VCSEL with polarized optical feedback: Experiment and model

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Abstract

We investigated a vertical-cavity surface-emitting laser (VCSEL) with polarized optical feedback. We found both experimentally and numerically that the system presents single-mode low-frequency fluctuations for a wide range of pump current. We also show that the polarized optical feedback defines a predominant polarization mode on the VCSEL. The model developed by Loiko et al. [1] that is an extension of the Spin-Flip model explains well part of the experimental observations.

Introduction

Optical feedback has attracted a lot of attention in the past as it is a source to observe the rich dynamics of semiconductor lasers. In particular, peculiar phenomena known as low frequency fluctuations (LFF) have been demonstrated. LFF consist of abrupt dropouts in power followed by a slow recovery. As emphasized in [2], LFF are very interesting from a physical point of view because of the different time scales involved.

In our work we chose a VCSEL instead of an edge-emitter laser (EEL) to get rid of the multimode dynamics appearing in EELs. Actually, VCSELs allow us to use a simple theoretical model, and therefore reduce the complexity of studying LFF.

It is well known that VCSELs emit linearly polarized light. Still, due to their geometry, VCSELs have an important drawback, the polarization of the emitted light is randomly selected between two orthogonal preferred orientations. For this reason, they are very sensitive to polarization instabilities.

There have been previous studies on VCSELs with isotropic optical feedback [3] [4], reporting anticorrelated LFF events in the two polarization modes (PM). Here, we want to go further into the LFF dynamics and we polarize the optical feedback favoring one of the two PMs, i.e. we define a predominant PM. Our experimental system presents clear single-mode LFF dynamics.

Experimental results [2]

In the experimental set-up, polarized optical feedback is applied to the VCSEL, i. e. the light emitted by the VCSEL is backreflected on a mirror and polarized before going back into the laser cavity, having a length of the external cavity $\sim$ 50 cm. As a result it is found that the VCSEL emits light in the same polarization direction as the incoming polarized feedback. This is due to the fact that the strength of the feedback compensates the weak

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anisotropies in the VCSEL. With such a configuration we get a 10 % threshold reduction and the first LFF events appear just above the reduced threshold.

In fig. 1 we show a typical trace of the experimental data, both in time and frequency domain. As can be seen from the left graph (fig. 1), the time series shows sudden power drop-outs and a slow recovery until the next drop-out. These phenomena are called LFF because of their similarities with the low frequency dynamics that have been already observed in other semiconductor lasers.

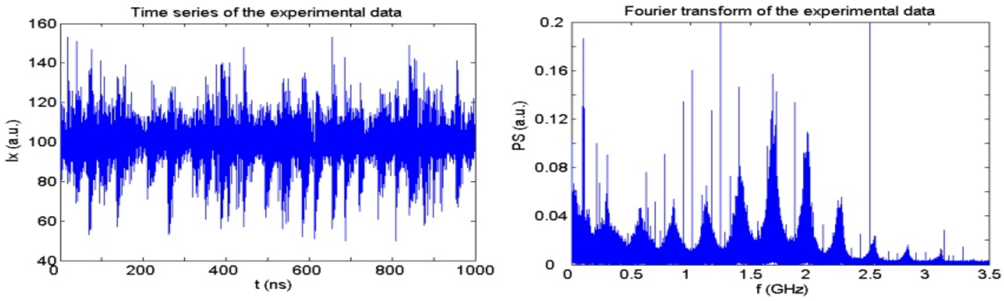

Figure 1: Time series of the experimental data and its corresponding numerical Fourier transform. The VCSEL is biased above the solitary laser threshold ($I \sim 3.6mA$; $I_{th} \sim 3.0mA$).

A Fourier transform of the experimental time series is shown in the right graph of fig. 1. The frequency peaks are separated by the inverse of the external cavity round-trip time ($\sim$ 300 MHz) and can clearly be seen a low frequency component corresponding to the LFF dynamics. Finally, we want to stress that the cut-off frequency of the photodiode ($\sim$ 2 GHz) limits the bandwidth of our experimental measurements and therefore part of the information is lost, as can also be seen in the spectrum.

Theoretical model

The theoretical model published by Loiko et al. [1] is an extension of the Spin-Flip model [5]. Actually, the polarized filtered feedback is added into one of the two typical linearly polarized modes of a VCSEL following the Lang-Kobayashi approach [6], which means that multiple reflections on the external cavity are neglected. The equations then read:

$$\frac{\mathrm{d}E_x}{\mathrm{d}t} = \{[\kappa(N-1)-\gamma_a]+i[\kappa\alpha(N-1)-\gamma_p]\}E_x+\kappa(i-\alpha)nE_y+fe^{-i\omega\tau}E_x(t-\tau) \quad (1)$$

$$\frac{\mathrm{d}E_y}{\mathrm{d}t} = \{[\kappa(N-1)+\gamma_a]+i[\kappa\alpha(N-1)+\gamma_p]\}E_y-\kappa(i-\alpha)nE_x \quad (2)$$

$$\frac{\mathrm{d}N}{\mathrm{d}t} = -N(1+|E_x|^2+|E_y|^2)+\mu-in(E_yE_x^*-E_xE_y^*) \quad (3)$$

$$\frac{\mathrm{d}n}{\mathrm{d}t} = -n(\gamma_s+|E_x|^2+|E_y|^2)-iN(E_yE_x^*-E_xE_y^*) \quad (4)$$

where $E_{x,y}$ are the two linear components of the electric field. N denotes the total carrier population and n is the carrier difference between the two spin channels. μ is the injected current normalized to threshold. The optical field decay rate is κ, α is the linewidth enhancement factor, γ_s is the spin-flip rate, and the linear anisotropies are γ_a (dichroism) and γ_p (birefringence). The feedback parameters are the feedback rate f and the external cavity roundtrip time τ. ω is the solitary laser frequency. The parameters κ, γ_p, γ_a, γ_s and f are normalized to the carrier decay rate γ ($\sim 1ns^{-1}$), while t and the delay time τ are normalized to γ^{-1}.

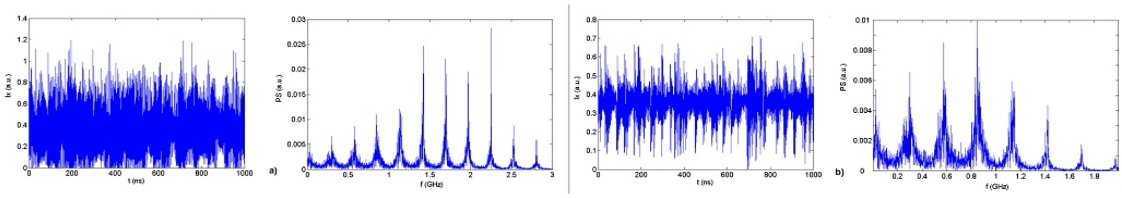

Figure 2: Time series of the numerical data and its corresponding numerical Fourier transform filtered with a butterworth filter order 5. a) Cut-off frequency 2 GHz b) Cut-off frequency 1 GHz Parameters: $\mu = 1.2$, $f = 30$, $\tau = 3.55ns$, $\kappa = 300ns^{-1}$, $\alpha = 3$, $\gamma_a = 0.5ns^{-1}$, $\gamma_p = 9.4ns^{-1}$, $\gamma_s = 50ns^{-1}$.

In fig. 2, we present two examples of the numerical data in time and frequency domain where we show the effect of applying a filter to the original data. Remember that the experimental measurements are limited in bandwidth.

Linearly polarized solutions

Since we choose the x-mode to be lasing we are interested in the x-polarized solutions, which are given by:

$$E_y = 0 \qquad e_x^2 = \frac{\mu}{N}_x - 1 \qquad \Gamma_a = \gamma_a - f cos\theta_x$$
$$E_x = e_x e^{i\varphi_x} \qquad \frac{d\varphi_x}{dt} = \alpha\Gamma_a - \Gamma_p \qquad \Gamma_p = \gamma_p + f sin\theta_x$$
$$N_x = 1 + \frac{\Gamma_a}{k} \qquad \theta_x = (\frac{d\varphi_x}{dt} + \omega)\tau$$
$$n = 0$$

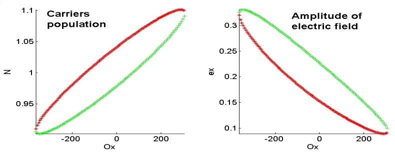

Figure 3: Linearly polarized solutions. Same parameters of fig. 2

For sufficiently large values of feedback there are several different steady state solutions (corresponding to modes of the external cavity). New steady state solutions are created in pairs for increasing feedback level, defining an ellipse in the (θ_x,N) plane. The anti-modes correspond to destructive interference between the field inside the laser and the feedback field and are always unstable (see fig. 3, dark dots) while the so-called external cavity modes corresponds to constructive interference and can be stable (see fig. 3, light dots).

Comparison

To compare the experimental and the numerical results, we compute the normalized autocorrelation functions. In such a manner, a graphical method to compare the results from a statistical point of view is obtained (see fig. 4).

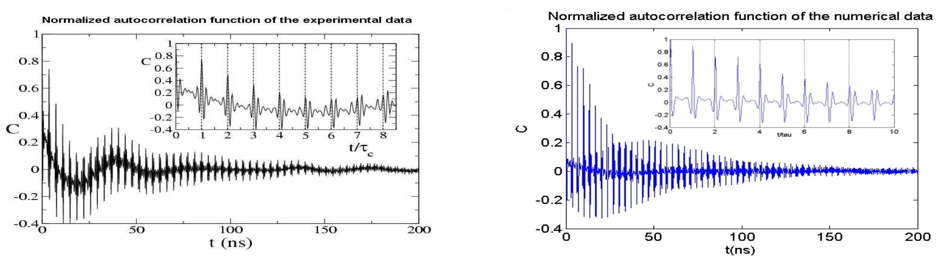

Figure 4: Normalized autocorrelation functions of the experimental data ($I = 3.18mA \Rightarrow \mu = 1.06$) and numerical data (Parameters: $\mu = 1.002$, $f = 20$, $\tau = 3.3ns$, $\kappa = 300ns^{-1}$, $\alpha = 4$, $\gamma_a = 1.5ns^{-1}$, $\gamma_p = 9.4ns^{-1}$, $\gamma_s = 50ns^{-1}$). A zoom of the first external roundtrips is shown in the insets

The left graph shows the autocorrelation of the experimental data, while the one of the numerical data is shown in the right graph. A slow modulation on the envelope of the autocorrelations corresponding to the LFF dynamics ($T \sim 40ns$) can clearly be seen in

the left graph while it is not so clear in the graph corresponding to the numerical data. Another important features are the separation of the main peaks of the autocorrelation by the external cavity roundtrip time, and the drift in the pulse pattern, i.e. the main peaks get lower while the neighboring peaks grow, as can be seen in the insets.
We also would like to point out that we have obtained the parameters values used in the simulations from the experimental measurements (when possible) and from the literature. The α-factor deserves an additional discussion, we have taken it to be 4 to avoid the appearance of stable points.

Conclusions

In this work we have studied the effect of the polarized filtered optical feedback in a VCSEL biased close to threshold. From the above discussion, we experimentally and theoretically identify clear single-mode low frequency fluctuations dynamics. It has been shown that the model reproduces well part of the experimental findings.
It is also worth saying that the nice features found in the LFF regime start to disappear when the current is increased and the system approaches the coherence collapse regime [7].
In future work, we are interested in the behavior of the secondary polarization (SP). It has been experimentally observed that the SP responds with a peak to every single dropout of the main polarization, when the VCSEL is pumped above the solitary threshold of the SP. Promising results to describe this response have been found theoretically defining a little misalignment between the polarizer and the direction of the linearly polarized mode of the VCSEL [7] [8] or including noise sources that arise from spontaneous emission processes [9].

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