Experimental noise-induced on-off intermittency in two bidirectionally-coupled diode lasers

Intermitencia encendido-apagado inducida por ruido en dos diodos láser acoplados bidireccionalmente

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ABSTRACT

Intermittent switches between chaotic and steady-state regimes are observed in experiments with two mutually-coupled diode lasers subject to common white gaussian noise. Both time series and power spectrum analyses yield typical scaling laws for on-off intermittency.

RESUMEN

Se reporta la observación de saltos intermitentes entre los regímenes de caos y estado estable en experimentos con dos diodos láser mutuamente acoplados sujetos a ruido blanco gaussiano común. Tanto el análisis de las series temporales como el del espectro de potencia arrojan leyes de escalamiento típicas para la intermitencia encendido apagado.

INTRODUCTION

Coupled semiconductor lasers present rich dynamics, interesting from a fundamental point of view and also because of their potential applications in secure chaotic optical communications, among many others (Pisarchik & Ruiz-Oliveras, 2010).

For moderate couplings and pumping currents near the lasing threshold, the optical emission of a laser subject to optical feedback presents power drops in the scale of micro- to nano-seconds (figure 1), so-called "low-frequency fluctuations" (LFF) (Hegarty, Huyet, Porta & McInerney,1998; Takiguchi, Fujino & Ohtsubo, 1999).

Figure 1. Drops in the optical power of a diode laser subject to optical feedback.
Source: Authors own elaboration.

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Chaos has been found in many systems belonging to natural and social sciences. Three universal routes to chaos have been observed: the period doubling, quasi-periodic, and intermittency. The last is characterized by irregular bursts (turbulent phases) that interrupt the regular phases (laminar phases) (Sacher, Elsäßer & Göbel, 1989).

Many types of intermittency have been found (Fujisaka, Kamifukumoto & Inoue, 1982; Platt, Spiegel & Tresser, 1993; Pomeau & Manneville, 1979), including on-off intermittency, where one dynamic variable of the system

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exhibits two distinct states as the system evolves in-time: the “off” state, when variables remain approximately constant in time (the laminar phases) and the “on” state characterized by irregular bursts of the variables away from their constant values. On-off intermittency obeys fundamental scaling laws. Near the onset of intermittency, the mean duration of the laminar phase exhibits a -1 power law with respect to a control parameter, while the probability distribution of the laminar lengths obeys a -3/2 power law (Henry, Platt & Hammer, 1994). On-off intermittency has been found in many systems, including electronic circuits (Hammer, Platt, Hammel, Heagy & Lee, 1994), a Nd:YAG laser (Gong & Kim, 2001), and a diode laser with periodically modulated length of the external cavity (Pisarchik & Pinto, 2002). The control of this type of intermittency has been proposed in references (Reategui-Jaimes-Reategui & Pisarchik, 2004).

Experimental Set-up

We used two diode lasers (Eblana Photonics, λ = 1542 nm) with matched optical spectra to avoid frequency detuning. The optical field of each laser was injected into the other one via a 90:10 fiber coupler. The polarization controller and the attenuator allowed us to maximize power in the system and to change the coupling strength, respectively. White Gaussian noise was applied to the pumping currents of both lasers with a noise generator. Their optical powers were detected using photo-detectors (PIN) and recorded by a digital oscilloscope and a power spectrum analyzer (figure 2).

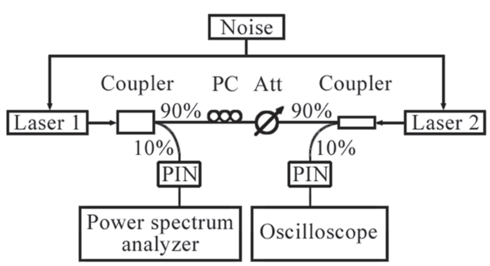

Figure 2. Experimental set-up. PC: polarization controller, Att: optical attenuator, PIN, Noise: white noise generator.
Source: Authors own elaboration.

Operating in the LFF regime, the lasers contribute mainly to a 0.65-MHz region of the power spectrum (figure 3).

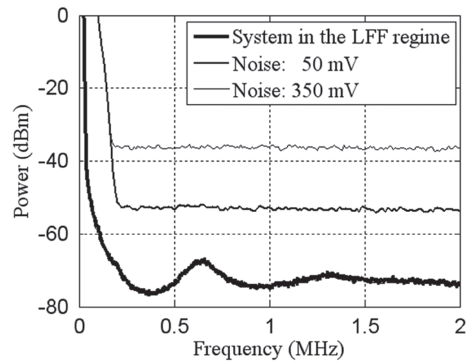

Figure 3. Power spectra of 50 and 350 mV noise (upper traces) and one of the lasers in the LFF regime (lower trace), averaged over 100 realizations.
Source: Authors own elaboration.

RESULTS

For a strong coupling, the lasers operate in the LFF regime, and when external noise is added to their pump currents, steady emission windows (laminar phases) appear in the time series, when noise exceeds a threshold of N_{th} = 109 mV. The statistical analysis of this intermittent behavior was performed by averaging 100 time series of 50-ms length each (figure 4).

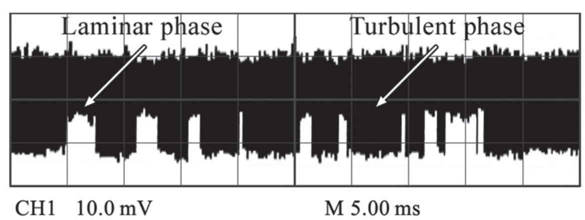

Figure 4. Laser time series showing intermittency behavior for 240-mV noise.
Source: Authors own elaboration.

In time domain, near the onset of intermittency, the average length of the turbulent phase, $< \tau >$, shows an exponential decay versus the external noise intensity used as a control parameter. In a log-log plot, the experimental points are fitted to a straight line with a -0.96 slope near the threshold (figure 5).

Another very important characteristic value for intermittency is the probability distribution of the laminar lengths. Figure 6 shows this distribution for 340-mV noise. This value has been chosen because of the large number of switching events in the time series that enables a relatively high precision of statistical analysis.

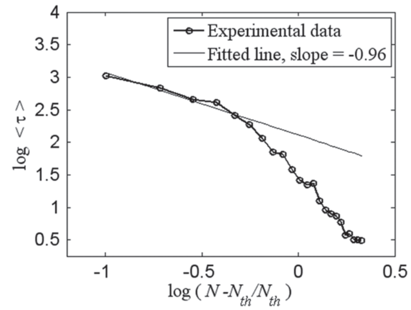

Figure 5. Average turbulent length versus normalized noise intensity in a log-log scale.The thin trace represents a fitted line near the onset of intermittency.
Source: Authors own elaboration.

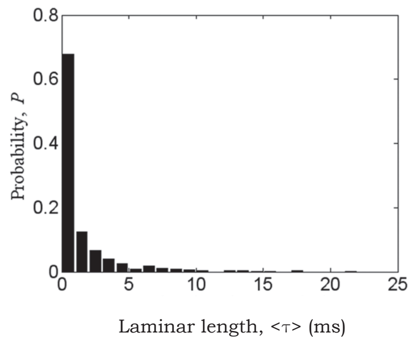

Figure 6. Probability distribution of laminar phases versus laminar length for *N*=340 mV.
Source: Authors own elaboration.

Figure 7 shows the probability distribution of laminar phases versus laminar length in a log-log scale. Evidently, this distribution obeys a power law with a critical exponent very close to -3/2.

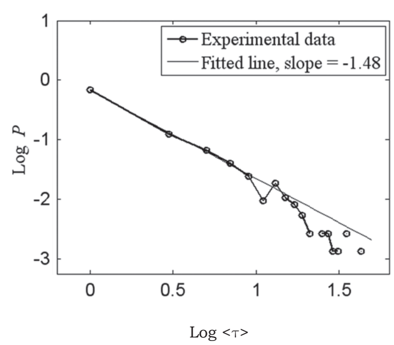

Figure 7. Log-log plot of the laminar phase versus laminar length for *N* = 340 mV. The thin line represents a linear fit with a -1.48 slope.
Source: Authors own elaboration.

Based on these results, we conclude that the type of intermittency is on-off intermittency.

Next, we will show that the intermittency observed can also be characterized by a scaling law for the signal-to-noise ratio (SNR) derived from the frequency spectrum analysis. Figure 8 shows a typical frequency spectrum (averaged over 100 realizations) of the laser intensity in the intermittency regime. The spectral component S_{LFF} centered approximately at 0.65 MHz reflects the turbulent phase contribution to the signal, while the external noise contribution is represented by S_N. As the noise intensity is increased, S_{LFF} decreases and S_N grows until the LFF spectral components vanish (the laminar phase dominates over the turbulent phase).

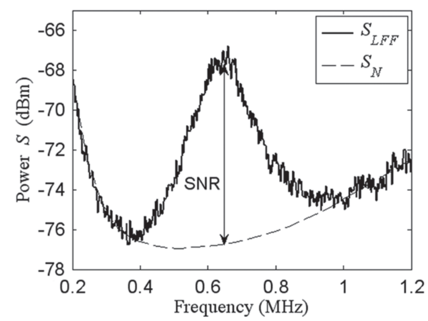

Figure 8. Power spectrum of the laser intensity averaged over 100 realizations in the LFF regime. SNR was measured as an access of the LFF spectral component (S_{LFF}) over background noise (S_N).
Source: Authors own elaboration.

In order to obtain a scaling relation from the power spectrum, we calculate SNR = $S_{LFF} - S_N$ (dBm) at the LFF's central frequency (0.65 MHz) as a function of the external noise. Figure 9 shows this dependence in a log-log scale.

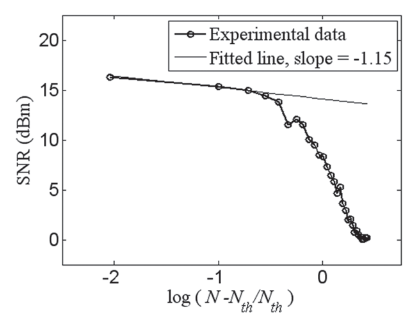

Figure 9. Signal-to-noise ratio versus noise intensity in a log-log scale. The thin line is a linear fit. N_{th} = 109 mV.
Source: Authors own elaboration.

The fitted line indicates that near the onset of intermittency, the SNR versus the normalized noise obeys a power law with a critical exponent of -1.15, that is, in agreement with the results obtained from the time series analysis. Such a coincidence occurs due to the fact that S_{LFF} is related to the average turbulent length.

CONCLUSIONS

We have experimentally studied the intermittent behavior of two mutually-coupled semiconductor lasers subject to external noise applied to their laser pump currents. For a strong coupling, the lasers intermittently switch from an LFF regime to a steady-state. Both the time series and power spectrum analyses reveal typical scaling relations for noise-induced onoff intermittency.

Our results have shown that close to the onset of intermittency, the mean laminar length obeys a -1 power law with respect to the noise intensity normalized to the noise threshold, while the probability distribution of the laminar lengths obeys a -3/2 power law. Moreover, the frequency spectrum analysis revealed a power law with a critical exponent very close to -1 for the signal-to-noise ratio as a function of the normalized noise intensity. These scaling relations are the key signatures of on-off intermittency.

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