Rapid oscillations in vertical-cavity surface-emitting lasers with optical feedback

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Abstract: - Vertical-cavity surface-emitting lasers are studied theoretically and numerically. Vertical-cavity surface-emitting lasers with optical feedback exhibit random transitions between the two orthogonal linearly polarized modes. The transitions between the two modes are induced by feedback and the two orthogonal linearly polarized modes are anticorrelated. We studied these anticorrelated oscillations by a stochastic delay differential equation. We find that these slow anticorrelated oscillations are accompanied by rapid oscillations with a period corresponding to 1.2 ns.

Key-Words: - Vertical-Cavity Surface-Emitting Lasers (VCSELs), Linearly Polarized (LP)

1 Introduction

When using Vertical-cavity surface-emitting lasers (VCSELs) in optical telecommunication systems, a small amount of light is inevitably fed back into the VCSEL cavity as the result, for example, of parasitic reflections at the cleaved end of a fiber or from the disk in CD players. As with any semiconductor laser, VCSELs are sensitive to optical feedback. VCSEL has received much attention since its proposal by K. Iga.[1]. The VCSEL shows up as a key device for optical telecommunication systems and all optical signal handling. It exhibits many advantages over the conventional edge emitting semiconductor laser (EEL) such as a single-longitudinal mode operation, low threshold current, circular beam, low cost, and a dense packing capability. VCSELs are also interesting from a fundamental viewpoint when considering their light polarization. The polarization of the emitted light is not fixed and often switches between two orthogonal, linearly polarized (LP) states (x and y). This polarization switching is a drawback in polarization-sensitive applications but on the other hand may lead to new and interesting applications for optical signal processing. VCSELs exhibit interesting polarization properties: they usually emit linearly polarized (LP) light but may switch between two orthogonal (x and y) LP modes [2]. Optical feedback from an external mirror can be used to control VCSEL light polarization. Because the delayed optical feedback may interact with the polarization competition in VCSELs, new time-dependent responses are also possible. A small amount of polarization-insensitive optical feedback (PIOF) is enough to destabilize a steady LP mode and induce mode hopping between two LP modes. This mode hopping is different from that observed for solitary VCSELs (i.e., without feedback) because the delayed feedback generates typical instabilities. Of particular interest is the observation of anticorrelated oscillations in the LP mode intensities exhibiting a frequency close to the external-cavity (EC) frequency that contrasts with the relatively slow time scale of the mode hopping. In this letter we study the anticorrelated oscillations.

2 Model

Numerical simulations are based on the San Miguel–Feng–Moloney (SFM) equations [5] extended to isotropic optical feedback by taking into account a single reflection in the external cavity:

$$\dot{E}_x = \kappa(1+i\alpha)[(N-1)E_x + inE_y] - (\gamma_a + i\gamma_p)E_x + fE_x(t-\tau)\exp(-i\phi_f) + [\beta_{sp}(N+n)/2]^{1/2}\xi_1 + [\beta_{sp}(N-n)/2]^{1/2}\xi_2, \quad (1)$$

$$\dot{E}_y = \kappa(1+i\alpha)[(N-1)E_y - inE_x] + (\gamma_a + i\gamma_p)E_y + fE_y(t-\tau)\exp(-i\phi_f) - i[\beta_{sp}(N+n)/2]^{1/2}\xi_1 + i[\beta_{sp}(N-n)/2]^{1/2}\xi_2, \quad (2)$$

$$\dot{N} = -\gamma_N[N - \mu + N(|E_x|^2 + |E_y|^2) + in(E_y E_x^* - E_x E_y^*)], \quad (3)$$

$$\dot{n} = -\gamma_s n - \gamma_N[n(|E_x|^2 + |E_y|^2) + iN(E_y E_x^* - E_x E_y^*)], \quad (4)$$

Where E_x and E_y are the slowly varying amplitudes of the linearly polarized components of the electric field, *N* is the total carrier difference between conduction and valence bands, and *n* is the difference between the population inversions of the spin-up and spin-down radiation channels. κ is the field decay rate, γ_N is the decay rate of *N*, γ_s is the spin-flip relaxation rate, α is the linewidth enhancement factor, μ is the normalized injection current (μ = 1 at threshold), γ_a is the linear dichroism, and γ_p is the linear birefringence. The terms proportional to $E_{x,y}(t-\tau)$ account for a delayed reflection from the external mirror (multiple reflections are neglected), τ is the external cavity round-trip time, *f* is the feedback rate, and $\phi_f = \omega_0\tau$ is the feedback phase, where ω_0 is the optical frequency of the polarization mode in the absence of birefringence and feedback. Spontaneous emission noise is taken into account through the last two terms in Eqs. (1) and (2). β_{sp} is the spontaneous emission rate and ξ_1, ξ_2 are two uncorrelated white noises with zero mean and unitary variance. A numerical study of vertical-cavity surface-emitting lasers with optical feedback demonstrates the existence of hopping between two LP modes Fig. 1 [2]. Although the solitary VCSEL operates in only one LP mode, a weak PIOF may induce a channelled curve similar to that in Fig. 1. The stiffness of laser equations makes it difficult to compute long dwell times. Of particular interest are the anticorrelated rapid oscillations. We investigate the mechanism responsible for these oscillations by considering the following stochastic delay differential equation:

$$\dot{x} = x(t) - x^3(t) + \varepsilon x(t-\tau) + \sqrt{2D}\xi(t) \quad (5)$$

where $\xi(t)$ is a Gaussian white noise of zero mean and unitary variance, τ is the delay time, ε is the feedback strength, and *D* is the noise level.

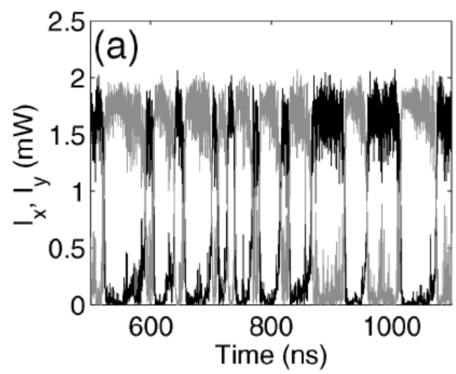

Fig.1. Numerical simulations. Time traces of I_x (black) and I_y (gray)

This equation has been analyzed for a long delay time of the order of the mean dwell time [3]. We have numerically simulated Eq.(5) by Matlab version 6.5 for our experiment. The model used in Matlab Simulink is shown in Fig.2, for simulation the delay time was chosen much smaller than the mean dwell time Fig.2 and Fig.3.

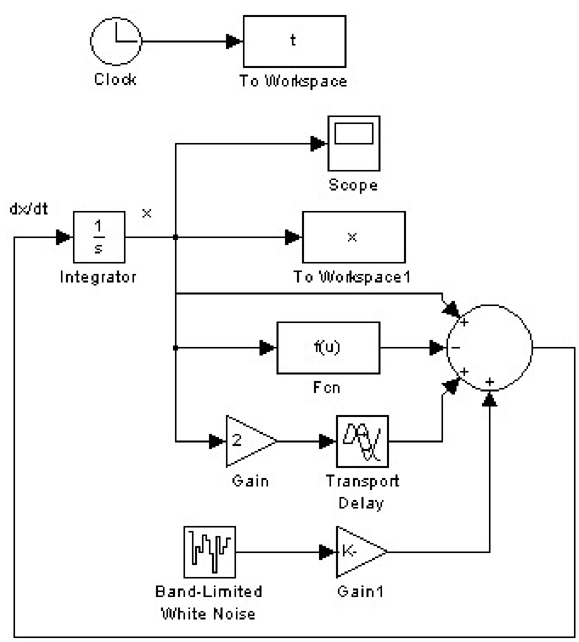

Fig.2. Numerical simulation of Eq. (5) by Matlab Simulink.

Feedback induces transitions between the two modes. The slow mode transitions Fig.3, is accompanied by fast oscillations. We also observe small fluctuations, which are inevitably the results of Band-Limited White Noise used in our simulation. Our simulation with Matlab version 6.5 demonstrates fast oscillations with a period corresponding to 1.2 ns.

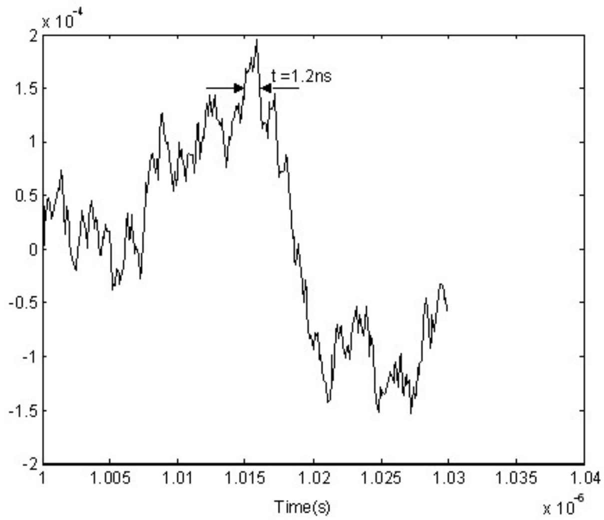

Fig. 3. Numerical simulation of Eq. (5) for τ = 1 ns, $\varepsilon = 2\,ns^{-1}$, and $D = 1\ ns^{-1}$.

3 Conclusion

In summary, by considering the stochastic delay differential equation, investigation of anticorrelated oscillations in vertical-cavity surface-emitting lasers (VCSELs) subjected to a weak polarization-insensitive optical feedback (PIOF), reveals oscillatory behavior. Our numerical study of stochastic delay equation with Matlab 6.5 present closer results with the numerical simulation of San Miguel–Feng–Moloney (SFM) equations [2].

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