Numerical observation of in-phase and out-of-phase pulses in the polarization modes of a VCSEL operating in the low-frequency fluctuations regime

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We investigate numerically the intensity behavior on a picosecond time scale of a vertical-cavity surface-emitting laser (VCSEL) subject to optical feedback and operating in the low-frequency fluctuations regime. By using the model proposed by M. San-Miguel, Q. Feng and J.V. Moloney [Phys.Rev.A, ***52****, 1728 (1995)], we show that the two orthogonal linearly polarized modes of the VCSEL can exhibit in-phase or out-of-phase pulses, depending on whether we examine the picosecond intensities of these two modes just after a power drop-out or in the time interval during which the total mean intensity is more or less constant until the next power drop-out.*

1. Introduction

A VCSEL subject to external optical feedback exhibits instabilities similarly to an edge-emitting laser [1]. One of these instabilities is the low-frequency fluctuations (LFF) regime, characterized by sudden drop-outs followed by gradual, stepwise, recoveries of the laser mean intensity. This name (LFF) originates from the fact that the time intervals between consecutive drop-outs are long compared to the other timescales involved in semiconductor laser dynamics like the period of the relaxation oscillations or the external cavity round-trip time.

One of the most interesting features of VCSEL's is that in these lasers, unlike in edge emitters, the polarization state of the emitted light is not fixed "a priori". Indeed a VCSEL generally emits a linearly polarized (LP) light, but the direction of linear polarization can switch between two orthogonal states when the injection current is modified or when some thermal effects show their importance [2]. An interesting question is to know if these two LP modes behave, within the LFF regime, in a similar way than two longitudinal modes of a conventional semiconductor laser. An other still opened question is to understand the role of the polarization switching in the stability of a VCSEL subject to external optical feedback.

In this paper, we investigate numerically the intensity behavior on a picosecond time scale of the two orthogonal linearly polarized modes and show, for what is believed to be the first time, that two distinct behaviors can be observed, depending on whether we examine these intensities just after a power drop-out or in the time interval during which the total mean intensity is more or less constant until the next drop-out. This observation is similar to what has been recently reported for edge-emitting lasers [3].

2. Numerical Results

The spin-flip model proposed by M. San Miguel et al. [4] (SFM model) has been widely used to interpret experimental results on polarization dynamics in VCSEL's, including polarization switching. We can write its extension for the case of isotropic optical feedback as the following :

$$\frac{dE_\pm}{dt} = \kappa(1+i\alpha)(N \pm n - 1)E_\pm - (\gamma_a + i\gamma_p)E_\mp + f\ E_\pm(t-\tau)\exp(-i\omega_0\tau) + \sqrt{\beta_{sp}\ (N \pm n)}\ \psi_\pm(t) \quad (1)$$

$$\frac{dN}{dt} = -\gamma(N-\mu) - \gamma(N+n)|E_+|^2 - \gamma(N-n)|E_-|^2 \quad (2)$$

$$\frac{dn}{dt} = -\gamma_s n - \gamma(N+n)|E_+|^2 + \gamma(N-n)|E_-|^2 \quad (3)$$

$E_\pm$ are the circularly polarized components of the slowly variable optical field. N and n are two normalized carrier numbers. N takes into account the total population difference between conduction and valence bands. n corresponds to the difference between the two distinct subpopulation inversion densities which couple separately to the emission of left and right circularly polarized light. κ is the field decay rate in the cavity, γ is the decay rate of the total carrier population, and γ_s is a rate which accounts for the coupling between the two subpopulation inversion densities due to spin-flip relaxation mechanisms. μ is the normalized injection current, with $\mu = 1$ at the lasing threshold. γ_a and γ_p are the intensities of linear dichroïsm and birefringence of the laser cavity, per intra-cavity round-trip time. α is the linewidth enhancement factor. f is the feedback rate, $\omega_0\tau$ is the feedback phase (ω_0 being the angular frequency related to the solitary laser wavelength at the lasing threshold), and τ is the external-cavity round-trip time. Finally the model takes into account the spontaneous emission process, with the last term in equation (1). β_{sp} is the spontaneous emission rate and $\psi_\pm(t)$ are two independent complex white noise of unitary variance and zero mean value. The rate equations (1) - (3) are solved numerically, with a set of parameters allowing the observation of power drop-outs [5]: $\kappa = 300\ ns^{-1}$, $\gamma = 1\ ns^{-1}$, $\gamma_s = 10\ ns^{-1}$, $\gamma_a = -0.1\ ns^{-1}$, $\gamma_p = 4\ ns^{-1}$, $\alpha = 3$, $\tau = 3$ ns, $\omega_0\tau = 6$ rad, $\beta_{sp} = 1e\text{-}4\ ns^{-1}$, $\mu = 1.3$, and $f = 100$ GHz.

Figure 1 presents the picosecond total intensity I_{tot} and the picosecond intensities in each polarized modes I_x and I_y, as well as what we have called a correlation, defined as the product of the picosecond intensities of the two orthogonal LP modes (x and y). The graphs on the left are relative to the situation just after a power drop-out, whereas the graphs on the right present the situation for a time interval chosen where the total mean intensity (averaged over 1 ns) is almost constant.

As we can see, just after a power drop-out (Fig.1, left) the two polarization modes exhibit a fast pulsating behavior, with pulses emitted synchronously. Indeed, the correlation presents sharp pulses with a large number of zero-value time intervals indicating emission of pulses in a synchronous way. The two modes oscillate in phase, and thus the total intensity does not show qualitative differences with respect to the individual modes : the total picosecond intensity has an average value close to zero, as it is the case for the LP modes.

In contrast, some time after the recovery process of the total mean intensity (Fig.1, right), the pulses in the LP modes broaden and are no more in phase. Indeed the correlation is by far lower than for the preceding case and shows only short zero-value time intervals. An exchange of energy between the two linearly polarized modes occurs, leading to a total intensity which fluctuates around a non-zero mean value. This behavior is similar to what is reported in [3] but for an edge-emitting laser.

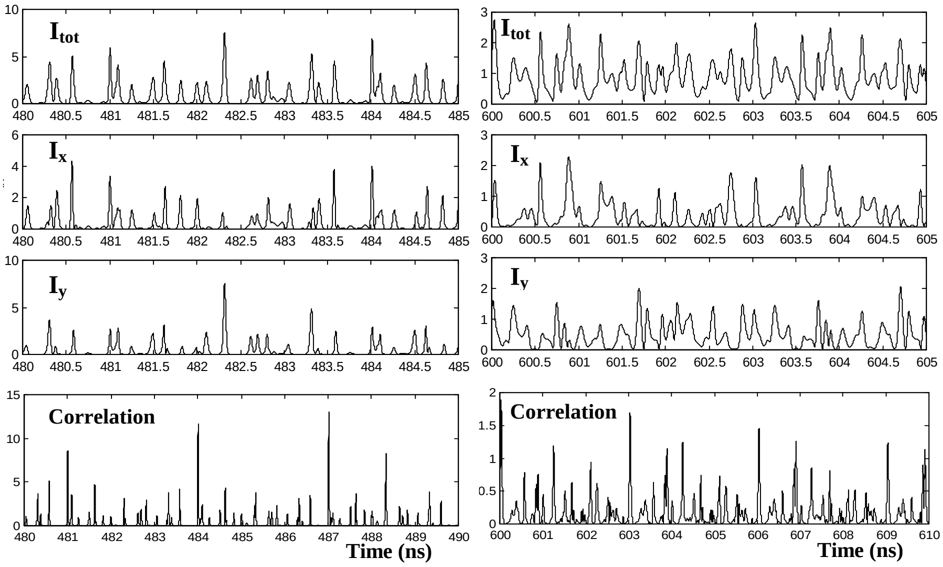

Figure 1: total picosecond intensity, picosecond intensities in each LP mode, and correlation (product of the picosecond intensities of the two LP modes of the VCSEL) vs.time. Left : just after a power drop-out, Right: time interval during which the total mean intensity is almost constant, thus after the recovery process. Equations (1) – (3), parameters in the text.

In the following, we investigate a simplified version of the SFM model by setting $\gamma_s \to \infty$ ($n = 0$) in the equations (1)–(3). In the basis of the linearly polarized components of the optical field, this model writes :

$$\frac{dE_x}{dt} = \kappa\,(1+i\alpha)\,(NF_x - 1)\,E_x - (\gamma_a + i\gamma_p)E_x + fE_x(t-\tau)\exp(-i\omega_0\tau) + \sqrt{\frac{\beta_{sp}}{2}N}\;\psi_+(t) + \sqrt{\frac{\beta_{sp}}{2}N}\;\psi_-(t) \qquad (4)$$

$$\frac{dE_y}{dt} = \kappa\,(1+i\alpha)\,(NF_y - 1)\,E_y + (\gamma_a + i\gamma_p)E_y + fE_y(t-\tau)\exp(-i\omega_0\tau) - i\sqrt{\frac{\beta_{sp}}{2}N}\;\psi_+(t) + i\sqrt{\frac{\beta_{sp}}{2}N}\;\psi_-(t) \qquad (5)$$

$$\frac{dN}{dt} = -\gamma\left[N - \mu + NF_x\,|E_x|^2 + NF_y\,|E_y|^2\right] \qquad (6)$$

According to Ref.[5], the gain compression functions $F_x = 1 - e_{xx}\,|E_x|^2 - e_{xy}\,|E_y|^2$ and $F_y = 1 - e_{yx}|E_x|^2 - e_{yy}|E_y|^2$ are necessary to observe LFF for the set of parameters quoted before. e_{xx}, e_{yy} are defined as the self-compression factors and e_{xy}, e_{yx} as the cross-compression ones. We investigate numerically this model, with the same parameters as before and with $e_{xx}= e_{xy}= e_{yx}= e_{yy}= 0.1$ [5].

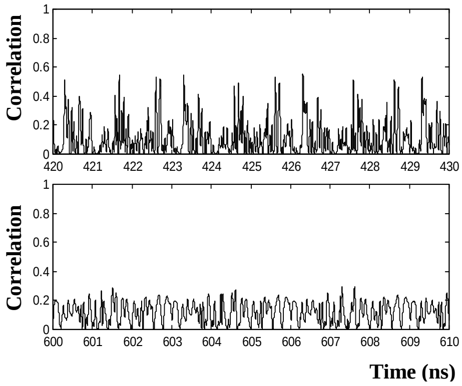

Figure 2: correlation vs. time. Upper graph : just after a power drop-out, lower graph : in a time interval during which the total mean intensity is almost constant, thus after the recovery process. The simulated equations are the equations (4) – (6) and the parameters are specified in the text.

The total mean intensity exhibits low-frequency fluctuations and is very similar to what is observed with the complete SFM model (1) – (3).

Nevertheless, we observe that, on a picosecond time scale, the intensity behavior is quite different from the one presented in Fig.1 : the LP modes never oscillate in phase, as it is shown in Fig.2. The correlation is as low just after a power drop-out (upper graph) as after the recovery process (lower graph), and shows only short zero-value time intervals. Furthermore, the fluctuations of intensities just after a power drop-out are lower in this last model than in the first one. This kind of behavior is observed regardless of the value of the injection current and the feedback rate.

3. Conclusions

We have investigated numerically the picosecond intensity behavior of the two linearly polarized modes of a VCSEL in the LFF regime, using a spin-flip model (SFM model). We have shown that two distinct behaviors can be obtained depending on whether we observe the picosecond intensities just after a power drop-out or after the recovery process. A simplified version of the SFM model, which does not allow to observe polarization switching (PS), has also been studied. This simplified model predicts qualitatively different behavior on the picosecond time scale than the complete model. Even if further investigations will be needed in order to clarify the importance of including gain compression factors in the complete SFM model, we can think from the presented results that the polarization switching plays a role within the LFF regime in a VCSEL.

References

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