Experimental observation of on-off intermittency in two mutually coupled semiconductor lasers

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Abstract
Intermittent switches between low-frequency fluctuations and stable emission are experimentally observed in two bidirectionally coupled semiconductor lasers subject to common Gaussian white noise applied to the laser pump currents. The time series analysis yields power-law scalings typical for on-off intermittency near its onset, with critical exponents of -1 and -3/2, respectively, for the mean turbulent length versus the noise intensity and probability distribution of the laminar phases versus the laminar length. The frequency spectrum analysis reveals a -1 power-law scaling for the signal-to-noise ratio versus the noise intensity.

Key words
Chaos, intermittency, noise, semiconductor laser, optical communications.

Introduction

Intermittency is a common behavior of many nonlinear dynamical systems. Characterized by irregular bursts (turbulent phases) interrupting a regular state (laminar phase) [1], this phenomenon occurs when the system passes through a critical point. Depending on the sort of the critical point, different types of intermittency are encountered, e.g., type I and on-off intermittency are related with saddle-node bifurcations, type II and type III with Hopf and inverse period-doubling bifurcations, respectively, and crisis-induced intermittency with a crisis of chaotic attractors. On-off intermittency is associated with the onset of transverse instability of a chaotic attractor embedded in an invariant submanifold of a dynamical system [2, 3]. A distinctive feature of this type of intermittency is that the system's parameter modulation has to be either random, chaotic, or periodic [4, 5, 6, 7, 8, 9].

In on-off intermittency, one or more dynamical variables exhibit two distinct states as the system evolves in time. In the "off" state (laminar phase), there are various time intervals where the variables remain approximately constant, whereas in the "on" state (turbulent phase), irregular bursts of the variables away from their constant values occur. The on-off intermittency is characterized by two fundamental statistical properties: power-law scalings near the onset of intermittency have -1 critical exponents for the mean duration of the laminar (or turbulent) phase versus a control parameter and -3/2 for the probability distribution of the laminar phases versus the laminar length [7]. These scaling relations have been experimentally proven in electronic circuits [10, 11], gas discharge plasma [12], spin-wave instabilities [13], nematic liquid crystals [14, 15], synthetic dynamos [16], a human balancing task [17], a distributed-feedback semiconductor laser [18], a diode laser with external cavity [8], and an optically injected dual-mode semiconductor laser [19].

This paper deals with the experimental observation of on-off intermittency in two bidirectionally coupled semiconductor lasers (SLs). The interest in delay-coupled SLs dynamics arises from its usefulness for both technical applications and fundamental research. The understanding of their dynamical behavior is highly important for advancing technology in optical communication using a chaotic carrier [20]. In nonlinear sciences, these lasers are canonical systems for studying general properties of delay-coupled oscillators which occur in many areas of science and in nature [21], such as neural networks [22], chemical reactors [23], and electronic circuits [24].

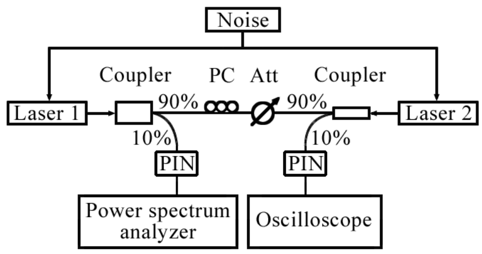

Fig. 1. Experimental setup. PC is a polarization controller, Att is a variable attenuator, PIN represents the photodetectors, and Noise is a noise generator.

Experimental Setup

The experiments are performed with two fiber-coupled discrete mode SLs (Eblana Photonics, 1542 nm), their current and temperature are stabilized with accuracies of ±0.010°C and 0.01 mA, respectively. As shown schematically in Fig. 1, the lasers are connected via 90/10 fiber beam-splitters; 90% of the output radiation is used for the coupling through a polarization controller (PC) to ensure parallel polarization and the remaining 10% is used for detection by InGaAs PIN photodetectors (Thorlabs PDA8GS, 9.5-GHz bandwidth). The signals from the photodetectors are analyzed with a frequency spectrum analyzer (Agilent Technologies EXA N9010A, 9 kHz–13.6 GHz bandwidth) and an oscilloscope (Tektronix TDS520, 500-MHz bandwidth). The optical spectra are measured with an optical spectrum analyzer (ANDO AQ-6315A) and an attenuator (Att) is used to control the coupling strength. Before exploring the dynamics of the two mutually coupled SLs, we ensured that the laser wavelengths and powers were as well matched as possible, by adjusting the laser temperatures and bias currents to avoid frequency detuning. The same Gaussian white noise is applied to the pump currents of both lasers from a noise generator (HP 33120A, 10-MHz bandwidth). Since the internal spontaneous emission noise intrinsic to any SL cannot by itself be rectified, the control effort can only be applied on the external noise.

Time Series Analysis

Depending on the laser parameters and attenuation, the SLs exhibit various dynamical regimes: continuous wave emission, chaos, or low-frequency fluctuations (LFF). For a relatively strong coupling, the lasers operate in the LFF regime and when external noise is applied, the windows of a steady-state emission (laminar phase) appear in the time series. A probable mechanism for such noise-induced intermittency is the influence of noise on the fixed point stability coefficient. The intermittent switches are easily detected when the external noise intensity N exceeds a threshold value N_{th} = 109 mV.

The intermittency observed is typified with a time series statistical analysis. For every noise value, 100 time series (50 ms each) are recorded (Fig. 2) and the mean duration of the LFF window (turbulent length) in the whole 5-sec time interval is calculated.

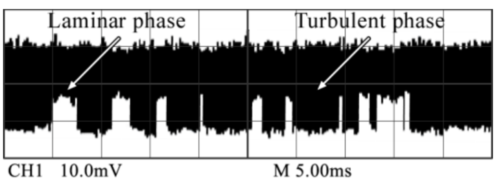

Fig. 2. Time series of laser intensity showing on-off intermittency for 240-mV noise. At this resolution, a shortest distinguishable laminar length is about 0.12 ms.

In a linear scale, the relationship between the mean turbulent length, < τ >, versus the external noise intensity used as a control parameter is well represented by an exponential decay, while in a log-log scale by a linear fit with a −0.96 slope, close to the onset of intermittency (Fig. 3). Since the scaling exponent of -1 has been proven to be a typical characteristic of on-off intermittency, we infer that this is the type of intermittency our system undergoes.

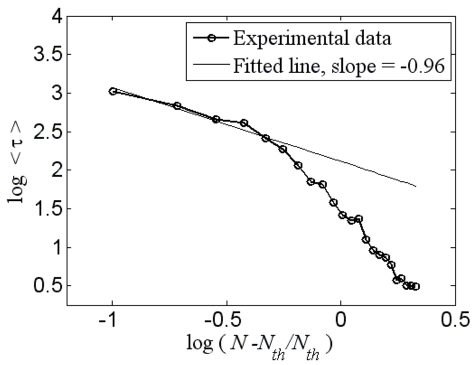

Fig. 3. Mean turbulent phase length versus normalized noise intensity in a log-log scale. The thin trace represents a fitted line near the onset of intermittency.

Another important intermittency feature is the laminar phase distribution. Figure 4 shows the probability distribution of the laminar phases in a linear scale, calculated from the 5-sec long time series at 340-mV noise intensity. This noise intensity is chosen because a large number of switching events in the time series at this value enables a relatively high precision of the statistical measurements. In a log-log scale (Fig. 5), one can see that the probability distribution obeys a power law with a critical exponent close to -3/2 that is also used as a defining feature for on-off intermittency.

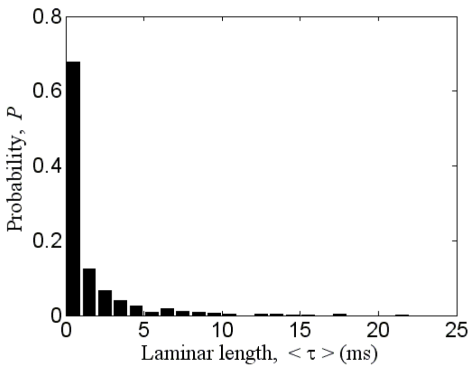

Fig. 4. Probability distribution of laminar phases versus laminar length for N = 340 mV.

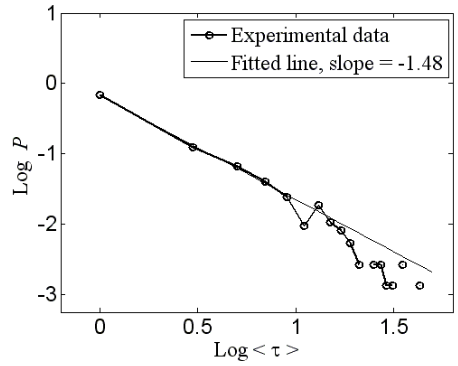

Fig. 5. Probability distribution of laminar phases versus laminar length for N = 340 mV in a log-log scale. The thin line represents a power law fit with a critical exponent of -1.48.

Power Spectrum Analysis

Now, we will demonstrate that the intermittency observed can be also characterized by a power-law scaling for the signal-to-noise ratio obtained from the frequency spectrum analysis. Figure 6 shows the typical power spectrum (averaged over 100 realizations) of the laser intensity in an intermittency regime. The spectral component S_{LFF} with the central frequency of approximately 0.65 MHz reflects the contribution of the turbulent phase, while the noise contributes mainly to the background spectral component S_N. As the noise intensity is increased, S_{LFF} decreases and S_N increases, thus leading to the complete disappearance of the LFF spectral component, meaning that the laminar phase dominates over the turbulent phase.

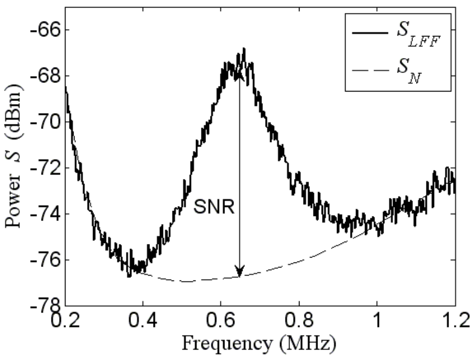

Fig. 6. Power spectrum of the laser intensity averaged over 100 realizations in the LFF regime. Signal-to-noise ratio SNR is measured as an excess of the LFF spectral component S_{LFF} over background noise S_N at the central LFF frequency (about 0.65 MHz).

To obtain the scaling relation from the power spectrum, we measure the signal-to-noise ratio SNR = $S_{LFF} - S_N$ (dBm) at the central LFF frequency (0.65 MHz) as a function of the noise intensity. Figure 7 shows this dependence in semilog scale and figure 8 in a log-log scale.

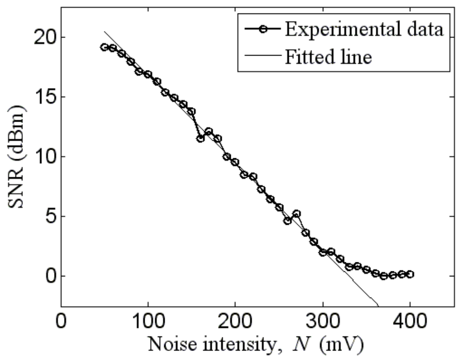

Fig. 7. Signal-to-noise ratio versus noise intensity in a semilog scale. The thin line is a linear fit. N_{th} = 109 mV.

Close to the intermittency onset, linear fits are good approximations up to a 340-mV noise. For stronger noise, the SNR approaches zero because the LFF windows almost disappear in the time series, while a noisy steady state (laminar phase) tendency becomes apparent. The fitted line in figure 8 shows that near the onset of intermittency, the SNR versus the normalized noise intensity obeys a power law with a critical exponent of −1.15, that is in good agreement with the scaling relation obtained from the time series analysis (compare with Fig. 3) since the averaged S_{LFF} is associated with the mean duration of the turbulent phase.

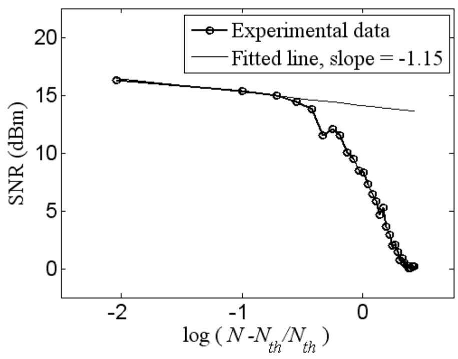

Fig. 8. Signal-to-noise ratio versus noise intensity in a log-log scale. The thin line is a linear fit with slope -1.15. N_{th} = 109 mV.

Conclusion

The intermittent behavior in two mutually coupled semiconductor lasers has been experimentally studied under the influence of external Gaussian white noise applied to the laser pump currents. For strong coupling, windows of a steady-state emission interrupting low-frequency fluctuations emerge in the time series. The time series analysis reveals power laws for the intermittency observed. Near the onset of intermittency, the mean turbulent length is found to obey a -1 power law with respect to the normalized noise intensity, while the probability distribution of the laminar phases over the laminar length displays a

-3/2 power law. These two scaling relations are consistent with the key signature of on-off intermittency. Furthermore, the analysis of the average power spectra exhibits the same -1 scaling exponent for the signal-to-noise ratio versus the noise intensity.

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