Optical feedback induces polarization mode hopping in vertical-cavity surface-emitting lasers

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Vertical-cavity surface-emitting lasers subjected to weak polarization-insensitive optical feedback are studied experimentally and theoretically. We find that the feedback induces random anticorrelated hopping between the two orthogonal linearly polarized modes. This polarization mode hopping is accompanied by rapid anticorrelated oscillations in the linearly polarized intensities at the external-cavity frequency. The study of a simple stochastic delay differential equation suggests that these oscillations generated by the delay are typical of any hopping phenomenon between states. © 2003 Optical Society of America

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Vertical-cavity surface-emitting lasers (VCSELs) exhibit interesting polarization properties: they usually emit linearly polarized (LP) light but may switch between two orthogonal (x and y) LP modes.[1] Optical feedback from an external mirror can be used to control VCSEL light polarization.[2,3] Because the delayed optical feedback may interact with the polarization competition in VCSELs, new time-dependent responses are also possible.[4]

In this Letter we show that 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)[5] 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. The analysis of a simple one-variable stochastic delay differential equation suggests that these oscillations are typical and caused by the interaction between the jump transition phenomenon and the delayed feedback. Our results are therefore thought to cast new light on the dynamics of bistable mode-hopping systems with delay and noise, which have been the subject of recent theoretical investigations.[6,7]

We use a proton-implanted 850-nm VCSEL with a threshold current $J_{\mathrm{th}} = 6$ mA (in the solitary case). The solitary VCSEL emits light in the fundamental transverse x-LP mode for currents as high as $2.25 J_{\mathrm{th}}$, at which the first transverse mode initiates. The VCSEL is subjected to a weak PIOF from a semitransparent mirror; i.e., the EC does not contain any polarization-selective optics. The EC length is $L = 20.2$ cm. The transmitted light is split into x- and y-LP modes. LP intensities are measured with two photodiodes with 1.5- and 4-GHz bandwidth, connected to a 4-GHz oscilloscope. LP-resolved optical spectra are measured with a plane Fabry–Perot interferometer with a free spectral range of 15 GHz and a finesse of ~100.

The feedback strength is such that it reduces the threshold current by ~2%. Figure 1 shows the polarization-resolved light versus current ($L-I$) curve with so-called channelled behavior,[2,3] i.e., showing multiple polarization switchings at periodically separated values of the injection current (see the inset in Fig. 1). In these channels the laser is linearly polarized along x or y, and the intensity is almost steady. In contrast, polarization mode hopping is observed if we fix the injection current at one polarization-switching point. The laser system then randomly dwells in the x- or y-LP mode with large residence times [see Fig. 2(a)]. The two LP modes are anticorrelated on this time scale. This behavior resembles that of the mode hopping in a solitary VCSEL.[5] However,

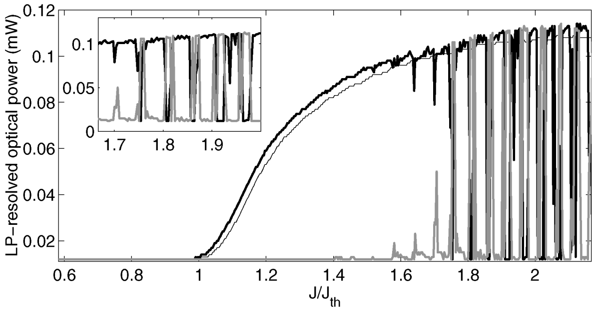

Fig. 1. LP-resolved $L-I$ curve. Thin black curve, x-LP mode in the solitary VCSEL. Thick black (gray) curve x- (y)-LP mode in the VCSEL subject to weak PIOF. The inset shows an enlargement in the channelled region.

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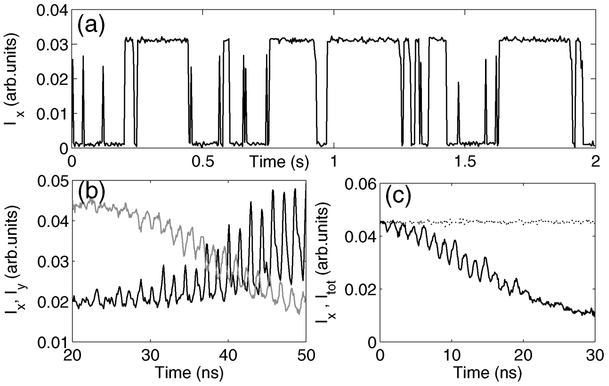

Fig. 2. (a) Polarization mode hopping for $J = 1.86J_{\mathrm{th}}$ close to a switching point in the L–I curve. (b) Anticorrelated oscillations at the EC frequency in the x- (black) and y-LP mode (gray). (c) Total intensity (dotted curve) and x-LP mode intensity (solid curve).

in addition to the slow polarization mode hopping, there exists a fast oscillatory behavior at the EC frequency ($f \sim 750$ MHz). These rapid oscillations appear more dramatically during a polarization-switching transition. Figure 2(b) shows an example of fast oscillations in the intensities of the two LP modes during a polarization switch. It shows that the LP modes are anticorrelated in the time scale of the EC frequency. These oscillations therefore vanish in the time trace of the total intensity [see Fig. 2(c)]. The intensities in the two LP modes were recorded with two photodiodes with different rise time and sensitivity, which explains the arbitrary units and the difference in the depth of the fast oscillations between the two LP modes. It is worth noting that anticorrelation at the EC frequency has also been reported experimentally in the LP mode intensities of a VCSEL subjected to a moderately strong PIOF operating in the chaotic low-frequency fluctuation regime.[8,9] However, the polarization dynamics in the low-frequency fluctuation regime significantly differ from those in the polarization mode-hopping regime that we analyze.

We complement our analysis by observing the LP-resolved optical spectra. Figure 3 shows the LP-resolved optical spectrum for an injection current such that the VCSEL emits in only one LP state. Several peaks are present and correspond to excited EC modes (ECMs), which are separated by $\Delta\nu_{\mathrm{ECM}} \equiv c/2L \sim 750$ MHz, where c is the speed of light. We observe that when the laser emits only the x- or y-LP mode the optical spectrum jumps between x- or y-LP ECMs. This is confirmed by optical spectra taken with a piezoscanning Fabry–Perot interferometer [see Fig. 3(b)]. The laser emits in one ECM (second trace), then hops to a neighboring ECM (third trace), and afterward lases in that ECM (fourth trace). Elliptically polarized ECMs are never observed, as confirmed by rotating the detection polarizers. Jumps between ECMs are also observed in the mode-hopping regime, but, in addition, the LP-resolved optical spectrum alternates between lasing and nonlasing because of the polarization mode hopping. ECM hopping has been reported for single-mode, polarization-stable edge-emitting lasers subjected to weak optical feedback.[10] However, the ECM hopping presented here is superimposed on polarization mode hopping.

We study the dynamics of a VCSEL subjected to weak PIOF by using two mode rate equations with delay:

$$\dot{E}_{x,y} = \frac{1}{2}(1 + j\alpha)(G_{x,y} - \gamma)E_{x,y} + \kappa E_{x,y}(t - \tau)\exp(-j\Omega_{x,y}\tau) + \sqrt{\beta_{\mathrm{sp}}N}\,\xi_{x,y}\,, \tag{1}$$

$$\dot{N} = \frac{J}{eV} - \frac{N}{\tau_e} - \frac{G_x}{\Gamma}|E_x|^2 - \frac{G_y}{\Gamma}|E_y|^2, \tag{2}$$

where

$$\Omega_{x,y} = \frac{m\pi c}{n_{0x,y}L_c}\left(1 - \frac{1}{n}\frac{\mathrm{d}n}{\mathrm{d}J}J\right), \tag{3}$$

$$G_{x,y} = a_{x,y}(N - N_{\mathrm{tr}})(1 - \epsilon_{s,c}|E_x|^2 - \epsilon_{c,s}|E_y|^2). \tag{4}$$

Here $E_{x,y}$ are the slowly varying x- and y-LP components of the electric field, N is the carrier density, N_{tr} is its transparency value, α is the linewidth enhancement factor, $\gamma \equiv 1/\tau_p$, τ_p (τ_e) is the photon (carrier) lifetime, J is the injection current, $n_{0x,y}$ are the refractive index of the x (y) mode at $J = 0$, L_c is the VCSEL effective cavity length, m is an integer, V is the volume of the active region, and e is the electron charge. The refractive index is taken to vary linearly with J, with a rate given by $\mathrm{d}n/\mathrm{d}J$, so that the optical frequency $\Omega_{x,y}$ is redshifted for increasing J; $a_{x,y} \equiv \Gamma v_g g_{x,y}$, where Γ is the confinement factor, v_g is the group velocity, and $g_{x,y}$ is the differential gain, with $g_y = g_x + \mathrm{d}g/\mathrm{d}\Omega(\Omega_y - \Omega_x)$. ϵ_s (ϵ_c) is the self- (cross-)gain saturation coefficient. $\tau \equiv 2L/c$ is the EC round-trip time, and κ is the feedback rate. β_{sp} is the spontaneous emission rate, and $\xi_{x,y}$ are two uncorrelated white noises with zero mean and unitary variance. We consider the following values of the parameters: $\alpha = 3$, $N_{\mathrm{tr}} = 4 \times 10^6\ \mu\mathrm{m}^{-3}$, $\tau_p = 1.3$ ps, $\tau_e = 1$ ns, $n_{0x} = 3.5000000$, $n_{0y} = 3.5000861$, $L_c = 1.97\ \mu$m, $m = 16$, $J = 2.1863J_{\mathrm{th}}$, $V = 2\ \mu\mathrm{m}^3$, $\mathrm{d}n/\mathrm{d}J = 1.2 \times 10^{-3}\ \mathrm{mA}^{-1}$, $\Gamma = 0.06$, $v_g = 8.85 \times 10^4\ \mu$m/ns, $g_x = 4 \times 10^{-8}\ \mu\mathrm{m}^2$, $\mathrm{d}g/\mathrm{d}\Omega = -5 \times 10^{-13}\ \mu\mathrm{m}^2$ ns, $\epsilon_s = 10^{-6}\ \mu\mathrm{m}^3$, $\epsilon_c = 2\epsilon_s$, $L = 20.2$ cm, and $\kappa = 2.7\ \mathrm{ns}^{-1}$.

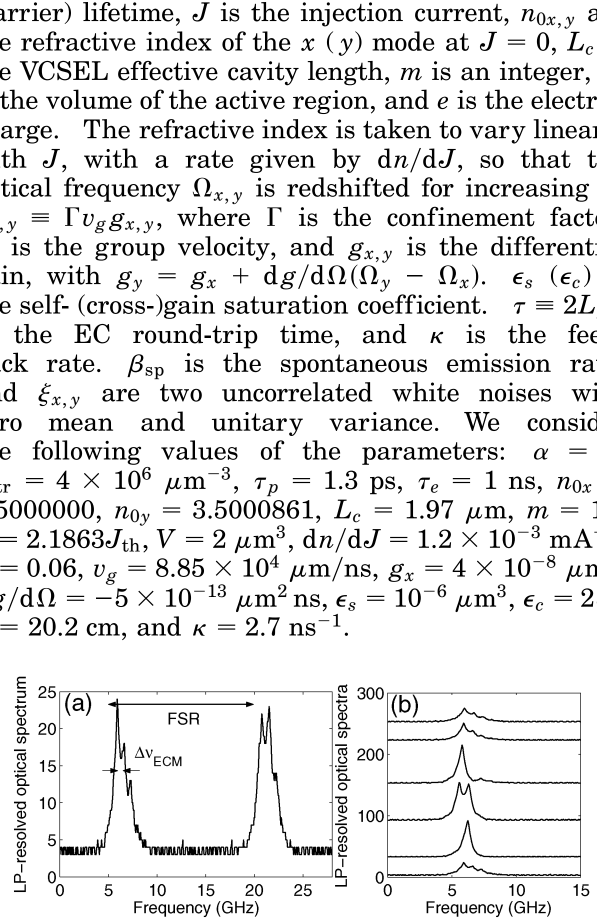

Fig. 3. (a) Optical spectrum in the y-LP mode for $J = 1.93J_{\mathrm{th}}$. (b) Same as (a) but at different times.

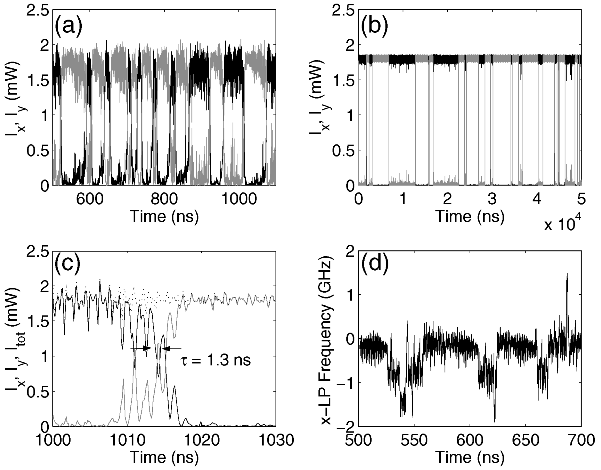

Fig. 4. Numerical simulations of Eqs. (1)–(4). (a), (b) Time traces of I_x (black) and I_y (gray) for $\beta_{\mathrm{sp}} = 10^{-6}\ \mathrm{ns}^{-1}$ and $\beta_{\mathrm{sp}} = 5 \times 10^{-8}\ \mathrm{ns}^{-1}$, respectively. See the different time scales. (c) Enlargement of (a). The total intensity I_{tot} is plotted by the dotted curve. (d) x-LP mode frequency versus time for the case in (a).

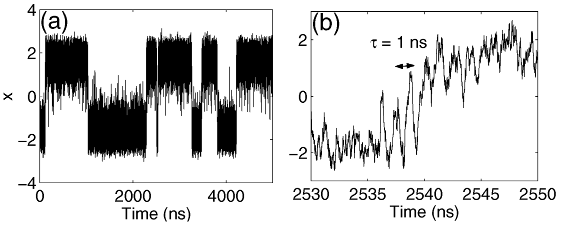

Fig. 5. Numerical simulation of Eq. (5) for $\tau = 1$ ns, $\epsilon = 2\ \mathrm{ns}^{-1}$, and $D = 1\ \mathrm{ns}^{-1}$. (b) Enlargement of (a).

Although the solitary VCSEL operates in only one LP mode, a weak PIOF may induce a channelled L–I curve similar to that in Fig. 2. By setting J close to one of the multiple polarization-switching points, we observe polarization mode hopping in good qualitative agreement with our experimental findings (see Fig. 4). The mean dwell time in one LP mode strongly depends on the level of spontaneous emission noise, as shown in Figs. 4(a) and 4(b). The stiffness of laser equations makes it difficult to compute long dwell times. Nevertheless, the comparison between Figs. 4(a) and 4(b) suggests that dwell times of the order of those shown in Fig. 2(a) can be simulated by Eqs. (1)–(4). Of particular interest are the anticorrelated rapid oscillations in the LP mode intensities at the EC frequency, which appear more dramatically during the low-frequency hops [see Fig. 4(c)]. Figure 4(d) gives the time evolution of the frequency in one LP mode, showing that the system lases in one ECM at a time and exhibits random jumps between ECMs as observed in the experiment. Our results suggest therefore that the fast oscillations are not caused by mode locking or beating between several ECMs. We investigate the mechanism responsible for these oscillations by considering the following simple stochastic delay differential equation:

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

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. Equation (5) admits two nonzero steady states ($x = \pm\sqrt{1+\epsilon}$) and no ECM solution. The noise induces a mode-hopping regime. This equation has recently been analyzed for a long delay time of the order of the mean dwell time.[7] We have numerically simulated Eq. (5) in the context of our experiment, for which the delay time is much shorter than the mean dwell time (see Fig. 5). The slow mode hopping [Fig. 5(a)] is complemented by oscillatory behavior with a period corresponding to the delay time [Fig. 5(b)], which is similar to the oscillations observed in our delayed VCSEL system. These oscillations have a deterministic origin and appear during the relaxation process, after the system has been kicked out of any of its two steady states.

In summary, VCSELs subjected to a weak PIOF may exhibit a polarization mode hopping that is complemented by time-delay-induced dynamics such as jumps between x- or y-LP ECMs and anticorrelated oscillations of the LP intensities at the EC frequency. Delay-periodic oscillations that complement mode hopping are shown here experimentally for the first time to our knowledge and are seen to be the result of the interaction between the switching process and the delayed feedback.

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