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Experimental control of power dropouts by current modulation in a semiconductor laser with optical feedback

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Abstract
The injection current of an external-cavity semiconductor laser working in a regime of low-frequency fluctuations (LFFs) is modulated at several MHz. The rate of power dropouts in the laser emission is correlated with the amplitude and frequency of the modulating signal. The occurrence of dropouts becomes more regular when the laser is driven at 7 MHz, which is close to the dominant frequency of dropouts in the solitary laser. Driving the laser at 10 MHz also induces dropouts with a periodicity of 0.1 μs, resulting in LFFs with two dominant frequencies.

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1. Introduction

Semiconductor lasers with optical feedback are a category of nonlinear systems that exhibit a variety of chaotic dynamics. Their interesting behavior is mainly related to the simultaneous existence of two different temporal scales: a relatively slow regime of large power fluctuations also called low-frequency fluctuations (LFFs) in the range of a few MHz when the laser emission drops to almost zero and fast oscillations on a scale of about 1 GHz as the output power is restored back to its initial level [1]. The chaotic oscillations arise when the laser is subjected to optical feedback obtained from a reflector placed in the optical path of the laser beam [2]. Coupling of two identical chaotic lasers can result in total synchronization of their nonlinear output and has shown great promise in achieving secure communications encoded with chaos between these types of optical systems [3]. A topic of great interest is the entrainment of the chaotic oscillations in laser diodes (LDs) [4], which can be achieved by modulating the driving current of the diode [5–7] at low frequency. Modulation of the injection current at high frequency resulted in LFFs synchronized with the driving signal [8].

In this work, the LFFs of an LD with optical feedback are experimentally studied when the injection current is modulated at frequencies close to the mean frequency of power dropouts. The synchronization state between the laser and the external modulator is studied by finding the statistics of power dropouts in the laser emission. The study uses Shannon's entropy on evaluating the distribution of time intervals between consecutive reductions in the laser intensity [9–11]. In addition, the synchronization between the laser and the modulator is investigated by introducing two new variables, the phase of the laser's LFFs and the phase of the driving signal [12]. The ratio of these two phases is estimated during the evolution in time of the chaotic laser [13].

The behavior of the synchronized chaotic diode laser with an external modulator is qualitatively similar to deterministic coherence resonance observed when one of the system's parameter such as the injection current is slightly modified [14] or when the state of pure coherence resonance, when noise is added, leads to more regular spikes in the laser emission [11]. In this paper, no noise is added into the system.

2. Experimental setup

The solitary laser with optical feedback has dropouts spaced randomly in time, between 0.01 and 0.9 μs. Modulating the laser at 7 MHz that corresponds to a period of 0.1428 μs induces power dropouts mainly with this periodicity, even at relatively small amplitudes of the modulating signal. A driving frequency of 10 MHz alters the laser dynamics

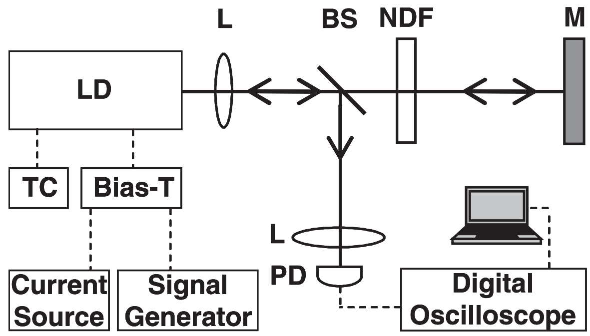

Figure 1. Setup of the LD driven by a periodic signal generator. PD, BS, NDF, M and TC stand for the photodiode, beam-splitter, neutral density filter, mirror and temperature controller, respectively.

by generating power dropouts with an average period of 0.1 μs, besides the intrinsic dropouts of the solitary laser. Although the applied periodic signal is frequency resonant with the intrinsic laser dropouts, an increase in its amplitude does not necessarily lead to perfect phase synchronization between the laser and the modulator, as was observed in a CO_2 laser [12, 15]. In [12], the random spikes in the laser emission exhibiting homoclinic chaos, with a repetition rate of a few kHz, were controlled by periodic electro-optic modulation of the cavity losses.

A single-mode Mitsubishi LD emitting at 663 nm and rated 40 mW at 100 mA was operated near the injection current threshold ($I_{\rm th} = 54$ mA) in an external cavity configuration, as shown in figure 1 [16]. The optical feedback was obtained from a mirror placed at 30 cm distance from the LD. The feedback could be adjusted by rotating a Thorlabs neutral density filter with variable transmittance. The level of feedback was adjusted until well-delimited intensity fluctuations were obtained in the laser emission at an injection current $I = 55$ mA. The temperature of the junction was kept constant at 24 °C. The diode laser was driven by a radio-frequency (rf) sinusoidal wave delivered by a WW 5061 Tabor Electronics waveform generator. The rf signal was added to the injection current of the laser driver using a ZFBT-6GW bias-tee with low insertion loses (0.16 dB at 10 MHz).

An ET-2030A photodetector with a rise time <500 ps converted the instabilities in the laser emission into electrical impulses. A Tektronix DPO7254 digital scope with a bandwidth of 2.5 GHz was used to acquire simultaneously the fluctuations in the laser intensity and the periodic signal coming from the wave generator. The sampling interval was 2×10^{-10} s. Time series of 5×10^5 points were recorded for dropout statistics.

The injection current of the diode laser was composed of the dc pump current and the rf component delivered by the modulator: $I(t) = I_{\rm dc} + I_{\rm m}\cos(\omega_{\rm m} t)$, where $\omega_{\rm m} = 2\pi f_{\rm m}$ is the frequency of the modulator. The modulation factor is $m = I_{\rm m}/I_{\rm dc}$. In figure 2, $f_{\rm m} = 7$ MHz was kept constant and m was increased from 5×10^{-3} in panel (a) to 3.4×10^{-2} and 5.7×10^{-2} in panels (b) and (c), respectively. In figure 2(a), the modulating signal produces little change in the times series of the laser emission. When the amplitude of the modulating signal was increased the dropouts were more regular in time and seemed to follow more closely the driving signal, as shown in figures 2(b) and (c). At the same time, at larger amplitudes the driving rf signal was apparently strong enough to determine a modulation of the laser output, up to 50% of the average level, in figure 2(c). At 10 MHz, the modulation in the laser intensity became more evident as m was increased from 5×10^{-3} in figure 3(a) to 3.5×10^{-2} and 5.8×10^{-2} in figures 3(b) and (c), respectively. The histograms in figures 2 and 3(d)–(f) correspond to the signals of figures 2 and 3(a)–(c), respectively.

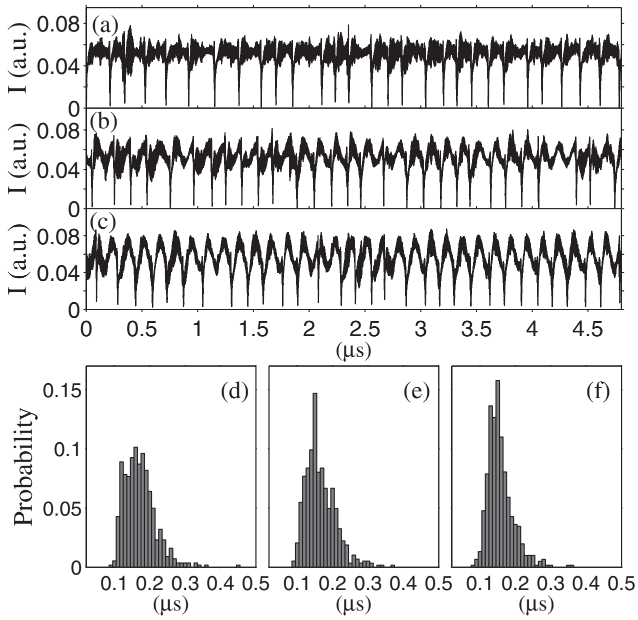

Figure 2. Modulation at 7 MHz: laser intensity in (a)–(c) and statistics of dropouts in (d)–(f) for $m = 5 \times 10^{-3}$, 3.4×10^{-2} and 5.7×10^{-2}, respectively.

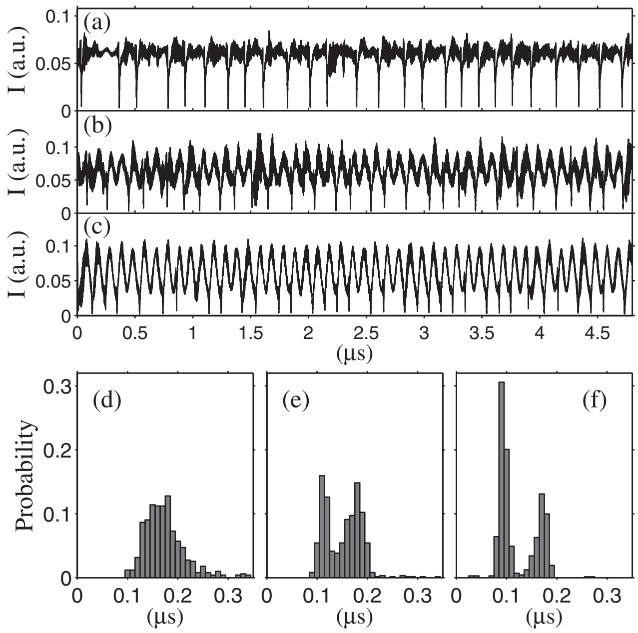

Figure 3. Modulation at 10 MHz: laser intensity in (a)–(c) and statistics of dropouts in (d)–(f) for $m = 5 \times 10^{-3}$, 3.5×10^{-2} and 5.8×10^{-2}, respectively.

3. Statistical analysis of driven power dropouts

Initially a powerful tool for assessing the outcome of a random variable in information theory, the application of Shannon's entropy has been extended to quantify statistical complexity in chaotic systems, including lasers [12, 17, 18]. In order to better evidence the effect of the modulator on the repetition rate of laser dropouts, the time intervals δt_j between consecutive dropouts are represented on a histogram with a number of M bins, each with width d. A probability is associated with each bin filled with N_i time intervals out of a total number N: $p_i = N_i/N$. The entropy of the assembly is $S = -\sum_{i=1}^{M} p_i \log p_i$ [18]. When all N events are uniformly distributed in the histogram, i.e. each bin contains the same number of elements, S becomes $S_{\max}$. For all other distributions $S < S_{\max}$, with the particular case when all N elements are grouped in a single bin and $S = 0$. A coefficient $\sigma = (S_{\max} - S)/S_{\max}$ is introduced for a particular distribution S to characterize the clustering or spreading of the elements represented in the histogram.

A typical recorded data file contains $N \approx 565$ dropouts, while the width of a bin is $d = 0.05\,\mu$s. Figure 2(d) shows relatively equally spread time intervals between 0.11 and 0.22 μs, meaning that these time intervals will appear with the same probability, suggesting a natural tendency of the laser to relax at a preferred rate [19]. In this case $\sigma = 0.287$. A weighted mean of these time intervals produces 0.155 μs or 6.45 MHz, which is close to the chosen modulation value of 7 MHz. At a larger modulation factor a pronounced clustering of these intervals about the peak at 0.15 μs is shown in figure 2(e), for which $\sigma = 0.294$. This is an indication that the higher the amplitude of the driving signal, the larger the number of induced dropouts at this particular rate of 0.1428 μs. For the largest m, the envelope of the distribution intervals is even narrower about the peak value as shown in figure 2(f), and $\sigma = 0.339$. The situation is somewhat similar at 10 MHz and for low m, when a relatively flat distribution is obtained, as can be seen in figure 3(d). However, when m is increased the time intervals cluster about 0.1 μs, and two distinct peaks in the distribution are seen in figure 3(e). As m is further increased the dropouts at 0.1 μs become predominant, as shown in figure 3(f). In this case, σ characterizes the clustering of LFFs' time intervals rather in a bimodal distribution: $\sigma = 0.308, 0.375$ and 0.472 for the cases of figures 3(d)–(f), respectively.

4. Phase evolution of cyclic signals

A numerical solution to the Lang–Kobayshi system of equations [2] describing the dynamics of the external-cavity laser shows the trajectory in the phase-space drifting past the cavity modes toward the maximum gain mode [20]. Occasionally the attractor collides with an unstable antimode and a crisis follows, manifested by an itinerancy of the trajectory toward the threshold level of the charge carrier. Exploiting this feature of the laser attractor, and in analogy with simple chaotic flows such as the Rössler [21], the phase $\Phi_L(t)$ of LFFs is introduced as a variable that increases in time with 2π for each dropout in the laser emission. In other words, for a 2π cycle the trajectory crosses the

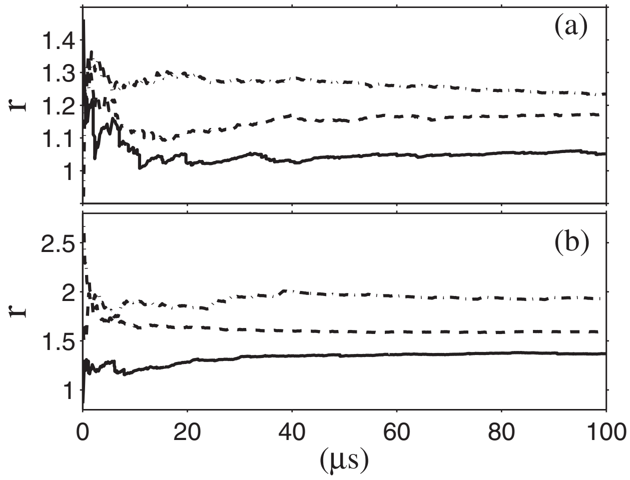

Figure 4. Evolution in time of $r = \Phi_m/\Phi_L$ for driving frequencies of 7 MHz in (a) and 10 MHz in (b). The curves (–·–), (- - -) and (—) correspond to the modulation cases of figures 2 and 3, with increasing values of m.

Poincaré section in the laser attractor. If the moments of laser emission fall-out are denoted by $t_1, t_2, \ldots$, the LFFs' phase at a time $t_j \leqslant t \leqslant t_{j+1}$ with $j = 1, 2, \ldots$, is $\Phi_L(t) = 2\pi(t - t_j)/(t_{j+1} - t_j) + 2\pi(j-1)$. Φ_L is defined as a piece-wise monotonically increasing function with a slope $2\pi/(t_{j+1} - t_j)$ for each time interval Δt_j. The moment t_1 is chosen as the reference time and corresponds to the first dropout in the acquired data file. We further introduce the phase of the modulator based on the representation of the analytic signal and the Hilbert transform. The analytic signal is the complex function defined as $\psi = s_m(t) + i\hat{s}_m(t) = A(t)e^{i\Phi_m(t)}$, where $s_m(t) = I_m \cos(\omega_m t)$ is the modulating signal. In our particular case of periodic modulation the phase Φ_m satisfies $d\Phi_m/dt = \omega_m$ and is unwrapped on the real axis. This means that for each modulator cycle, Φ_m increases with 2π. We define the correlation ratio between the modulator and the laser as $r(t) = \Phi_m(t)/\Phi_L(t)$. For $r = 1$ the laser and the driver run in phase. Occasional phase slips in time between the two phase variables can occur and r becomes rational. When the time between two consecutive dropouts is significantly longer than the period of the modulating signal, $dr/dt > 0$ and r becomes larger than 1. In this case, the laser lags behind the modulator. On the other hand, when the laser power falls at a faster pace $dr/dt < 0$, and the modulator lags behind the laser. In this case, r falls below 1. A phase correlation of the type $r(t) \approx k/l$ at all times, where k and l are integers, is more probable rather than a 1 : 1 synchronization in phase of the two systems [18].

We applied the above procedure to our driven laser, for the modulating frequencies of 7 and 10 MHz. In the first case shown in figure 4(a), $r \approx 1.23$ and 1.17 for the modulation factors $m = 5 \times 10^{-3}$ and $m = 3.4 \times 10^{-2}$, respectively. It becomes clear that as m is increased, the laser is forced to follow up closely with the driver and rare phase slips occur. At $m = 5.7 \times 10^{-2}$, the correlation approaches the 1 : 1 synchronization: $r = 1.05$. In all cases r settles to a constant value after a transient time where phase slips are observed. At 10 MHz and $m = 5 \times 10^{-3}$ the modulator phase is ahead of the laser phase as expected and $r = 1.93$. As m is increased to 3.5×10^{-2} and 5.8×10^{-2}, r passes through 1.5 from 1.59

to 1.37, respectively. $r = 1.5$ means that on average three complete cycles of the modulator correspond to two dropouts in the laser power. For $r < 1.5$, more dropouts are induced at the modulator frequency, as shown in figure 3(f).

5. Conclusions

The LFFs of an external-cavity semiconductor diode laser were driven by a periodic modulation of the injection current and became more regular when the frequency of the modulating signal was very close to the rate of intrinsic LFFs in the solitary laser. Moreover, power dropouts at a slightly higher rate could be induced by increasing the frequency of the modulating signal by about 40%, leading to the observation of LFFs with two dominant frequencies. The power dropouts were statistically analyzed using Shannon's entropy and a ratio between two phase variables that vary cyclically in time, of the modulator and of the LFFs.

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