Experimental study of polarization switching of vertical-cavity surface-emitting lasers as a dynamical bifurcation

Jon Paul

School of Informatics, University of Wales, Bangor, Dean Street, Bangor LL57 1UT, Wales, UK

Cristina Masoller

Department de Fisica i Enginyeria Nuclear, Universitat Politecnica de Catalunya, Colom, 11, E-08222 Terrassa, Spain, and Instituto de Fisica, Facultad de ciecias, Universidad de la Republica, Igua 4225, Montevideo 11400, Uruguay

Yanhua Hong, Paul S. Spencer, and K. Alan Shore

School of Informatics, University of Wales, Bangor, Dean Street, Bangor LL57 1UT, Wales, UK

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We study the role of the bias current sweep rate in measurements of polarization switching (PS) of vertical-cavity surface-emitting lasers (VCSELs). We show that the polarization-resolved $L-I$ (light–intensity) curve depends on the current sweep rate. As the current sweep rate increases, the PS occurs at higher bias currents for upward scans and at lower bias currents for downward scans. We also show that the delay of the dynamical bifurcation follows a power law relationship with the frequency of the ramp, in good agreement with recent theoretical predictions. © 2006 Optical Society of America

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Vertical-cavity surface-emitting lasers (VCSELs) have many advantages compared with conventional, edge-emitting semiconductor lasers. They have single-longitudinal-mode emission with a circular output profile and very low threshold currents and can be integrated into large 2D arrays. However, because of their circular transverse geometry the orientation of the polarization of the emitted light is not fixed by geometrical constraints (as it is in edge-emitting lasers). Because of residual anisotropies (that break the circular transverse symmetry) the output of a VCSEL is linearly polarized along one of two orthogonal directions. When a VCSEL begins to lase, one linear polarization dominates, and when the bias current is increased in many devices it is observed that the emission switches to the orthogonal linear polarization. Such polarization switching (PS) is detrimental for the use of VCSELs in polarization-sensitive applications and has received a lot of attention.[1–8]

The PS is an example of a dynamical bifurcation in which a control parameter μ is time dependent and a change of μ (in the PS case, a change of the bias current) is accompanied by a transition from one state to another (in the PS case, a change in the polarization of the emitted light). The static bifurcation point is such that for a time-independent parameter one state is stable if $\mu<\mu_c$ and another state is stable if $\mu>\mu_c$. When the control parameter μ is time dependent, varying continuously in time from $\mu_i<\mu_c$ to $\mu_f>\mu_c$, the bifurcation is shifted from the static point μ_c, and the dynamic bifurcation occurs at $\mu^*>\mu_c$.[9]

In optics a well-known example of a dynamic bifurcation is the laser turn-on, which corresponds to a sweep across a bifurcation representing the transition from the off to the on state. A recent experimental study of a semiconductor laser turn-on and turn-off[10] showed that when a very low-frequency triangular signal (of a few hertz) is used to scan the bias current (upward and downward) the turn-on and the turn-off of the laser are continuous, taking place at a value that defines the threshold, $J=J_{\mathrm{th}}$. This corresponds to a quasi-static situation in which the laser reaches the steady state before the bias current changes appreciably. However, when a higher-frequency triangular signal (of several kilohertz) was used to scan the bias current, it was observed that the laser turns on suddenly at $J^*>J_{\mathrm{th}}$, and as the current decreased, the intensity decreased continuously, remaining proportional to the bias current until the turn-off at $J=J_{\mathrm{th}}$ (thus, hysteresis was observed for $J_{\mathrm{th}}<J<J^*$). The delay in the laser turn-on, defined as the difference between the time when bias current reaches the static threshold [t such that $J(t)=J\mathrm{th}$], and the time at which the laser actually turns on ($t^*>t$ when the laser intensity is suddenly amplified above the spontaneous emission level), was observed to follow a scaling law with the bias current sweep rate.

A recent theoretical study[11] of PS as a dynamical bifurcation predicts similar effects: a variation of the PS point with the bias current sweep rate and a power-law relationship between the delay of the bifurcation and the sweeping rate. Our aim in this Letter is to experimentally investigate the PS as a dynamical bifurcation. We show that the polarization-resolved $L-I$ (light–intensity) curve depends on the speed of the ramp used to vary the bias current. As the sweep rate increases, the PS occurs at higher bias current for upward scans and at lower bias current for downward scans, in good agreement with the predictions.[11] In addition, we show that there is a power-law relationship between the delay of the bifurcation and the current sweep rate.

The experimental setup is shown in Fig. 1. A commercial single-longitudinal-mode VCSEL was driven by an ultralow-noise current source and was temperature controlled to within 0.01 K. The laser output was collimated by using an antireflection-coated laser diode objective lens. The half-wave plate (HWP) and polarization beam splitter (PBS) were used to direct the orthogonal polarization components of the VCSEL to detectors D1 and D2. Two optical isolators (ISO1 and ISO2) with greater than −40 dB isolation were used to prevent light feedback from the detectors into the VCSEL. The outputs from the detectors were stored in a 1 GHz bandwidth digital oscilloscope (OSC). The current supplied to the laser was controlled by a signal generator, and a triangular modulation signal (of amplitude 0.45 mA peak to peak) was added to the VCSEL through the current source. The voltage on the laser changed from $J_{\min} = 1.55$ mV to $J_{\max} = 2.0$ mV. The frequency of the modulating signal, f, was varied to study the influence of the speed of the current ramp.

At threshold the output of the laser is linearly polarized in one direction, defined as the X polarization. When the bias current is increased above a certain value, it is observed that the polarization switches to the orthogonal polarization (defined as the Y polarization). The PS point depends on the speed of the bias current ramp, as shown in Figs. 2 and 3. Figures 2(a) and 2(b) display results for a slow ramp, while Figs. 3(a) and 3(b) display results for a fast ramp ($f = 60$ Hz and $f = 20$ KHz, respectively). Figures 2(a) and 3(a) display the time evolution of the X and Y polarizations during one cycle of the modulating signal, while Figs. 2(b) and 3(b) display the polarization-resolved L–I curve for several cycles of the modulating signal. The PS point for increasing (decreasing) bias current is defined as when the intensity of the suppressed $Y(X)$ polarization suddenly grows from the spontaneous emission level. Because PS is a stochastic process driven by spontaneous emission noise (as it is the laser turn-on[12]), the switching events occur at slightly different times, and thus there is a dispersion of the circles (diamonds) that indicate the PS point for increasing (decreasing) bias current.

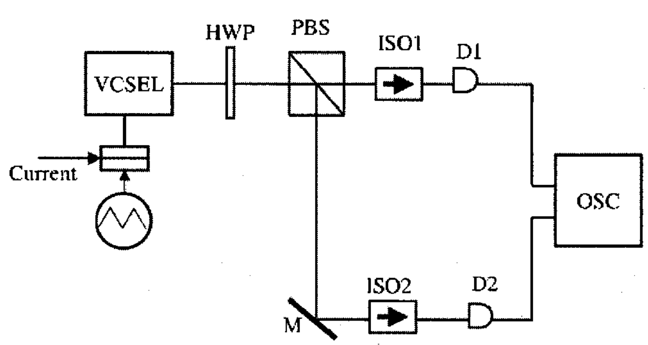

Fig. 1. Schematic diagram of experimental arrangement. HWP, half-wave plate; PBS, polarization beam splitter; ISO1, ISO2, optical isolators; D1, D2, photodetectors; M, mirror; OSC, oscilloscope.

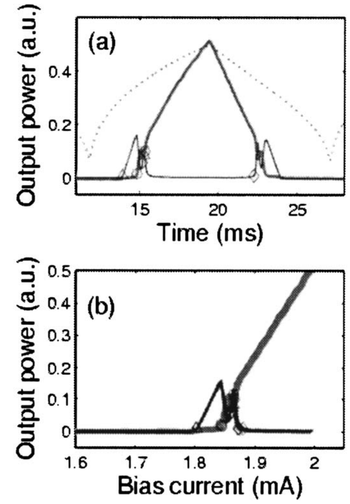

Fig. 2. (a) Time evolution of the X polarization (thick gray curve) and of the Y polarization (thin black curve) during one cycle of the modulating signal of $f = 60$ Hz (shown with a dotted curve, shifted vertically by 1.5 mA for clarity). (b) Polarization-resolved L–I curve (several cycles of the modulating signal are shown). The PS point for increasing current, for decreasing current, and the turn-on for increasing current are indicated by circles, diamonds, and triangles, respectively.

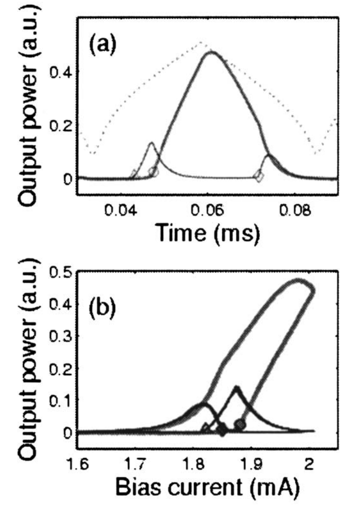

Fig. 3. (a) Time evolution of the X polarization (thick gray curve) and of the Y polarization (thin black curve) during one cycle of the modulating signal of $f = 20$ kHz (shown with a dotted curve, shifted vertically by 1.5 mA for clarity). (b) Polarization-resolved L–I curve (several cycles of the modulating signal are shown). The PS point for increasing current, for decreasing current, and the turn-on for increasing current are indicated by circles, diamonds, and triangles, respectively.

For a slow current ramp no hysteresis is observed [Fig. 2(b)]. The laser turns on and turns off, for upward and downward current scans, at the same value of the bias current ($J_{\text{th}} = 1.8$ mA), and the PS (which is accompanied by polarization anticorrelated oscillations), occurs at about the same value of the bias current ($J_{\text{PS}} \sim 1.85$ mA) for both upward and downward current scans. In contrast, for a fast current ramp a clear hysteresis cycle is observed [Fig. 3(b)]. Both the laser threshold and the PS point occur at different bias currents for upward and downward current scans. No oscillations accompany the PS, as there is a monotonic increase of the Y polarization accompanied by a monotonic decrease of the X polarization (this is probably due to a slow response of the photodetector). Also, in Fig. 3(b) it is seen that the X- and Y-polarization time traces for increasing and decreasing bias currents do not superpose. This is due to the fast sweep rate of the current that prevents the laser from being at equilibrium: the laser retains a memory, and the intensity is slightly lower when the current is being increased than when the current is being decreased (a similar effect is observed on studies of the laser turn-on and turn-off[10]).

A plot of the bias current for which the PS occurs for increasing injection, J_1^*, and for decreasing injection, J_2^*, versus the frequency of the ramp, Figs. 4(a) and 4(b), reveals that J_1^* (J_2^*) increases (decreases) with f. Hence, fast ramps enlarge the hysteresis region, in good agreement with recent theoretical predictions based on the spin-flip model.[11] The theory also predicts a power-law relationship between the delay on the bifurcation and the slope of the bias current ramp. To test whether a similar relation exists in the experiment, we plot on a log–log scale the time at which the PS takes place (t_1^*, measured from the minimum of the ramp for upward scans, and t_2^* from the maximum of the ramp for downward scans) versus the frequency of the ramp. Figures 3(c) and 3(d) clearly reveal a scaling law of the type $\log(t_{1,2}^*) = a\log(f)+b$, with $a=-0.95$, $b=-1.85$ for t_1^* and $a=-0.95$, $b=-1.89$ for t_2^*. These observations are also in good agreement with the predictions.[11] Moreover, using the model from Refs. 2 and 11, we have performed simulations with parameters corresponding to the experimental situation and found power-law relations with similar coefficients. In current work simulations also show that a and b vary with the details of the current ramp, and a comparison between theory and experiments is ongoing.

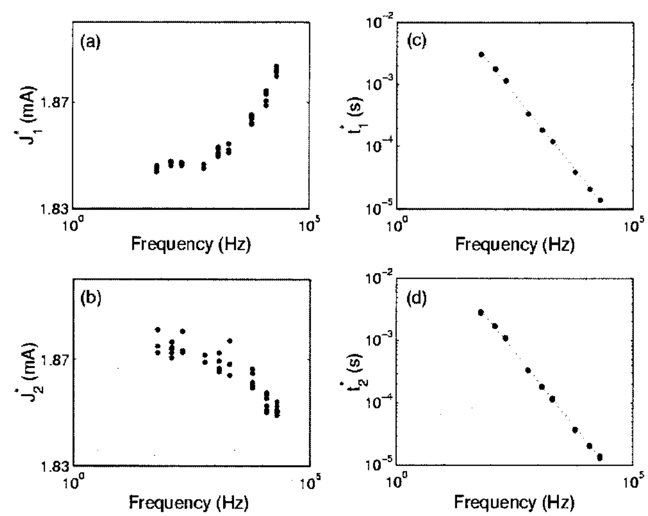

Fig. 4. Log-linear plot of the PS point for (a) increasing and (b) decreasing bias current versus the frequency of the ramp. Log–log plot of PS time for (c) increasing and (d) decreasing bias current versus the frequency of the ramp. The dashed lines indicate the linear fit $\log(t_{1,2}^*) = a\log(f) + b$.

Concluding, we have studied experimentally the polarization switching of VCSELs from the point of view of a dynamical bifurcation, i.e., a bifurcation that takes place when a control parameter changes continuously in time. The dynamical bifurcation point is shifted with respect to the static point, and the delay in the bifurcation follows a power-law relationship with the frequency of the ramp. Our results demonstrate the important role of the bias current sweep rate on measurements and control of polarization switching of VCSELs.

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