 4. Normalized standard deviation of the time interval between successive LFF drops as a function of the injection current and for different values of the spontaneous emission rate.

Conclusion

Martinez Avila and coworkers [8] have experimentally and numerically investigated the dynamics of a laser diode operating in the low frequency fluctuation regime. They have estimated the parameters of their laser. Using the same parameter values, my numerical simulations reveal that the mean time between successive intensity drops and its normalized standard deviation are barely modified when spontaneous emission noise is taken into account. This contrasts with the results of many numerical studies.

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