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Intermittent dynamics in lasers: Distribution mapping and random number generation

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Abstract—We study the properties of intermittent dynamics occurring in semiconductor lasers embedded in five photonic integrated circuits subjected to optical feedback with different delay times. Intermittency is a transition between two different dynamics induced by a change in the value of a control parameter (feedback strength, injection current). Intermittent waveforms exhibit the features of both dynamics, distributed in a succession of laminar regions and bursts. Typical intermittent dynamics puts into play steady states or low-amplitude periodic dynamics in the laminar regions while bursts are made of chaos or high-amplitude oscillations. We show how the distribution of intermittency is affected as the injection current and feedback strength in the lasers are varied. This is done by mapping all the dynamics observed in two-dimensional bifurcation diagrams corresponding to the five values of feedback delay times (scaling from 33 to 265 ps). We also propose a method based on the irregularity ruling the succession of the laminar regions and bursts specific to intermittency to generate random numbers.

1. Introduction

The recent development of photonic integrated circuits (PICs) has led to major technological advances in optics, allowing in particular to reduce the spatial extension of optical devices considerably [3]. Monolithic PICs have been designed to yield optical chaos to be used for applications in telecommunications [4], fast random bit generation [5, 6, 7, 8] and all-optical self-pulsation generation [9, 10]. The main advantage that PICs offer is the possibility to implement different optical functions such as light emission, amplification and detection in a single device having a minimal spatial extension (sub-centimeter scale). This property opens the way to investigations of the dynamical diversity observed in semiconductor lasers [11].

We report different organizations of the dynamics yielded in semiconductor lasers embedded in PICs subjected to different optical feedback delay times (ranging from 33 to 265 ps). We focus on the variation of the distribution of the dynamics the laser injection current, the feedback strength and the feedback delay time are varied. We first present the how changes in the external cavity length can induce different distributions of the dynamics in given ranges of injection current and feedback strength. Then we focus on a particular dynamics, termed intermittency, and explain how its existence is conditioned by the feedback delay time. Intermittency is a dynamical behavior in which the time trace is organized into laminar regions and bursts, successively following each other in time. We explain the mechanism of this intermittent dynamics and its role in the bifurcation diagrams. Finally, we propose a method to generate random numbers based on the intermittent dynamics, taking advantage of the temporal randomness ruling the irregular successions of laminar regions and bursts. This method differs from the traditional method based on the irregularities of the amplitude of chaotic waveforms [2], with which we bring a comparison of the performances.

2. Experimental setup and observations

Each PIC used in our research consists of a semiconductor laser bounded by a photodiode and an external cavity composed of two independent semiconductor optical amplifiers and a passive waveguide ended by a reflector. The structure of the PICs is presented in Fig. 1. The external cavity lengths range from 1.3 to 10.3 mm, giving external cavity frequencies between approximately 4 and 30 GHz.

In order to understand the distribution of the various dynamics observed in the PICs, an experimental two-dimensional bifurcation diagram obtained by varying the feedback strength J_{SOA1} and injection current J/J_{th} for a PIC having a 3.3-mm external cavity length is presented in Fig. 2. The colors correspond to the different behaviors observed when changing these two parameters. The laser exhibits a large variety of dynamics with regions of steady states, periodic, quasi-periodic dynamics, chaos and low-frequency fluctuations, as can usually be seen in regular

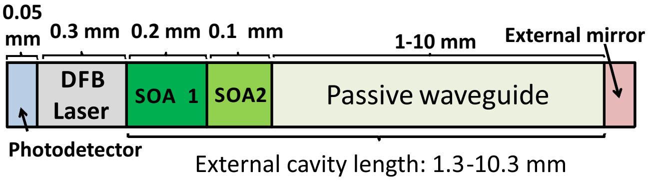

Figure 1: Photonic integrated circuits. DFB laser: distributed feedback laser, SOA: semiconductor optical amplifier. In each PIC, the external cavity includes two SOAs (0.2 and 0.1 mm) and a passive waveguide (1, 2, 3, 4 or 10 mm).

laser systems.

An interesting feature particular to PICs, is the presence of regions of intermittent dynamics which are usually found at the borders of regions of chaos. This optical intermittency is represented in Fig. 3 in which a characteristic double dynamics is visible as the temporal waveform is constituted of laminar regions of low amplitude and bursts of high amplitude irregularly following each other. The existence of intermittency in this optical system with feedback is a consequence of the possibility to obtain very short feedback delay times with the integrated optics technology. In these devices, intermittency is a phenomenon inherent to the formation and destabilization of chaos as it brings and takes out chaos content through the bursts.

3. Random number generation based on intermittent dynamics

The irregular temporal distribution of the laminar regions and bursts in the temporal waveforms showing intermittent dynamics motivates to use this kind of dynamics to generate random numbers. By contrast to traditional methods consisting in sampling the amplitude of a chaotic output waveform, we propose in the present case to use the temporal randomness ruling the succession of consecutive bursts as a source for random numbers. The principle we implement consists in a first time in counting all the times of the laminar regions (times between consecutive bursts). Then all the obtained values are converted into an equivalent number of sampled points, by taking into account the sampling rate of the oscilloscope used for the temporal acquisitions. The following step is a 2n modulo operation applied to these numbers of sampled points. The lengths of the laminar regions are defined as the remainders obtained in this operation, in which n is an integer between 1 and 16. As a final step, the values of the laminar times are changed into binary sequences of n bits. The method used for sampling the laminar times is illustrated in Fig. 4.

In order to study the performances of the random number generation process by using this method, we carry out a comparison between this direct method and two enhanced methods, using respectively the XOR and bit order reverse methods. We demonstrate that the random number genera-

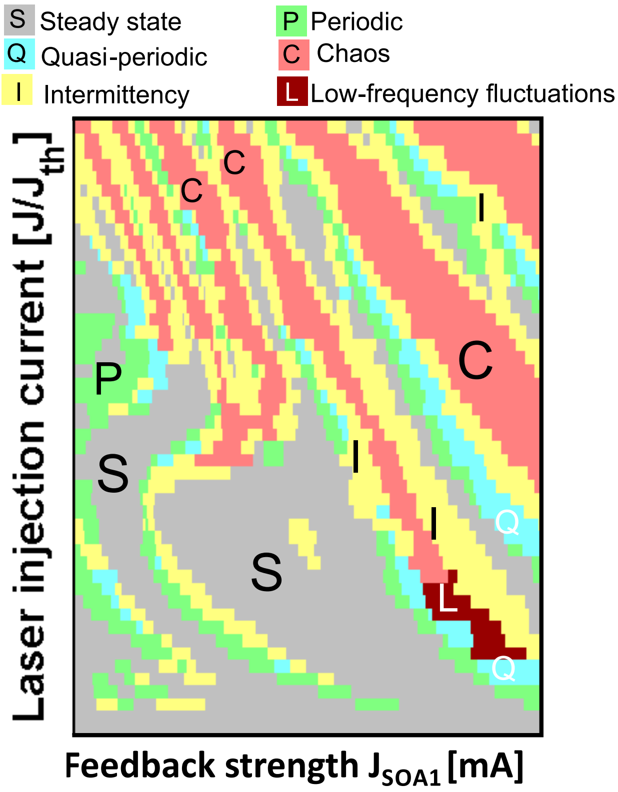

Figure 2: Two-dimensional bifurcation diagram obtained when changing the injection current and the feedback strength in the laser embedded on the PIC with 3.3-mm external cavity.

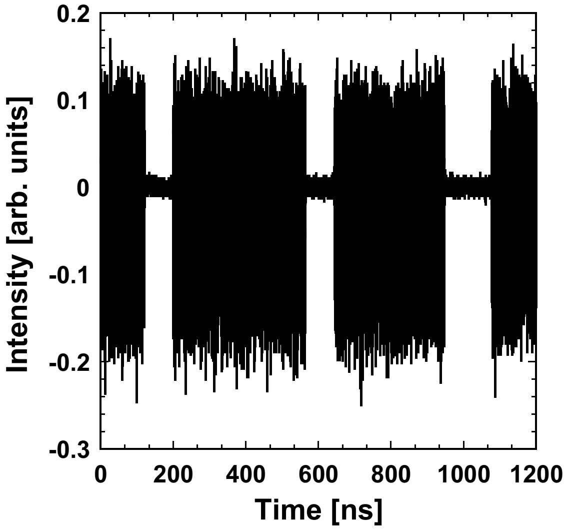

Figure 3: Typical example of intermittency seen in the time trace of the laser output power. The bursts are made of chaos and the laminar regions are steady states.

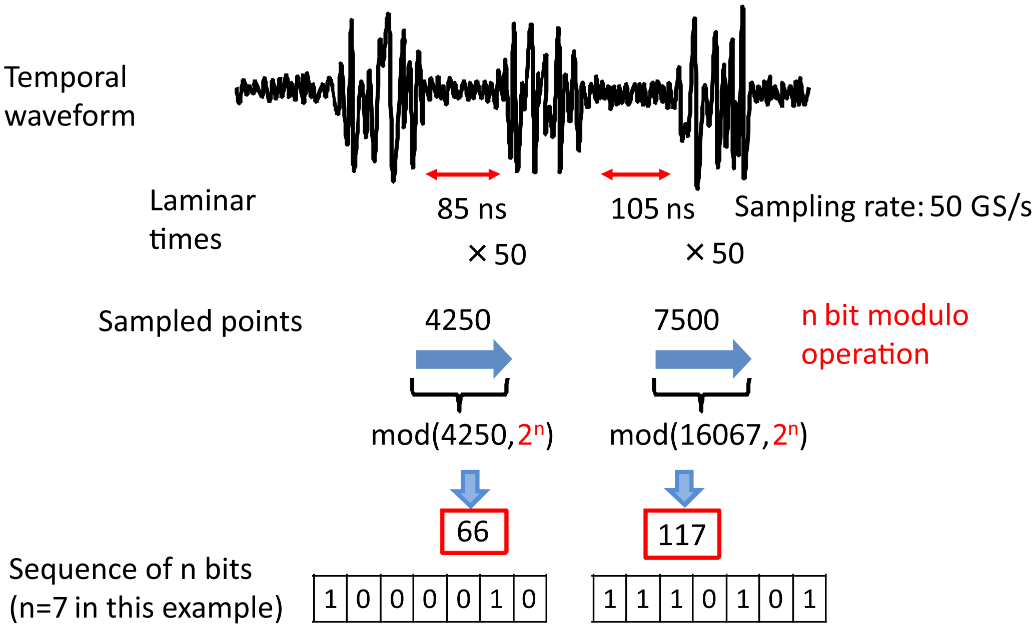

Figure 4: Method for generating random number from a direct conversion of the times of the laminar lengths of the temporal waveform.

tion speed can reach 50 Mbits per second.

4. Conclusion

We presented an experimental analysis of the distribution of the different dynamics that can be yielded in photonic integrated circuits with optical feedbacks from external cavities of a few millimeters. Under the effect of the injection current and the feedback strength, the two-dimensional mapping of the lasers show different properties. In particular, the presence of intermittent dynamics accompanying the stabilization and destabilization of chaotic dynamics has been evidences for different feedback delay times. We also proposed a method for generating random numbers from optical intermittent dynamics based on the temporal randomness governing the cadency at which bursts rise in the temporal waveform of the laser emitted power. By comparing several post-process methods with different sets of parameters, we demonstrated that random number generation was possible with this method.

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