Control of slave chaotic dynamics by master current modulation in a chaotic coupled laser system

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Two semiconductor lasers operated under external optical feedback conditions in low-frequency fluctuations (LFF) chaotic regime were optically coupled into a master - slave synchronization scheme. The modulation of master injection current induces in the emission of two coupled systems power dropouts at two dominant frequencies. The dropouts rates were studied using the statistical analysis and were correlated with the modulation frequency and the frequencies of natural LFF oscillations of master and slave emissions. Modulation at a frequency included in the range bounded by master and slave natural LFF frequencies has, as effect, the clustering of slave dropouts on two frequencies: the driven and the master natural LFF ones. If modulation frequency is out of this range, it has only the role to group dropouts periods on two frequencies, different from the modulation one. This behavior is consistent with the phase correlation between master laser and external modulator at the used driven frequencies.

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1. Introduction

In an external-cavity semiconductor laser (ECSL) system, as a result of optical feedback on external reflector, field series of nonlinear (chaotic) behaviors of optical radiation emitted by the laser are obtained [1]. As against other sources of radiation used in information technology, such as quantum dot laser [2], fiber laser [3], light-emitting diode [4] etc., chaotic semiconductor lasers based on optical feedback effect are attractive for many applications [5], including optical communications [6–8] and encoded data transmission [9–11]. This is due to their main properties such as broadband spectrum [12,13], possibility of synchronization [14], and existence of different temporal scales of the intensity oscillations [15–17]. In applications, control [18–20] and synchronization [21–23] of chaotic dynamics are some of the most important challenges; they are often analyzed relative to the coupling regime which can be performed in an unidirectional or bidirectional scheme [24–26].

The low-frequency fluctuations (LFF) chaotic regime [27] is one of the most studied issues of ECSL systems and it is obtained for laser operation near lasing threshold. These fluctuations are noticed as cyclic dropouts, almost to zero, of output light power; the time intervals between dropouts depend on laser operation parameters. LFFs occur in the base-band region (up to 100 MHz) and represent envelopes for fast oscillations (of the order of magnitude 1 GHz) whose time period is connected with external cavity length [17]. In the study of LFF chaotic dynamics two topics received a considerable interest: its control (through the modulation of diode injection current, optical phase, or external cavity length) [28–30] and its synchronization into an uni- or bi-directional scheme [23,31,32].

In the present work, two ECSL systems were optically coupled into a master - slave synchronization scheme. Both master and slave systems include each, a semiconductor lasers (SL) operated under external optical feedback conditions in low-frequency fluctuation chaotic regime [23]. The injection current of the master is modulated at frequencies close to, but different from, the master and slave natural LFF oscillations frequencies. Driving the master laser induces in both laser emissions LFFs with two dominant frequencies. The synchronization state between the chaotic dynamics of the coupled lasers and the external modulation is studied using the statistical analysis of power dropouts of laser emission of the two coupled lasers [30]. The results show that modulation at a frequency bonded by those of master and slave natural LFF oscillations has as effect, the clustering of slave dropout periods on two main values: those corresponding to driven and master LFFs. If driven frequency is out of the range limited by master and slave natural LFF frequencies, modulation has the role to group the slave dropout periods, but at other values than the modulation one.

The results allow to better understand the mechanisms of action of an external periodic signal added to the injection direct current of a chaotic laser [33,34] that contribute to the synchronization regimes stability and the emission dynamics control of the coupled systems which contain, each, a chaotic laser.

2. Experimental setup

The utilized experimental setup (Fig. 1) consists of two identical ECSL systems with external cavity lengths of about 64 cm (feedback delay time τ=4.3 ns), optically coupled through a coupling attenuator in a bidirectional lag synchronization scheme [23]. The coupling ratio between the chaotic lasers was about 1.2, being defined as the ratio of master optical injection and solitary (without feedback) slave laser output power. The solitary lasers were single-mode Mitsubishi ML101J8 diode emitters at 663 nm; for each, at optimal parameters, injection current 110 mA and temperature 24 ^{o}C, is obtained a beam power of 40 mW. Lasers were operated near threshold current I_{th} = 54 mA were emission is multimode. The operation parameters were, for master, I = 1.05*I_{th} and T = 22.50 ^{o}C, and for slave, I = 1.05*I_{th} and T = 23.67 ^{o}C, stabilized with an accuracy of 0.01 mA and 0.01 C, respectively.

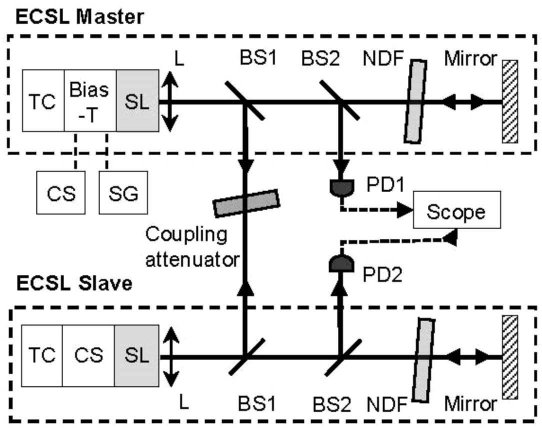

Fig. 1. Setup of two chaotic lasers coupled bidirectionally into a master-slave synchronization scheme. SL, semiconductor laser; TC, temperature controller; Bias-T, frequency domains multiplexor; CS, direct current source; SG, signal generator; BS, beam splitter; NDF, neutral density filter; PD, Photodiode

A WW5061 Tabor Electronics waveform generator adds a sinusoidal signal to the dc injection direct current applied on master laser using a multiplexor ZFBT-6GW bias-tee device [30]. For laser emission signals acquisition and analysis two photodetectors (Becker&Hickl, APM-400-P, and Laser 2000, ET-2030A) were used. A 2.5 GHz Tektronix DPO7254 digital oscilloscope acquired simultaneously the signals. Time series of 5×10^{5} points acquired at a 2×10^{-10} s sampling interval were recorded for dropout statistics.

The dynamics of coupled lasers with external modulation has been studied at two frequencies for a modulation factor m = 3.4 × 10^{-2} [30], where m is defined as the ratio between the rf modulation current intensity and dc intensity.

3. Results and discussions

In this work measurements were made by modulating master dc injection current at 8 and 15 MHz Driven frequencies are different from those of master (10 MHz) and slave (3.4 MHz) natural (without modulation) LFF oscillations. It was aimed to achieve a correlation of the rate of power dropouts for master and slave laser intensities under optical coupling conditions, with modulation frequency. Driving the master at the two frequencies, induces dropouts with a periodicity of 0.125 μs, and 0.067 μs, respectively, resulting in LFFs with two dominant frequencies. At a first estimation, it was observed that slave LFFs become more regular in the coupled system; also, when master is modulated at 8 MHz, close to its natural LFF frequency, the master and slave LFF oscillations have the same frequencies. The modulation at 15 MHz out of the frequency range bounded by the master and slave natural LFF frequencies induces in the chaotic dynamics of both lasers a clustering of the dropouts at two frequencies, as well: the modulation and master natural frequencies, for master; and, the master natural frequency and another, different from the modulation one, for slave.

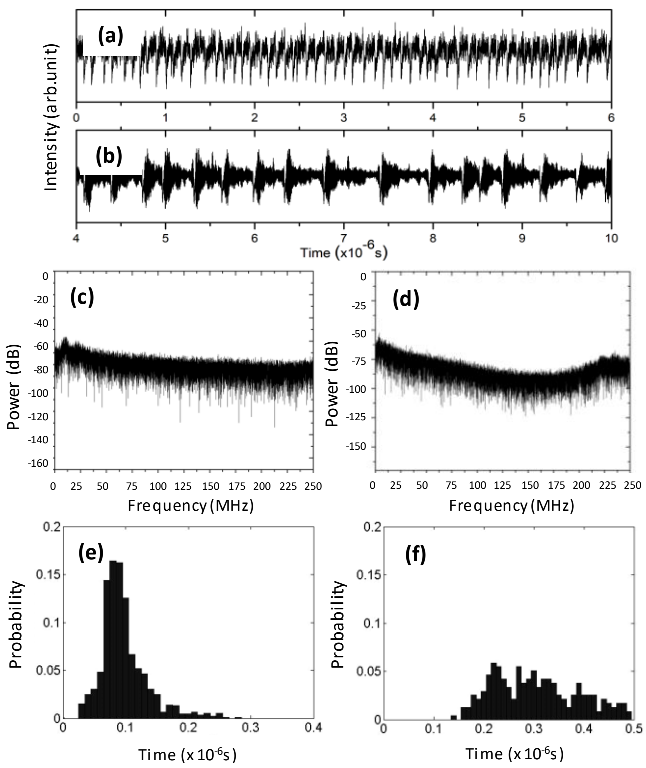

Fig. 2. Laser emission dynamics of master (a, c and e) and slave (b, d and f) chaotic systems in the absence of optical coupling: (a) and (b) laser intensity time series; (c) and (d) associated power spectra, and (e) and (f) histograms of power dropouts

The synchronization state between chaotic coupled lasers and external modulator was studied exploring the statistics of the power dropouts of laser emission intensity. For this purpose, a program based on Shannon's entropy has been developed to evaluate the time periods distributions between consecutive laser intensity events (power dropouts) [30,31].

In Fig. 2 are presented the intensity time series, the associated power spectra and the statistics of dropouts for master (Figs. 2a, c and e) and slave (Figs. 2b, d and f) emissions; these are made in the absence of optical coupling and modulation.

In the case of master dynamics shown in Fig. 2, the presence of a dominant frequency of natural LFF oscillations centered on 10 MHz (time period of 0.1 μs) is observed both in power spectrum (Fig. 2c) and dropout statistics (Fig. 2e). For slave system, the power spectrum and dropout histogram indicate the existence of a frequency broad band centered on 3.4 MHz (time period of 0.3 μs), showing three dominant peaks at 4.5 MHz (0.22 μs), 3.4 MHz, and 2.5 MHz (0.4 μs).

The optical coupling between the unmodulated master and slave leads to delayed synchronization of about $\tau_S = 4.6$ ns of their chaotic dynamics, and it is visible in the intensities time series (Fig. 3a). In this case, the dominant frequency of master and slave LFF oscillations corresponds to the one of the master natural LFFs, 10 MHz (0.1 μs) (Figs. 3b and c).

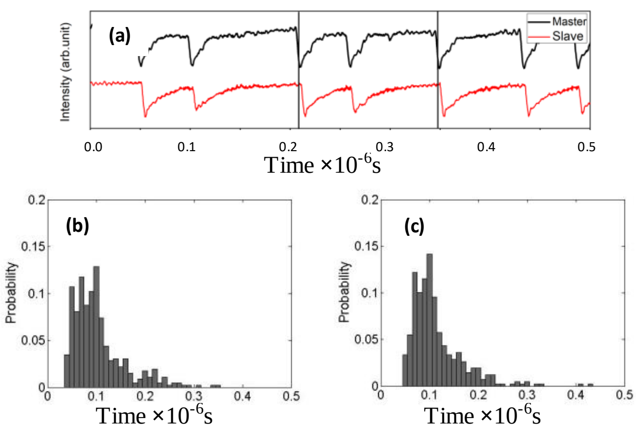

Fig. 3. Laser emission dynamics of master and slave systems optically coupled, without modulation; (a) laser intensity time series of master and slave systems coupled into a lag synchronization scheme (plotted lines are vertically shifted to assure a better view); (b) and (c) histograms of dropouts for master and slave, respectively

In Figs. 4a and c are shown the intensity time series and power dropouts histogram of master laser modulated at 8 MHz, in absence of optical coupling. In the histogram, comparing it with the previous case shown in Fig. 2e (master without modulation), it is observed that dropouts time periods are grouped around the frequency of natural LFF oscillations, 10 MHz (0.1 μs), and the modulation frequency, 8 MHz (0.125 μs). At 15 MHz external modulation (Figures 4b and d), the synchronization of the chaotic dynamics of master ECSL system with the modulator is more obvious. One observes events clustering in a bimodal structure, with maxima centered at 0.067 μs, determined by external modulation, and 0.1 μs, determined by the frequency of natural LFF oscillations.

The chaotic dynamics of master and slave ECSL systems once coupled are changed in the presence of modulation compared to the case without modulation.

Comparing the master and slave intensity time series at 8 MHz modulation (Fig. 5a), it can be observed that the two chaotic dynamics are lag synchronized, but at a short delay time, 3 ns, as against the unmodulated case. The dynamics of both chaotic systems reflected in histograms (Figs. 5b and c) shows a clustering of LFF periods on two frequencies, the master natural one (10 MHz; 0.1 μs), and that induced by modulator. Also, in master intensity time series fluctuations of low amplitude are noticed (e.g., like those indicated by arrows, Fig. 5a) to which slave dynamics is not synchronized.

This shows that the slave system only couples (synchronizes) to master chaotic dynamics, and not to oscillation dynamics, determined by the external modulator. So, at this modulation frequency, only the oscillations induced by the modulator to which master dynamics synchronizes can induce changes in the dynamics of another system that is synchronized with it. The modulation-induced oscillations observed in master intensity dynamics have smaller amplitudes than natural LFF dropouts due to the use of an average modulation factor at an injection dc current close to threshold, which does not affect LFF dynamics [30].

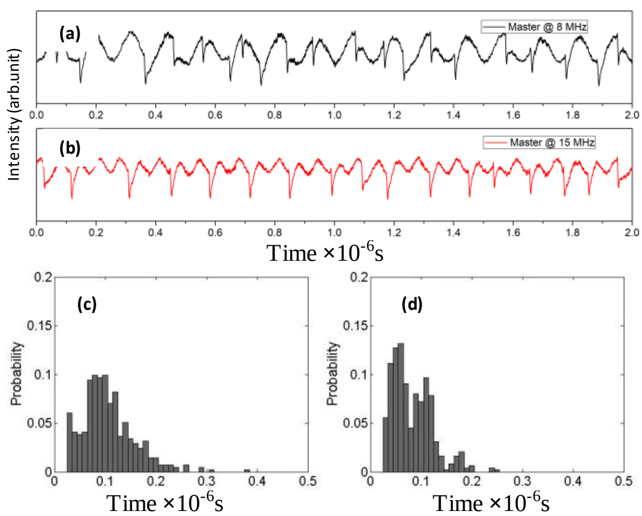

Fig. 4. Laser emission dynamics of master system with modulation at (a and c) 8 MHz and (b and d) 15 MHz, in the absence of optical coupling; (a) and (b) intensity time series, and (c) and (d) histograms of power dropouts

The intensity time series of master and slave systems for master modulation at 15 MHz (0.067 μs) (Figure 6a) seem to be slightly different than at 8 MHz. A first difference is observed in the synchronization regime which became of zero-lag type [23]. Due to perfect synchronization regime, slave laser appears to strongly synchronize with master only on the chaotic dynamics determined by master natural LFF oscillations, not to the one determined by modulator. Also, the histograms of master and slave dropouts (Figs. 6b and c) differ from those at 8 MHz modulation. A more visible and pronounced clustering of master and slave dropouts around the frequency of master natural LFF oscillations occurs; this behavior was found for systems coupling without modulation (Fig. 3), as well. The clustering process takes place, also, around a second dropout period. This corresponds for master system, to the modulation frequency 15 MHz; for slave, it is different, both from modulation and slave natural LFF oscillations frequencies.

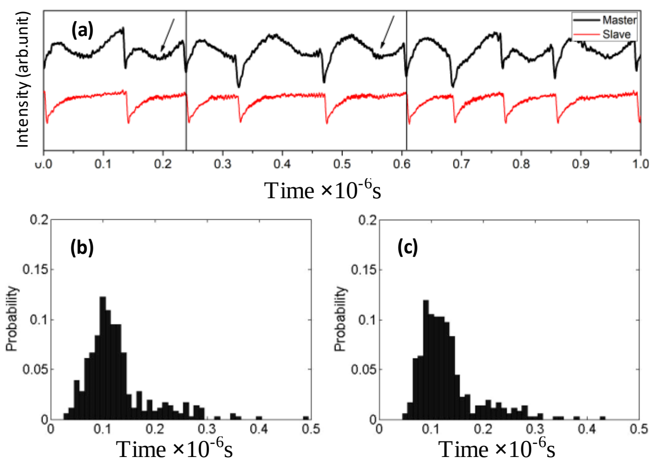

Fig. 5. Laser emission dynamics of master and slave systems optically coupled, for modulation at 8 MHz; (a) intensity time series, (b) and (c) histograms of master and slave power dropouts, respectively. Arrows indicate intensity oscillations induced by the modulation for which master LFF dynamics does not engage

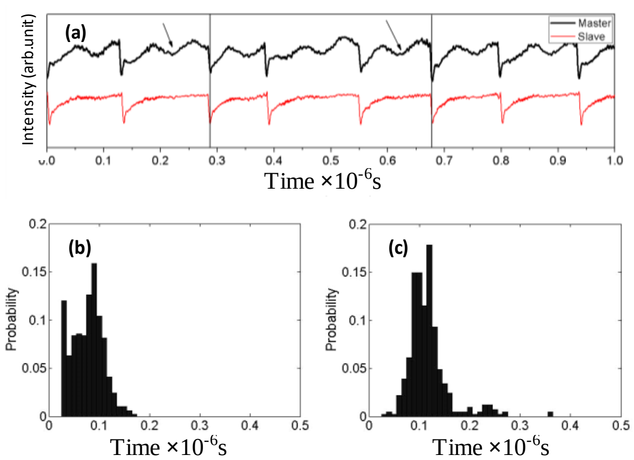

Fig. 6. Laser emission dynamics of master and slave systems optically coupled, for modulation at 15 MHz; (a) intensity time series; (b) and (c) histograms of master and slave power dropouts, respectively. Arrows indicate intensity oscillations induced by the modulation to which slave LFF dynamics is synchronized.

So, modulation at a frequency outside of the range bounded by master and slave natural LFF oscillations, and higher than these, will have no control on slave chaotic dynamic; it just has an effect of dropouts clustering at a second time period, other than the modulation one. In this case, the slave second frequency, which corresponds to a time period of approximately 0.125 μs appears to be totally random. As it is indicated by arrows in Fig. 6a, this frequency can be determined by the intermittent synchronization of the slave LFF dynamics with the low amplitude dropouts induced by modulation at a shorter time period than that of master natural LFF oscillations. The value of second slave frequency of clustering process is depend of the frequency to which the master is modulated, but it is possible to be influenced by the modulation factor [33].

The behavior of entrainment phenomena of master chaotic LFF oscillations is in accordance with recent observations made on the chaotic dynamics of an ECSL system driven by an external periodic signal added to dc component [34]. These observations were made function of modulation frequency, waveform, amplitude, and dc intensity. Thus, function of modulation waveform, driven dropouts dynamics appears to be most sensible for sine waveform (as against pulse-up and pulse-down modulations) at low frequencies, e.g. below ~10 MHz. In our operation conditions, dc current is fixed close to threshold ($I = 1.05*I_{th}$), and sinusoidal modulation is chosen at 8 and 15 MHz, the master system is at the limit of a good entrainment of chaotic dynamics by modulation. But, due to the modulation made around the natural LFF frequency (10 MHz) at a medium modulation factor (which plays an important role [33]), $m=3.4 \times 10^{-2}$, higher that those used in ref. [34], a good entrainment of power dropouts was obtained with frequency increase (Fig. 4).

At the same time, a medium to larger modulation factor does not lead to perfect phase synchronization of the laser and modulator, although the applied periodic signal is frequency resonant with the LFF dropouts of laser emission. With increase of the difference between the two frequencies, laser and modulator run further from the perfect phase synchronization (in phase) regime [30]. This is observed in the histograms of master and slave systems synchronized in conditions of external modulation (Figs. 5 and 6) which is a consequence of intrinsic characteristic of the coupled chaotic systems that synchronize only on master chaotic dynamics. At 8 MHz, close, but not identical to natural LFF oscillations frequency, laser and modulator run almost in phase, and the corresponding period (0.125 μs) is present in slave dynamics. At 15 MHz, when laser and modulator are not in phase, the corresponding period (0.067 μs) is not present; in this case, a higher clustering of events appears at periods between 0.1 and 0.125 μs (10 and 8 MHz).

On the other hand, it appears that master – slave synchronization regimes are influenced by external modulation frequency. When dropouts period is shorter than that of the driven signal, the modulator lags behind laser, and contrariwise, when it is longer, laser lags behind modulator [30]. If, for modulation at 8 MHz the coupled lasers evolve into a lag synchronization regime (with a delay time between their dynamics shorter than that of the unmodulated case of the coupled systems), at 15 MHz they move to a synchronization regime without delays (zero-lag). This behavior is consistent with theoretical and experimental results reported about time delays in the synchronization of coupled chaotic lasers [35] operated under external forcing conditions [36]. Namely, the behavior corresponds to the case of coupling of the identical chaotic lasers, bidirectionally coupled, with almost identical external cavities and coupling delay times, $\tau \approx \tau_s$ (in the limit of 10%), but with small differences between the used parameters (e.g. set temperatures). The additional external signal added to the master in conditions of synchronization, contributes to lowering of the excitability threshold of the slave leading to a decrease of coupling delay time. Thus, the influence of external modulator on synchronization regime is higher when modulation frequency is higher than that of natural LFF oscillations.

4. Conclusions

Measurements about the control of nonlinear (chaotic) dynamics of the emissions of two chaotic external-cavity semiconductor lasers coupled into a master-slave synchronization scheme have been made by master dc current modulation. The injection current was modulated separately at 8 and 15 MHz, frequencies which are different from those of natural LFF oscillations of master (10 MHz), and slave (3.4 MHz) systems, respectively. Driving master laser at the two frequencies induces dropouts with a periodicity of 0.125, and 0.067μs, respectively, which results in LFFs with two dominant frequencies. Statistical analysis of driven power dropouts of the coupled ECSL systems shows that the rates of dropouts become (a) the same for master and slave, and they correspond to the driven and master natural LFF frequencies, when master laser and modulator run in phase, and (b) different for master and slave, when master and modulator are not in phase, even if the applied periodic signal is frequency resonant with LFF dropouts of the master laser intensity. The results show also that master modulation at a frequency that is not in the range bounded by master and slave natural LFF oscillations frequencies has no control on slave chaotic dynamics. It has only the role to clustering the periods of dropouts, but at values other than the modulation one.

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