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The rule of bias current of semiconductor laser in chaos communications

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ABSTRACT

The dynamics of chaotic behavior of semiconductor laser diode with optical feedback from single mode fiber loop mirror has been experimentally studied. In the represented configuration the feedback strength was constant while the control parameter with laser injection current was variable, we found a wide range of optical intensity oscillation dynamics such as limit cycles, quasiperiodic and chaos oscillations. These dynamics were analyzed by time series and their extracted FFT power spectrums, phase diagrams (attractors), inter-spike intervals (ISI), these measurements enhanced by bifurcation diagram which clarified the chaotic regimes. Efficient bandwidth of chaotic signals has been calculated and observed to be increased with injection current. The complexity of chaotic system was measured by Shannon's entropy function.

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Introduction

Semiconductor lasers with external cavities exhibit a variety of dynamical phenomena, depending on key parameters, comprising feedback strength, feedback delay, pump current, feedback type, and laser nonlinearity [1]. Optical chaos has attracted considerable attention in the recent years due to its great application in various fields such as chaos based communication encryption, chaotic lidars, fast bit sequence generators [2]. The feedback can be from the mirrors of the laser cavity itself, or it can come from reflections off other optical components in the system. As such, the feedback is typically time-delayed. Dynamically, semiconductor lasers subject to optical feedback are then described by differential equations with a time delay [2–4]. A particular dynamical behavior occurs for moderate feedback near the solitary laser threshold, and is referred to as low-frequency fluctuation (LFF), in the LFF region, the laser output intensity displays irregular, apparently random and sudden dropouts [5]. A chaotic attractor is a trajectory in the phase space of chaotic variables and is frequently used of the analysis of chaotic oscillations, the chaotic attractor behaves in a rather different way from fixed state or periodic oscillations, a bifurcation diagram is used to investigate chaotic evolutions or the change of a certain parameter [6]. Some of nonlinear dynamics and laser diode instabilities have been investigated using fast Fourier transforms (FFT) [7]. The influences of the laser diode injection current on synchronization properties of two coupled semiconductor laser diode have been reviewed in [8]. The inter-spike interval (ISI) histogram distribution displays a structure of sharp peaks that correspond to unstable periodic orbits embedded in a chaotic attractor [6,9]. Entropy is a powerful tool for the analysis of time series, as it allows describing the probability distributions of the possible state of a system, and therefore the information encoded in it [10].

Experimental setup

We consider an optical feedback configuration consisting of a pigtailed single mode semiconductor laser ($\lambda = 1550$ nm) connected to variable optical attenuator (VOA) which in turn is connected to the 2×2 coupler (DC), one branch of 2×2 DC connected to 1×2 coupler (YC), the two output branches of YC are connected together to form a fiber-loop mirror, while the another branch of DC is connected to a fast response (<1 ns rise time with trans impedance amplifier) photo detector (PD) that is connected to sampling digital storage scope (LeCrew 500 MHz), the digital oscilloscope is connected to the PC computer, the setup is shown in Fig. 1. The fiber system (laser's pigtail, VAO, 2×2 DC and YC couplers) is composed of a single mode fiber (SMF) type

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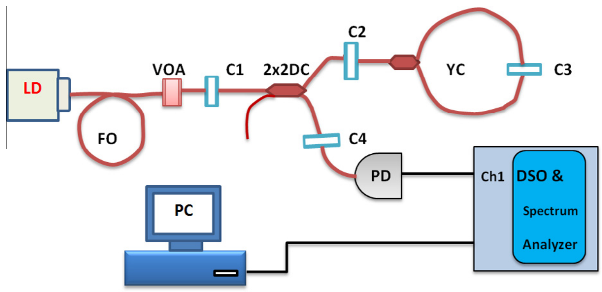

Fig. 1. Experimental setup of laser diode with optical feedback systems. **C1–C4**: fiber optic connecters, **2** × **2 DC**: 2 by 2 directional coupler, **YC**: 1 by 2 **Y**-couplers **PD**: hi speed photodetectors **FO**: fiber optic, **VOA**: Variable optical attenuator DSO: digital storage oscilloscope.

and the whole length is about 7 m that forms an external cavity of optical feedback providing a round trip time about 70 ns.

The optical feedback fiber system made from normal silica single mode fiber (SMF), the polarization was unmaintained and hence the feedback was incoherent. During changing of the laser injection current we recorded the time series of the generated chaotic signals and their FFT spectrums, the step of changing the optical power was 0.01 mw.

Results and discussion

Time series analyses were performed on each captured data set of the generated chaotic signals time series from every laser diode power value which was considered as a control parameter of chaotic spiking evolution as shown in the Fig. 2(a1–a12), these analyses involved power spectrum FFT as in Fig. 2(b1–b12), phase diagram represented by the attractors plotted by embedding technique as in Fig. 2(c1–c12), and inter spike intervals ISI as in Fig. 2(d1–d12). We see from the Fig. 2(a1–a12) that the changes in time series of generated chaotic signals by increasing laser diode power PLD (by increasing its injection current) causes increasing in both the numbers and the amplitude of the spiking rate. Fig. 2(b1–b12) show the changes of the power spectrum FFT of the chaotic signal for each value of the laser diode power PLD, the changes of the power spectrum of the chaotic signal refers to changes in the relaxation oscillation of the laser diode [4,6], and from these power spectrums we deduced the efficient bandwidth (BW) which is defined as the span between the DC and frequency where 80% of the energy is contained within this region, see Ref. [8], and because of our digital oscilloscopes sampling limitation (maximum resolution of the digital oscilloscope was about 1 ns/div of time domain which corresponded maximum sampling rate 25 Gsps of maximum measured frequency about 12 GHz that is according to Nyquest sampling condition $f_s \geqslant f$ where f_s is the sampling frequency and f is a frequency to be measured) therefore we couldn't measure the frequencies beyond 12 GHz, this is what makes the FFT power spectrum to appear as a semi flat spectrum as seen in Fig. 2(b1–b12). From Fig. 2(c1–c4) the phase diagram or the attractors (plotted by embedding or time lagging procedure) can be seen such that they yield limit cycles trajectories at specified values of the laser powers (0.04 mw, 0.2 mw or in laser current 10.33 mA, 11.66 mA respectively) see Fig. 2(c1 and c4). In the laser powers values (0.08 mw, 0.12 mw and 0.29 mw in laser current 10.66 mA, 11 mA and 12.42 mA respectively) as seen in the Fig. 2 (c2,c3,c5) the attractors tend to appear as an increase in density of limit cycle loops which corresponds to quasi chaotic oscillation cases due to low frequency fluctuations (LFF) which occur when chaotic itinerancy is linked with fast chaotic pulsation then the LFF dropouts occur due to a crisis, such that the trajectory gets attracted by a stable manifold of one of the anti-modes (points of destructive interference) and then is rejected back into the low gain region, with the consequence that the power drops and a new cycle is started (Sano et al. 1994 [1] and Mork et al. 1988 [12]). When the laser power is adjusted on the values (0.35, 0.48, 0.55, 0.68 and 1.2 mw in laser current 12.91 mA, 14 mA, 14.58 mA, 15.66 mA and 20 mA respectively) it exhibits chaotic oscillation cases, as can be seen in Fig. 2(c6–c9). Whereas the maximum trajectory dense of the attractors occurs at the laser powers 0.794 and 0.91 mw corresponding to injection currents of the laser ILD = 16.5 mA and 17.55 mA respectively indicating hyper-chaotic oscillations, as shown in Fig. 2(c10 and c11). Fig. 2(d1 and d12) shows portraits of the effects of laser diode power PLD on the inter-spike interval (ISI) histogram distribution consisting of an exponentially decaying function of time, typical of random processes displaced by the pulse duration acting as a refractory time [9], such distribution reflects the dynamics of chaotic spiking durations, and give insight about distribution of inter-spike durations [5]. ISI distributions in the case of chaotic cases are more broadened than in the case of limit cycles or quasi-periodic cases, as seen in Fig. 2(d1–d12). The complete behavior of the system is shown by the Bifurcation diagram, Fig. 4 of the chaotic spike light intensity as a function of injection current of laser diode ILD, as can be seen the amplitude of chaotic intensity gradually increases with the increase of the injection current, reaching to maximum amplitude of bifurcation at current value ILD = 17.58 mA, beyond this region the amplitudes drop abruptly and this is due to that on increasing the injection current the laser power causes saturation of the photodetector's responsivity and eventually dropping of its output amplitudes. There are some regions in the bifurcation diagram (for the laser diode currents 10.3 mA, 10.66 mA, 11 mA, 11.66 mA, 11.75 mA and 11.83 mA) that have low amplitudes and do not exhibit chaotic oscillations but rather exhibit limit cycles and quasi periodic. Shannon's entropy is widely used as a first natural approach to quantify the information content of a system. Given any arbitrary probability distribution $P = \{p_i\!: i = 1 \ldots M\}$, the widely known Shannon's logarithmic information measure is defined by [11] (Fig. 3):

$$S[P] = \sum_{i=1}^{M} p_i ln p_i \tag{1}$$

Regarding the measure of the uncertainty associated to the physical process described by P. If $S[P] = 0$ our knowledge of the underlying process described by the probability distribution is maximal [10,11]. Fig. 5 shows the effects of injection current ILD on the entropy value of generated optical chaotic spiking which is calculated from Shannon's entropy formula see Eq.(1), the entropy measures the random processes (or system complexity) and it's values extended from zero which is full regular process and the one which is a full random process [10,11]. We note in Fig. 5 that the entropy value gradually increases with increasing injection current, the lower values of entropy (<0.25) occur at current values 10.3 mA, 10.5 mA, 11.6 mA and 11.8 mA which indicates the occurrence of quasi periodic oscillations and this is ensured from a bifurcation diagram in Fig. 4, beyond the value ILD = 12 mA the entropy increases with increasing ILD to reach the maximum value at ILD = 17.58 mA, beyond this value the entropy decreases to reach an average value of 0.8 for almost values of current.

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