Diode lasers with optical feedback: statistics for low frequency fluctuations

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Abstract

The instabilities in semiconductor lasers produced by optical feedback are studied experimental and numerically. The diode laser used was a SDL-5401-G1 operating at near 850nm wavelenght. An external mirror at distances 0.5m and 5m gave the feedback. Time series of the laser output pulses are identifyed with chaotic dynamics reported in previous work in the recent literature. One regime observed was low frequency fluctuations (LFF) and the other the coherence collapse (CC). Maps of next minimum peak of the pulses were constructed, from the time series, and verified to be associated to deterministic chaos. The results are compared with the numerical solutions of the Lang-Kobayashi equations.

The dynamics of semiconductor lasers with optical feedback has been studied in depth since 1989 [1]. A diode laser with time delayed is an infinite dimensional dynamical system. It may potentially exhibit very rich dynamics and this complexity makes such systems very interesting for general studies of non linear dynamics [1, 2].

The basic experimental set-up configuration used is the one showed in fig. 1. The stability of the temperature of the laser support is better than 0.01^oC. A AR-coated collimator is placed at the laser output in order to reduce the beam divergence. A high reflectivity external mirror (90%) is placed at a distance from the laser in order to re-inject part of the light emitted, back into the laser cavity. This distance can be varied between 0.5m and 1.0m. The intensity-output is detected by a 1.5 GHz bandwith Si-PIN-S5973 photodiode. The signal is amplified with a 0.10-1.0 GHz bandwith amplifier and analyzed by a digital oscilloscope (300MHz bandwith). The laser is a SDL-5401-G1 whose active region is made of $GaAlAs$. The emission wavelength is around 850nm and the solitary laser threshold current, $I_{th,sol}$, is 16mA. Above this value the intensity of the diode laser without feedback is constant in time.

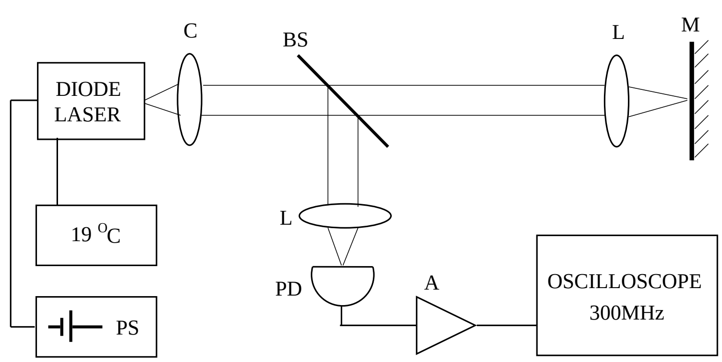

Figure 1: Experimental Set up: L lens, PS power supply, PD Photodiode, C collimating lens, BS beam splitter, M mirror, A amplifier.

The amount of feedback depends both on the tilt of the mirror and the collimation of the beam. The output intensity at different values of the pumping current becomes unstable depending on the amount of feedback. In our experiment we have always maintained alignment for which the reduction of the threshold current is maximized, the feedback level was moderately strong, showed by a threshold reduction of 9%.

For pumping current values close to the solitary laser threshold, the system is stable. For pump values exceeding the threshold of the solitary laser, the intensity as function of time shows trains of pulses of power drops, lasting tens of nanoseconds and separed by regions of higher averages intensity, as shows fig. 2 for a pump current of 25.5mA. The characteristic rate of such fluctuations (10-100MHz) is much smaller compared with the typical semiconductor laser rates (carrier and photon lifetime, relaxation oscillations), hence the name low frequency fluctuations (LFF) [3, 4, 5]. At higher injection currents, the frequency of pulsations increases as shown in fig. 2; the system entered the region of the so-called coherence collapse, at which the line width broadens up to hundreds of GHz [6].

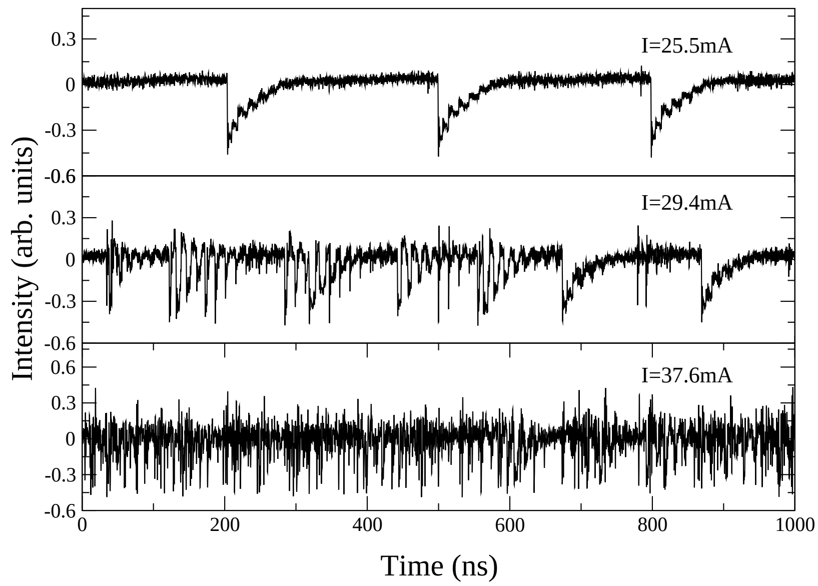

Figure 2: Experimental time series of the diode laser with optical feedback for different currents.

A detailed analysis is required in order to understand the mechanisms underlying the dynamics [5]. We analyze the LFF regime using statistical methods and special measurements like return maps. In fig. 3 we show the intensity, histogram of time between successive drops and return map of the signal of laser for a pump current of 23mA. The measurements were performed over data samples of more than 10^4 drop pulses. The return map shows a cloud of points without structure as we can expect from a system whose dynamics is controled by noise. Our measurement confirms the experimental results obtained in Ref. [5] for LFF regime.

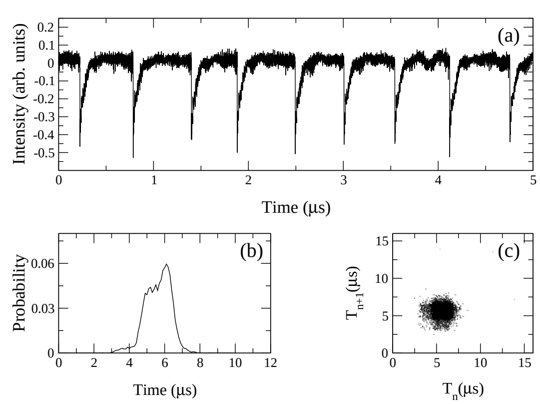

Figure 3: (a) Experimental time serie of the diode laser with optical feedback. (b) Histogram of time between dropouts. (c) Return map of the time intevals between successive drop pulses.

The theorical model usually used to describe the dynamics of semiconductor lasers with optical feedback is the one by Lang-Kobayashi [7]. This theorical aproach was originally developed for a single-mode semiconductor laser and weak feedback levels. The effect of optical feedback is included in its first approximation by means of the re-injection of the field itself with a time delay corresponding to an external-cavity round-trip. The Lang-Kobayashi equations read:

$$\frac{dE}{dt} = \frac{(1+i\alpha)}{2}\left[G - \frac{1}{\tau_p}\right]E + \kappa E\left(t-\tau\right)e^{-i\omega_o \tau} \tag{1}$$

$$\frac{dN(t)}{dt} = J - \frac{N}{\tau_s} - G(N)\left|E(t)\right|^2 \tag{2}$$

τ_s is the carrier lifetime, τ_p is the photon lifetime and ω_o is the solitary laser frequency. The optical gain is $G = G_N(N - N_o)/(1 + \epsilon E^2)$, where G_N is the modal gain, N_o the carrier density at transparency, and ϵ the gain saturation coefficient. α is the linewidth enhancement factor, J is the current density and κ is the feedback rate.

In fig. 4 we show the calculated time evolution of the light intensity using eqs. (1)-(2) for different currents J, also are shown the histograms of the time between dropouts and respective return maps. The parameters fixed are $\alpha = 3.5$, $\tau = 6ns$, $1/\tau_p = 282ns^{-1}$, $1/\tau_s = 1.66ns^{-1}$, ϵ=5x10^{-7}. One may observe that the frequency of the fluctuations increases as the current is increased [fig. 4], confirming the experimental results obtained in fig. 2.

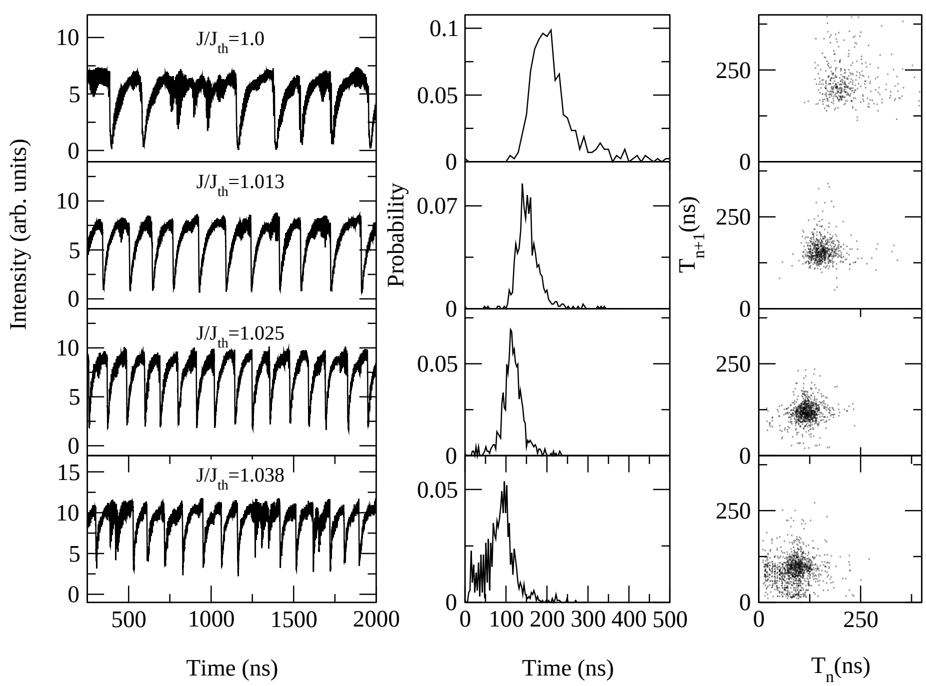

Figure 4: Calculated time evolution of the light intensity under external feedback conditions according to Eqs. (1)-(2), for different currents, with κ=22ns^{-1}. Also are shown the histograms of time between dropouts and respective return maps. The ploted intensity values have been numerically short time averaged (1ns) to simulate the experimental bandpass detection.

The histograms allow us to measure the average time ($< T >$) between pulses as a function of the current [fig. 5(a)]. Our measurement confirms the experimental results obtained in Ref. [8]. The fig. 5(b) shows the mean dropout time interval as a function of the feedback rate. It shows an increase of the average period as the feedback rate increases. To our knowledge this analysis has not been performed elsewhere.

Although the Lang Kobayashi equations were originally derived for a single mode and low feedback rate, the results here presented show that this model gives results semi-quantitatively similar to experimental behavior observed in a moderate feedback system with multi-mode operation.

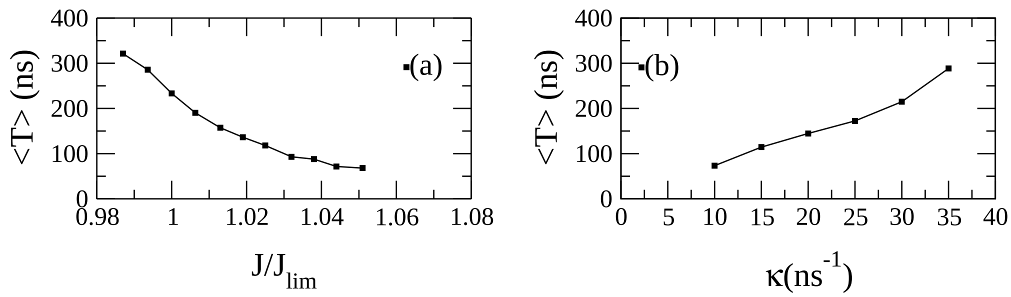

Figure 5: (a) Calculated mean dropout time interval as a function of the current, with κ=22ns^{-1}. (b) Mean dropout time interval as a function of the feedback rate κ, with J/J_{th}=1.013. The lines are just to aid visualization.

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