Experimental investigation of stochastic processes in vertical-cavity lasers

S. Barbaya\textsuperscript{a,c}, G. Giacomelli\textsuperscript{a,b,}\textsuperscript{*}, S. Lepr\textsuperscript{d,b}, F. Marin\textsuperscript{e,b}, I. Rabbiosi\textsuperscript{a,f}, A. Zavatta\textsuperscript{g}

\textsuperscript{a}Istituto Nazionale di Ottica Applicata, Largo E. Fermi 6, 50125 Firenze, Italy
\textsuperscript{b}Istituto Nazionale di Fisica della Materia, unit\textsuperscript{à} di Firenze, Italy
\textsuperscript{c}Lab. de Photonique et de Nanostructures CNRS, Marcoussis, France
\textsuperscript{d}Dip. di Energetica, Firenze, Italy
\textsuperscript{e}Dip. di Fisica, and LENS, Firenze, Italy
\textsuperscript{f}Physics Department, Strathclyde Univ., Glasgow, UK
\textsuperscript{g}Dip. di Sistemi e Informatica, Firenze, Italy

Abstract

We review the experimental characterization of stochastic processes in vertical cavity lasers. The system described here allows for several promising experimental studies which are presented in this work.

\textsuperscript{*}Corresponding author. Istituto Nazionale di Ottica Applicata, Largo E. Fermi 6, Firenze 50125, Italy. E-mail address: giacomelli@inoa.it (G. Giacomelli).

PACS: 42.65.Sf; 42.55.Sa; 42.50.−p

Keywords: Bistability; Stochastic resonance; Phase synchronization

The noise-induced dynamics in a bistable system is the subject of deep investigations since long time, due to its general interest which involves several fields, such as biology, economics, geophysics. In all those fields, the experimental studies are usually difficult and not well detailed, due to the lack of reproducibility of most systems and because laboratory, controllable conditions are generally not achievable. The most accurate results are usually obtained from numerical simulations or by implementing a model with electronic circuits.

Recently, a different possibility was offered by the vertical cavity semiconductor laser (VCSEL), which often presents a bistable emission and a fast and controllable response.
Main characteristics of VCSELs are a short cavity with high Fresnel number and a highly symmetric geometry. As a consequence, the emission is on a single longitudinal mode, but usually with a non-trivial transverse structure. Moreover, the crystal axes directions define two perpendicular, linear polarizations that can both be present in the laser emission. In particular, when sweeping the pump current the laser polarization can switch from one direction to the other and a polarization bistable region can exist. In such regions, the laser shows noise-induced jumps between the two polarizations and the transition rates can be controlled both by selecting the working point and by adding a well-defined amount of extra noise. This behaviour has been observed both in single transverse mode lasers [1] and in multiple transverse modes samples [2], where the polarization switch often comes together with a change of the lasing mode.

A more involved situation, of particular interest for the studies of stochastic processes, is found in VCSELs with a broad emitting area presenting spatially localized inhomogeneities. Due to these properties, the lasing action is in well-defined, localized regions, in general with different wavelengths. For our samples, the typical size of such spots is about 2 μm on a 15 μm diameter cavity. The position of the spots (emitters) remains the same, changing laser current and temperature: the pattern maintains a regular structure, differently from the filamentation in broad-area VCSELs [3]. For such lasers, the switches are not only on the emission polarization, but also in the spatial configurations: the single emitters can switch on and off, or change polarization and wavelength. As a consequence, the system behaviour can be monitored by the detected intensity after selecting the polarization or a spatial region. An example is shown in Fig. 1 (left). When biasing the laser within the bistable region, random jumps occur between the emission configurations following a Kramers statistics.
Fig. 2. Left: temporal evolution of the phase difference between input and output signals for three different values of applied noise, increasing from bottom to top. Right: average output frequency as a function of the input noise, for three different amplitudes of the applied modulation.

A single sample can show several transition regions, when changing the pump current. As shown in Fig. 1 (right) for a typical sample, the Kramers times range from tens of nanoseconds up to some seconds. The statistical analysis can be carried on along the transition region, changing the current, giving in general asymmetric, controllable rates and probability distributions [2].

A well-defined amount of noise can be added to the pump current, giving a dynamics that can be well described by a simple Langevin model, with a quasi-potential that is directly inferred from the experimental probability distributions. Such feature allowed us to study noise-induced phenomena such as Stochastic Resonance (SR) (for a review, see e.g. Ref. [4]), where the response of the system to a small input signal is greatly enhanced by a suitable amount of noise. Several aspects of SR have been analysed in previous works [5,6].

A further interesting phenomenon that can be experimentally studied thanks to the VCSELs is the noise induced, phase synchronization of the system to an applied sinusoidal modulation (for a review, see e.g. Ref. [7]). At this purpose, we define the phase of the output signal by means of suitable methods such as the Hilbert transform. The phase difference $\phi$ with respect to the input is then analysed varying the amount of applied noise. We report in Fig. 2 (left) the temporal evolution of $\phi$ for three different values of noise. For a particular, resonant amount of noise (corresponding to the central trace in the figure), the phase synchronization is achieved for long periods interrupted by phase slips. For both higher and lower noises, an average drift in $\phi$ (giving a slope in the traces) is originated by frequent slips, always in the same direction. More precisely, for high noise the system jumps too frequently, yielding a $2\pi$ phase gain for every excess jump. On the contrary, for low noise the switches are often lost.

A quantitative measurement is performed by evaluating the average output frequency as a function of noise. We have done it for different values of the input modulation amplitude and the result is shown in Fig. 2 (right). The resonant noise corresponds to an average output frequency equal to the input frequency and it is shown in the figure.
by the crossing of the horizontal line. Around this value, the frequency trace flattens and we can define a region where the system is nearly synchronized. For increasing modulation amplitudes, the width of this region increases.

A more general control of the system, acting both on the temperature and on the pump current, allows the access to even more intriguing situations involving multi-stability between several configurations of the emitters. An example of the hysteresis cycle for a tristable situation is plotted in Fig. 3 (left). In this situation, a sinusoidal input signal and variable noise can lead to multiple SR between the different states. An example is reported in Fig. 3 (right) where, in the lower trace, a small input modulation induces an oscillatory behaviour between two states thanks to the added noise.

In conclusion, the VCSEL allows for detailed experimental studies of stochastic processes with accurate quantitative measurements of statistical indicators and precise control of the system parameters. The results can be compared in details with theoretical predictions. While some phenomena, such as SR and aperiodic SR, have already been characterized in previous works, other aspects presented in this article will be the subject of future extended investigations.

References